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THE SENSITIVITY OF ENVIRONMENTAL SURVEYS TO ATMOSPHERIC RELEASES FROM NUCLEAR FACILITIES

by

Charles Alfred Pelletier

A dissertation submitted in partial fulfillment
of the requirements for the degree of
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1966

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THE SENSITIVITY OF ENVIRONMENTAL SURVEYS TO ATMOSPHERIC RELEASES FROM NUCLEAR FACILITIES

Charles Alfred Pelletier

The sensitivity of an environmental survey is expressed in terms of the minimum detectable release rate MDR. The MDR is defined as that release rate which produces a radioactivity level which is just detectable above background in the environment. A method of determining the radioactivity level which is just detectable above background is discussed. The method is based on the confidence interval of the difference between the average radioactivity level near a facility and the level in an area remote from the facility, both levels being measured simultaneously, the latter serving as background for the former. The method is applied to data collected as part of the environmental survey for the Enrico Fermi Atomic Power Plant. The data include measurements of gross beta radioactivity in air, external gamma radiation exposure and gross beta radioactivity deposited on precipitation collectors. A mathematical model is developed which relates the stack release rates of iodine-131, noble gases and particulate radioactivity to their respective environmental levels. Meteorological data collected at the Fermi site are used as inputs to the model.

It is found that the minimum detectable radioactivity level MDL is proportional to the background level in the environment $\bar{x}_b$, i.e.,

$$MDL = G\,\bar{x}_b$$

In the case of airborne particulate radioactivity the average value of G is found to be about 0.3 for one or two week sampling periods. For sampling periods of one year, the value of G is found to be reduced to about 0.1. Values of G for the other sample media are given and the dependence of G on several sources of variation in an environmental survey is discussed.

The MDR is directly proportional to the MDL, i.e.,

$$MDR = \frac{1}{R(Q=1)} \; MDL$$

where R(Q=1) is an average radioactivity level produced by a unit release rate from the facility.

The value of R(Q=1) for particulate radioactivity is found to be about 7×10^{-14} μCi/cc per μCi/sec for the air sampler near the Fermi Plant. Values of R(Q=1) for releases of noble gases and iodine-131 are also given.

The applicability of the methods and results to other locations is discussed.

PREFACE

The most important consideration in environmental monitoring is sample collection. To collect a representative sample consistently takes patience, persistence, mechanical ability and just good common sense. I acknowledge with pleasure the excellent work of Mr. James Burns in collecting the samples on which this study is based. I thank Mr. Robert Quattro for his good work in processing the samples, and Mrs. Janet Chorbajian for her help with the mathematics in this study. I thank Mr. Harold Wedlick for assuming many of my work responsibilities while writing the thesis and Mrs. Donna Luckhardt for doing such a good job of typing the first draft of the thesis. My special thanks go to Dr. G. Hoyt Whipple for his patience and understanding throughout this study.

I acknowledge with gratitude the whole-hearted support of the National Sanitation Foundation and particularly that of the late Walter F. Snyder, former executive director. I gratefully acknowledge the Fallout Studies Branch of the U.S. Atomic Energy Commission for financial support in developing parts of the mathematical model (contract No. AT(11-1)-1333).

Finally, I thank my wife Linda. Without her patience and strength this thesis would not have been completed.

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I NATURE OF THE PROBLEM

For the purposes of this investigation an environmental survey shall consist of the collection and analysis for radioactivity of airborne dust, rain, water, milk and other environmental media, as well as the measurement of external radiation exposures.

An environmental survey may be carried out from two points of view. One is the public health point of view in which all the radioactivity in the environment is of interest. The other point of view is that of the facility operator who is primarily interested in only that portion of the environmental radioactivity resulting from his operations.

Environmental surveys are standard practice for large nuclear facilities such as fuel reprocessing plants, uranium ore refineries and large research, test and production facilities like the national laboratories in the United States. These surveys are carried out before and during the operation of the facility. Surveys before operation are usually referred to as pre-operational, and those during operation, as operational. The Hanford Plant near Richland, Washington collects about 40,000 samples annually.[1] This survey is one of the largest in the world. It seems to be generally accepted that environmental surveys for these large operations are necessary because in the words of Blatz[2] "Such plants, if operated without the proper safeguards, could cause a

gradual increase in the local environmental radiation background and appropriate precautions should be taken."

On the other hand, the value of environmental surveys (particularly pre-operational surveys) for civilian nuclear power reactors is being questioned both in this country and abroad.[2-8] In spite of this controversy, all operating power reactors in this country carry out some form of environmental survey.[7] The controversy centers around two questions: First, are environmental surveys sensitive enough to detect releases of radioactivity that are considered significant; and, second, even if these surveys can detect sufficiently small releases, is the information gained worth the price? The first question is purely technical; the second involves not only technical, but also economic, legal, public relations and even moral considerations.

The purpose of this research is to provide a partial answer to the first question: How sensitive are environmental surveys? The problem divides itself into two parts: First, the minimum radioactivity levels which an environmental survey can be expected to detect above background; and, second, the radioactivity levels in the environment which can be expected as a result of releases from a nuclear facility. The term, sensitivity of a survey, is used here to mean the smallest release rate which will produce the minimum detectable radioactivity levels in the environment.

In order to hold the problem to a reasonable size, only the sensitivity of environmental surveys to airborne releases is considered, and the radioactivity measurements are restricted to those which are relatively easy to make on a routine basis and/or to those which have been

found to be the most sensitive in detecting the presence of fallout from nuclear weapons testing.[8] The measurements are: 1) filterable airborne gross beta radioactivity; 2) non-volatile gross beta radioactivity deposited on precipitation collectors; 3) iodine-131 concentrations in the milk of cows; and 4) exposure to the radiations from noble gases and their daughter products.

II. MATHEMATICAL FORMULATION OF THE PROBLEM*

A. Minimum Detectable Radioactivity Levels

1. In the absence of environmental background

In the absence of environmental background radioactivity, i.e., background radioactivity at the collection site, the minimum level of radioactivity which can be detected is a function of the size of the sample and the efficiency and background counting rate of the counter used to assay the sample. Incidently, the absence of background at the collection site and the presence of background at the site of counting are deliberately inconsistent. Note that, in this study environmental background consists of the debris from nuclear weapons testing as well as the naturally occurring radionuclides.

The random error associated with a net counting rate n_x is given by:[9]

$$ERR_Z = Z \left(\frac{n_x + n_b}{t_s} + \frac{n_b}{t_b} \right)^{1/2} \quad (1)$$

where: ERR_Z = error (cpm)**

Z = a statistic, the value of which depends on the confidence level with which one wishes

---

*The mathematical model to be described is programmed and is available in the MAD language from the author.

**See Appendix B for the explanation of symbols and abbreviations.

to declare the error ERR_Z. The values of Z for the 95% and 99% confidence levels are 1.96 and 2.58, respectively.

n_x = net counting rate of the sample (cpm)

n_b = background counting rate (cpm)

t_s = length of time for counting sample (min)

t_b = length of time for counting background (min)

The error expressed as a fraction of the net counting rate n_x is given by the following expression:

$$FC_Z = ERR_Z/n_x \tag{2}$$

where: FC_Z = fractional error

Substitution of equation 2 into equation 1 gives the minimum detectable net counting rate as a function of t_s, t_b, n_b, F_Z and Z as shown in the next equation:

$$n_x(\text{minimum}) = \frac{Z^2}{2\, t_s\, FC_Z^2} \left\{ 1 + \left[1 + \frac{4 n_b FC_Z^2 t_s (t_b + t_s)}{Z^2\, t_b} \right]^{1/2} \right\} \tag{3}$$

For small values of n_x (minimum) the optimum ratio t_s/t_b is 1,[9] which simplifies equation 3 somewhat.

The minimum detectable radioactivity (henceforth referred to as the MDA) is found by dividing n_x(minimum) by the counting efficiency as shown in the next equation.

$$MDA = \frac{4.5 \times 10^{-5} n_x(\text{minimum})}{EFF_C} \quad (4)$$

where: MDA = minimum detectable radioactivity (μCi)

EFF_C = counting efficiency (cpm/dpm)

4.5×10^{-5} = a constant to convert dpm to μCi.

The MDA in equation 4 is common to all types of samples encountered in an environmental survey except the measurement of exposure to beta and gamma radiation.

The minimum radioactivity level which can be detected in the absence of environmental background radioactivity is given by:

$$MDL = MDA/SS \quad (5)$$

where: MDL = minimum detectable radioactivity level (units depending on medium being sampled)

SS = sample size (units depending on medium being sampled)

The minimum detectable exposure level from beta and gamma radiation (which also will be referred to as the MDL) has no useful meaning in the absence of background and therefore is not included in this section.

It should be noted that in the absence of background, it is the radioactivity in a single sample that is important as far as the MDL is concerned. It will be shown in the next section that in the presence of background, it is the average radioactivity level of several samples that is important.

2. In the presence of environmental background

As already mentioned, the operator wishes to distinguish the radioactivity released by his facility from the background radioactivity. The method to be described is one way of making this distinction. It consists of measuring the average radioactivity level near the facility over a period of time and subtracting from it the average radioactivity level measured in an area remote from the facility over the same period of time. Ideally, if the background levels are the same near and far from the facility, and the facility releases no radioactivity, the difference between the two measurements would be zero. In practice, however, the difference is almost never zero. For several reasons, a random error is associated with each measurement. The magnitude of this random error determines the magnitude of the MDL.

The minimum radioactivity level which can be detected above the environmental background is based on the one-sided confidence interval of the difference between two means and is given by:

$$MDL = (\bar{x}_f - \bar{x}_b) + t_{theo} S_p (1/N_f + 1/N_b)^{1/2} \quad (6)$$

where: MDL = minimum detectable radioactivity or exposure levels above background (units depending on the medium)

$\bar{x}_f$ = average radioactivity or exposure level measured in an area close to the facility (units of the MDL)

$\bar{x}_b$ = average radioactivity or exposure level measured in an area remote from the facility (units of the MDL)

t_{theo} = a constant, the value of which depends on the number of samples making up the averages $\bar{x}_f$ and $\bar{x}_b$, and the confidence level with which one wishes to declare the MDL. For five samples in each group and for the 99% confidence level, $t_{theo} = 2.9$.[13] Note that t_{theo} in equation 6, and Z in equation 1 are analogous.

N_f = number of observations in the area close to the facility

N_b = number of observations in an area remote from the facility

S_p = pooled sample standard deviation.

where:

$$S_p = \frac{(N_f-1)S_f^2 + (N_b-1)S_b^2}{N_f + N_b - 2}$$

and

S_f^2, S_b^2 = sample variance for the area near facility and background area respectively

where:

$$S^2 = \frac{\sum_{i=1}^{N} (\bar{x}-x_i)^2}{N-1}$$

The minus sign in the confidence interval is deleted because only values significantly greater than $\bar{x}_f$ are of interest. Equation 6 applies to all the measurements made in this investigation.

Before the MDL is calculated, $\bar{x}_b$ and $\bar{x}_f$ must be tested to determine whether they are significantly different. The value of the MDL has no meaning unless $\bar{x}_b = \bar{x}_f$. The t test is used to test for significant differences. It is formulated in the present notation as follows:[12]

$$t = \frac{\bar{x}_f - \bar{x}_b}{S_p(1/N_f+1/N_b)^{1/2}} \tag{7}$$

If t is greater than t_{theo}, then $\bar{x}_f$ is declared significantly larger than $\bar{x}_b$. If t is less than $-t_{theo}$, then $\bar{x}_b$ is declared significantly larger than $\bar{x}_f$. During the preoperational survey it is important to find out whether $\bar{x}_b$ and $\bar{x}_f$ are significantly different.

B. Relation of Stack Release Rate to Environmental Levels of Radioactivity

1. Air concentrations of radioactivity neglecting ground deposition and radioactive decay

A mathematical expression relating the rate of release of a contaminant into the atmosphere to the resulting air concentration at some point in the atmosphere should meet the following three requirements:[14]

1) It should describe the variation of the concentration of the contaminant within the plume (distribution of contaminant within the plume).
2) It should describe the dimensions of the plume at any distance downwind from the point of release (dimensions of the plume).
3) The quantity of the contaminant should be accounted for at all points in space and time (continuity).

The derivation of the diffusion model relating stack release to air concentration is described under the headings in parentheses after each of the three requirements.

Distribution of the contaminant within the plume: The contaminant is assumed to have a Gaussian, i.e. normal, distribution about the centerline of the plume in both the vertical and the horizontal directions. The bulk of the experimental evidence for elevated sources supports this assumption,[14] even at fairly large distances from the point of release.[18] The only consistent evidence which tends to refute the assumption is in the case of the vertical distribution from a ground level source.[15] Here evidence is available which shows that the distribution may be closer to an exponential one. However, Pasquill[15] has shown that the difference in the centerline concentrations for the two distributions is less than a factor of 2.

The following equation describes the concentration of a contaminant at any point downwind from a continuously emitting point source in infinite space.[15]

$$\chi(x,y,z) = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z} e^{-1/2\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)} \qquad (8)$$

where: χ = concentration at any point ($\mu Ci/m^3$)

Q = emission rate ($\mu Ci/sec$)

$\bar{u}$ = average wind speed (m/sec)

σ_y, σ_z = standard deviations of the Gaussian distribution in the y and z directions respectively (m)

y, z = distance from the centerline of the distribution in the y and z directions respectively (m)

Equation 8 has been derived from the classical Fickian diffusion equation by assuming that the diffusing power of the atmosphere (usually called the diffusivity) and the average wind velocity $\bar{u}$ are constant with height.[19,22] However, there is no doubt that the diffusivity and $\bar{u}$ do vary with height in the lower layers of the atmosphere. Equation 8 has also been derived by applying the continuity condition to an already assumed normal distribution of concentration.[15]

Two different treatments have been applied to equation 8 to make it applicable to sources on or near the ground; a reciprocal theorem postulated by Bosanquet and Pearson and later proved mathematically by Smith,[22] and the method of images used by Sutton.[20] The end result of both treatments is the same. The effect is to add the concentrations from two sources, one emitting a contaminant from a height H and the

other emitting a contaminant from a height -H assuming that the ground is not there. The resulting expression is:

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} e^{-\frac{y^2}{2\sigma_y^2}} \left(e^{-\frac{(z-H)^2}{2\sigma_z^2}} + e^{-\frac{(z+H)^2}{2\sigma_z^2}} \right) \quad (9)$$

Since equation 8 has no theoretical justification when applied to atmospheric diffusion problems, neither has equation 9. Equation 9 should be thought of as an interpolation formula which, when used with appropriate values of σ_y and σ_z, predicts downwind concentrations with acceptable accuracy.

Equation 9 is used exclusively in the present model.

Dimensions of the plume: The best known and probably the most widely used adaptation of equation 9 is that of Sutton.[19] His values for σ_y and σ_z are based on an extension of G. I. Taylor's work on the statistical properties of atmospheric turbulence.[21] Specifically, it is based on an assumed frequency distribution of eddy sizes. The following expressions for σ_y and σ_z may be deduced from Sutton's work.[19,15,22,23]

$$\sigma_y = \frac{1}{\sqrt{2}} C_y x^{1-n/2} \quad (10)$$

$$\sigma_z = \frac{1}{\sqrt{2}} C_z x^{1-n/2} \quad (11)$$

where: C_y and C_z = virtual diffusion coefficients ($m^{n/2}$)

x = distance downwind from the source (m)

n = stability parameter

From a theoretical standpoint, equations 10 and 11 are applicable only to cases of neutral stability. However, it can be said that, in general, Sutton's equations give acceptable results when C_y, C_z and n are determined by diffusion experiments.

Recent atmospheric diffusion research has been directed away from the development of diffusion equations with fixed parameters, such as Sutton's n, C_y and C_z, and towards a more flexible expression for the dimensions of the plume. This is a result of studying the properties of atmospheric turbulence itself.

In line with these developments Pasquill[16,24] has developed an ingenious method for determining σ_y and σ_z. He has shown that the mathematical expressions for the statistical effects of finite sampling and averaging time on the measurement of a random variable are the same as certain mathematical extensions of G. I. Taylor's theoretical work.[16,25] By assuming a simple relationship between the Lagrangian* and Eulerian** variations of wind velocity, Pasquill has derived the following relationships between the plume dimensions, σ_y and σ_z, and the standard deviation of the wind direction measured at the point of release.

$$\sigma_y/x \simeq [\sigma_\theta]_\tau, \; x/4\bar{u} \tag{12}$$

$$\sigma_z/x \simeq [\sigma_\phi]_\tau, \; x/4\bar{u} \tag{13}$$

---

*The velocity variations of an element of air moving downwind with an average speed $\bar{u}$.

**The velocity variations at a fixed point.

where: σ_θ = standard deviation (radians) of the horizontal wind directions measured at the point of release. The wind directions are values formed by taking $x/4\bar{u}$ second averages from a continuous wind trace. The total number of wind directions used to compute σ_θ is $4\tau\bar{u}/\bar{x}$. The value 4 is the result of the assumed relationship between the Lagrangian and Eulerian variations in velocity.

τ = duration of release, or the duration of measuring the release, whichever is shorter (seconds).

σ_ϕ = standard deviation (radians) of the vertical wind directions measured at the point of release computed in the same manner as σ_θ.

All the other symbols have the same meaning as in the previous equations.

Equation 12 and 13 require that the atmospheric turbulence be homogeneous over the distance x. This is a good assumption in the absence of unusual surface topography[24] and wind shear (changing wind direction with height). The data of Hewson, et al. show that equation 12 can underestimate σ_y determined by photographic methods by about a factor 2 in the presence of substantial wind shear in a stable atmosphere.[26] The discrepancy between the two methods of measuring σ_y is less with the same wind shear in neutral and unstable atmospheres.[26] The standard deviation in the z direction apparently is unaffected by wind shear.

The meaning of Pasquill's equations are important to the later development of the diffusion model. The meaning and relationship of his equations to those of Sutton's will be discussed in terms of equation 12. For given values of $\bar{u}$ and τ, σ_y/x will decrease with x. This is because the averaging time $x/4\bar{u}$ increases with x, and the longer the averaging time the smaller the standard deviation because the contribution from the smaller eddies is damped out. The rate of decrease of the standard deviation with averaging time depends on the relative frequency of the smaller eddies making up the whole turbulence regime. Sutton's equation 10 expresses the same thing when written in the following form:

$$\sigma_\theta = \sigma_y/x = \frac{1}{\sqrt{2}} C_y x^{-n/2} \tag{14}$$

Equation 14 shows that σ_y/x decreases as a power of x, the power depending on the assumed value of n.

For given values of $\bar{u}$ and x, σ_y/x increases with τ because as τ increases, more of the larger eddies are included in the computation of σ_θ. Sutton's equation 10 does not permit time variations of σ_y. The usual practice is to make the values of C_y larger for larger values of τ. It is important to note that Sutton's equation is used to calculate an average value of χ over the sampling time τ while Pasquill's equation gives an instantaneous value of χ.

Equation 13 has the same meaning for vertical diffusion as equation 12 has for horizontal diffusion. However, because vertical diffusion is bounded by the ground below and usually by an isothermal or inversion

layer aloft, the eddies are not as large as in the unbounded horizontal direction, and consequently σ_z is not as dependent on τ as is σ_y.

The sampling periods used for environmental monitoring are usually no shorter than one day nor longer than one month. Furthermore, the samplers measure time-integrated concentrations rather than instantaneous or average concentrations. Therefore, the model is set up to compute a daily integrated concentration. Integrated concentrations for periods longer than one day are found by summing the daily integrated concentrations.

A combination of both Pasquill's and Sutton's expressions for σ_y and σ_z are used in the model which, for better understanding is considered in its component parts.

In the case of horizontal diffusion the average value of σ_y for the first hour of diffusion is calculated using Sutton's equation 10 with values for the C_y and n recommended by Hewson, et al. for three atmospheric stability categories measured on the site of the Enrico Fermi Atomic Power Plant.[27] Table 1 lists these values.

The next equation shows the relationship between σ_y, x and τ used in the model for periods of release greater than 1 hour.

$$\sigma_y = x\,[\sigma_\theta]_1\,\tau^d \tag{15}$$

where: $[\sigma_\theta]_1$ = an average σ_θ for 1 hour releases computed from equation 14 using the values in table 1 (radians)

d = a coefficient computed from measured values of $[\sigma_\theta]_{24}$ and values of $[\sigma_\theta]_1$

$$d = \ln\left([\sigma_\theta]_{24}/[\sigma_\theta]_1\right)/3.19$$

TABLE 1

RECOMMENDED* VALUES OF C_y AND n

Stability**	n	C_y
Inversion	0.55	0.40
Weak Lapse	0.25	0.40
Strong Lapse	0.20	0.40

*Recommended by Hewson, et al.[27] for use in reactor hazards evaluation at the Enrico Fermi Atomic Power Plant Site. The values are appropriate to releases lasting on the order of one hour.[27]

**Inversion - positive temperature lapse rate

Weak Lapse - temperature lapse rate less than 0 and greater than the dry adiabatic (-1°C/100m)

Strong Lapse - temperature lapse rate less than the dry adiabatic

$[\sigma_\theta]_{24} = \sigma_\theta$ for a 24 hour release, the values of which are measured and used as inputs to the model

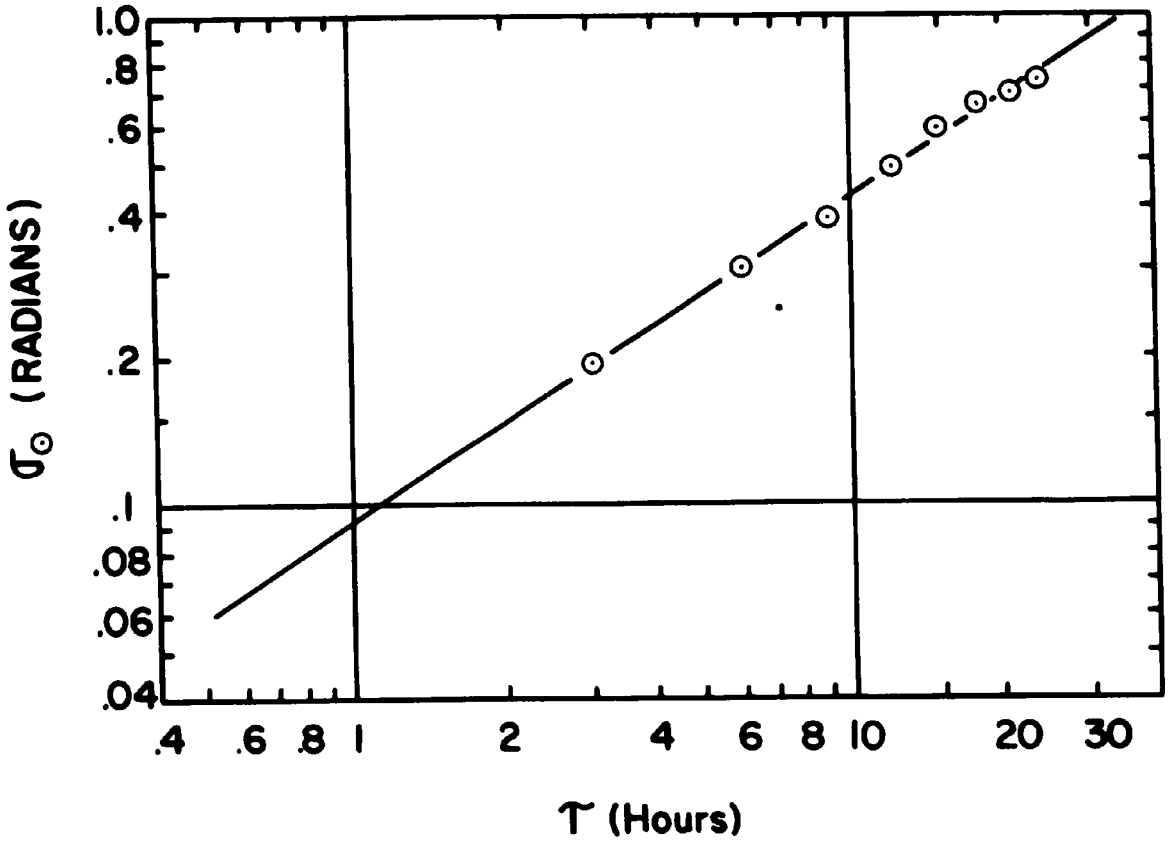
Equation 15 was adapted from Pasquill's equation 12 in the following manner: The form of the relationship between σ_θ and τ was found to be logarithmic as shown in Figure 1. Figure 1 shows three-year average values of σ_θ plotted against τ. The values of σ_θ are computed from hourly average values of the wind direction at 100 feet.

The average wind speed at the Fermi site is about 5 m/sec. Therefore, an averaging time $x/4\bar{u}$ of 1 hour is equivalent to a distance of 72,000 meters. The value of σ_θ at this distance, computed from equation 14 using the data of Hewson et al. for the weak lapse condition, is 0.07 radian. This value is in good agreement with the values shown in Figure 1.

Of course, σ_θ for any given day may vary considerably from those shown in Figure 1, and therefore d is computed from the measured value of $[\sigma_\theta]_{24}$ and whichever value of $[\sigma_\theta]_1$ is found to be applicable that day.

There are two features of equation 15 worth noting. It is assumed that for the first hour, diffusion is dependent only on the prevailing atmospheric stability, but that for τ greater than 1 hour this dependence decreases until at 24 hours horizontal diffusion is independent of stability. The second feature is that for small values of τ, σ_θ decreases with x as n/2, but as τ increases, the rate at which σ_θ decreases with x also decreases, i.e. n becomes smaller, and at 24 hours equals zero. This is reasonable because for large τ's, σ_θ assumes values which are

FIGURE 1. THREE-YEAR AVERAGE VALUES OF $\sigma_\odot$ AS A FUNCTION OF THE SAMPLING TIME $\underline{T}$. The standard deviation $\sigma_\odot$ is computed from hourly average values of the horizontal wind direction.

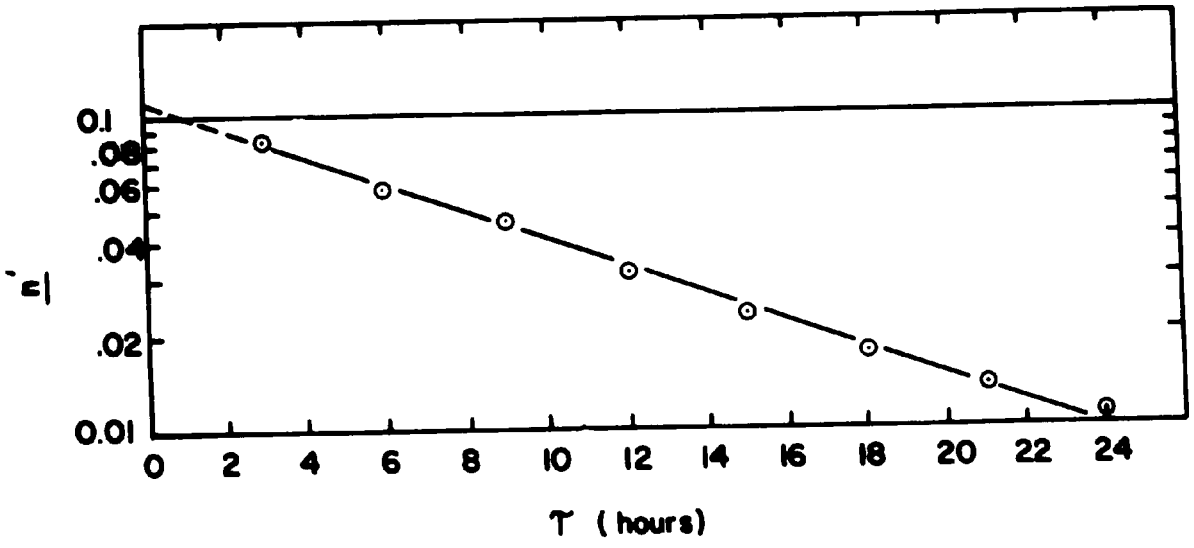


roughly an order of magnitude larger than those for small τ's. In other words, over long periods of time the larger eddies obliterate the effect of the smaller eddies.

No direct verification of this second feature was possible with the wind direction data collected at the Fermi site because of the already large averaging time used to compute σ_θ. However, horizontal wind direction measurements, averaged over 15 minute intervals, were available from a study being made at Tecumseh, Michigan.[29] These data were collected at an elevation of 75 feet at the Tecumseh Airport. The terrain in this area is open and flat. Tecumseh is about 35 miles due west of the Fermi site. The data used were those collected in 1962 and 1963. For each of eight values of τ, ranging from 3 to 24 hours, average values of σ_θ were computed for 15, 30 and 60 minute intervals. Two consecutive and 4 consecutive 15 minute values of the wind direction were averaged to obtain the values of σ_θ for the 30 and 60 minute intervals respectively. The values of σ_θ for a given value of τ were found to decrease with increasing averaging time. Furthermore, the decrease of σ_θ with averaging time appeared to be logarithmic. Figure 2 shows the absolute values of the slopes of these log-log plots as a function of the sampling time τ. The slopes are given the symbol n' because they are analogous to Sutton's n/2 in equation 14.

The relationship is clearly exponential for values of τ between 3 and 24 hours. Values of n' between 0.1 and 0.11 are found by extrapolating the curve to sampling times of 1 hour and less. These are equivalent to values of n between 0.20 and 0.22 which agree well with Hewson's estimates for strong and weak lapse conditions at the Fermi site. For the purposes

FIGURE 2. ABSOLUTE VALUES OF THE AVERAGE SLOPES n' OF LOG-LOG PLOTS OF $\sigma_\odot$ VS. AVERAGING TIME $X/4\bar{\mu}$ AS A FUNCTION OF THE SAMPLING TIME τ.



of this investigation the important thing to note about Figure 2 is that it provides evidence in support of equation 15.

In the rare event that $[\sigma_\theta]_{24}$ is less than $[\sigma_\theta]_1$, the value of $[\sigma_\theta]_1$ is used throughout the day. If the lapse rate changes during the day, a new value of $[\sigma_\theta]_1$, computed from equation 14 using the appropriate parameters in Table 1, is used at the instant the lapse rate changes.

In the case of vertical diffusion, Pasquill has given estimates of σ_z for six stability categories[24] for those without the instrumentation to measure σ_ϕ in equation 13. Figure 3 shows these estimates expressed as h, where $h = 2.15\ \sigma_z$. The six categories represent grades of atmospheric stability, from A the most unstable, to F the most stable. The symbol h represents the height at which the concentration is 10% of that on the centerline of the plume. Pasquill's values of h are based partly on theory, partly on experimental data, and partly on measurements of σ_ϕ.[24] The dashed lines indicate areas of greater uncertainty in the estimate of h.

Hewson, et al.[30] have measured σ_z for various values of n at the Fermi site. Columns 1 and 2 of Table 2 show the results of their measurements. Columns 3 and 4 show the values of the same parameters recommended by Hewson, et al. for use in analyzing for the consequences of an accidental release from the Fermi reactor. By multiplying σ_z in equation 11 by 2.15, values of h corresponding to those of Pasquill can be computed for the recommended and the measured values of C_z and n in Table 2. The results are shown in Figure 4. For reference Pasquill's values of h are shown as thin lines.

FIGURE 3. PASQUILL'S ESTIMATES OF h (= 2.15 σ_{my}) FOR SIX ATMOSPHERIC STABILITY CATAGORIES.

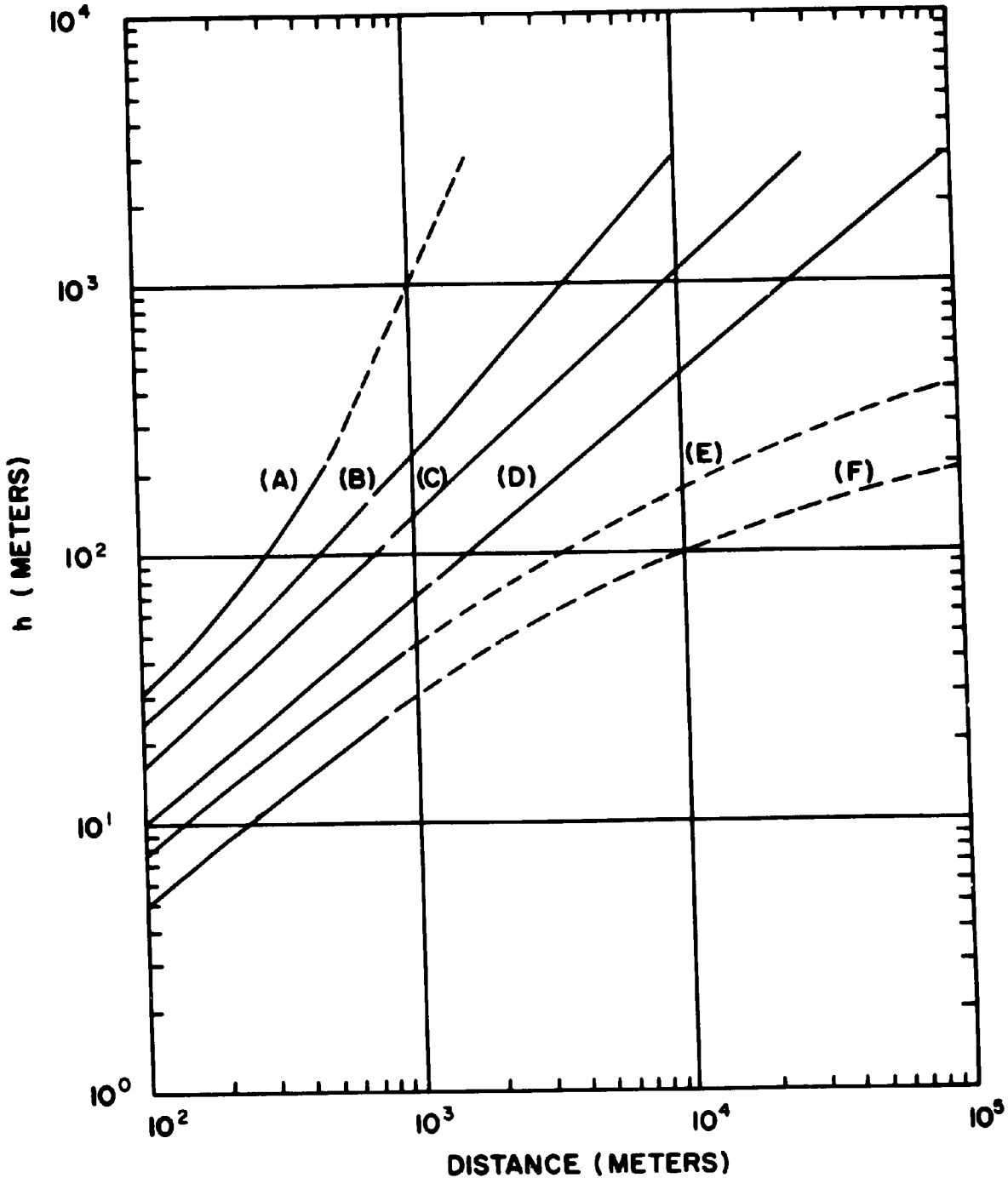


TABLE 2

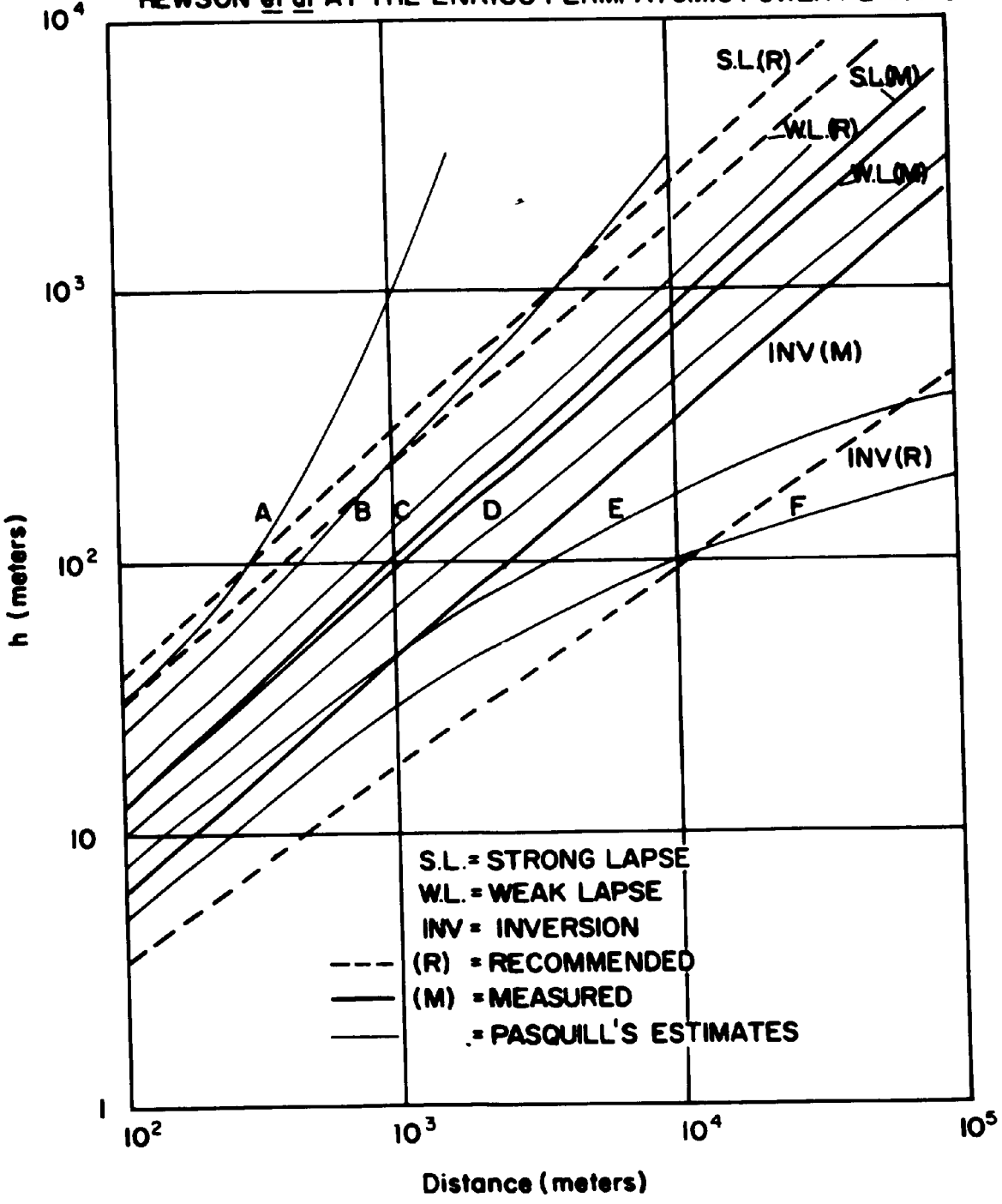
MEASURED AND RECOMMENDED* VALUES OF C_z AND n

	MEASURED		RECOMMENDED*	
Stability Category**	n	C_z	n	C_z
Inversion	0.30	0.08	0.55	0.08
	0.30	0.09		
Weak Lapse	0.25	0.15	0.25	0.35
	0.23	0.14		
Strong Lapse	0.20	0.14	0.20	0.40
	0.20	0.13		

*Recommended by Hewson, et al. for use in reactor hazards evaluation at the Enrico Fermi Atomic Power Plant site.(27)

**The stability categories are the same as those in Table 1.

FIGURE 4. A COMPARISON BETWEEN PASQUILL'S ESTIMATES OF h AND THOSE MEASURED[30] AND RECOMMENDED[27] BY HEWSON et al AT THE ENRICO FERMI ATOMIC POWER PLANT SITE.



Both of Hewson's measurements of C_z during the strong lapse condition were made when there was an inversion aloft.[30] This tended to suppress vertical diffusion.[30] Apparently these measurements were thought to be atypical because the recommended value of C_z for the strong lapse condition is almost three times greater. Both measurements of C_z during inversions were made when the wind was blowing off Lake Erie.[30] Usually lake breeze inversions are broken up by ground roughness after traveling a mile or two inland.[30] This probably caused the relatively high value of C_z for the assumed value of $n = 0.30$.[30] Apparently 0.55 was considered a better value of n for describing the average diffusion conditions during inversions at the Fermi site.

The temperature lapse rate varies continuously with time, and Pasquill's six vertical diffusion categories permit better definition of these time changes than do Hewson's three categories. Because of this and because Hewson's measurements do not preclude the use of Pasquill's estimates of h at the Fermi site, Pasquill's estimates are used for vertical diffusion in the model. When an inversion is present and the wind is blowing off Lake Erie, Hewson's measured values of h are used to estimate vertical diffusion. This seems advisable since the lake breeze effect is unique to locations such as the Fermi site.

It is assumed that Hewson's stability categories correspond to Pasquill's as shown in Table 3. This correspondence is based on the comparison of Hewson's values of h (both measured and recommended) and Pasquill's values of h shown in Figure 4. In order to determine the frequency with which Pasquill's categories occur in each of Hewson's broader categories, Bryant's[31,32] reported frequencies of the six categories

for sites in England, Scotland and Wales are used. The frequencies in each of Hewson's categories are shown in Table 3.

In order to use a digital computer to solve the model it was necessary to express mathematically Pasquill's estimates for vertical diffusion. Table 4 shows the mathematical expressions of σ_ϕ which, when converted to values of h, agree with those shown in Figure 4 to within a few percent. The expression for σ_ϕ for the lake breeze inversion also is included in Table 4.

The upper limit of vertical diffusion is usually bounded by a layer of air having an isothermal or inversion lapse rate. Holsworth has developed a method of estimating the height at which vertical diffusion is limited by these layers.[33] He calls this height the maximum mixing depth (mmd). The mmd is the height at which the dry adiabatic lapse rate, drawn from the maximum daily surface temperature, intersects the most recent vertical temperature profile. Holsworth gives average monthly values of the mmd for 45 stations in the United States. To apply his monthly values to a daily diffusion model, it is necessary to know the frequency distribution of the daily mixing depths making up the monthly average. Data collected at 16 locations in the United States during the months of January and July, 1956[34] were analyzed to determine the frequency distribution of the daily mixing depths. Let mmd_i be the mixing depth for a single day and $\overline{mmd}$ the monthly mixing depth. The statistic $mmd_i/\overline{mmd}$ averaged for all 16 locations was found to follow a near normal distribution for the month of July and a skewed distribution for the month of January. Figure 5 shows the frequency distributions for $mmd_i/\overline{mmd}$ in July and January. These frequency distributions, with the

TABLE 3

THE CORRESPONDENCE BETWEEN THE STABILITY CATEGORIES OF HEWSON AND PASQUILL

Pasquill's Categories	A	B	C	D	E	F
Frequency	0.064**	0.311	0.624	1.00	0.374	0.626*
Hewson's Categories		STRONG LAPSE		WEAK LAPSE	INVERSION	

*The fraction 0.626 includes the relative frequency of a seventh category G which is not included because no estimates of h were given.(24)

**Relative frequencies based on Bryant's work.(31,32)

TABLE 4

MATHEMATICAL EXPRESSIONS OF σ_ϕ FOR PASQUILL'S SIX STABILITY CATEGORIES[24] AND FOR THE LAKE BREEZE INVERSION

Stability Category	σ_ϕ (radians)			
A*	$.142e^{+.162x}$	$+.0078x^{1.53}$	$-.035$	
B**	$.102e^{+.0485x}$			
C**	$.01e^{-9.03x}$	$+.006e^{-1.49x}$	$+.013e^{-.34x}$	$+.052e^{-.00325x}$
D**	$.018e^{-2.3x}$	$+.0068e^{-.436x}$	$+.0078e^{-.0914x}$	$+.0187e^{-.00317x}$
E**	$.011e^{-3.29x}$	$+.0145e^{-.532x}$	$+.0078e^{-.0914x}$	$+.0054e^{-.0113x}$
F**	$.0081e^{-5.25x}$	$+.01e^{-.549x}$	$+.0061e^{-.0975x}$	$+.00261e^{-.011x}$
LAKE BREEZE INVERSION***	$.0601x^{-.15}$			

*x in Meters

**x in Kilometers

***Derived from the measurements of C_z and $\underline{n}$ by Hewson et al.[30]

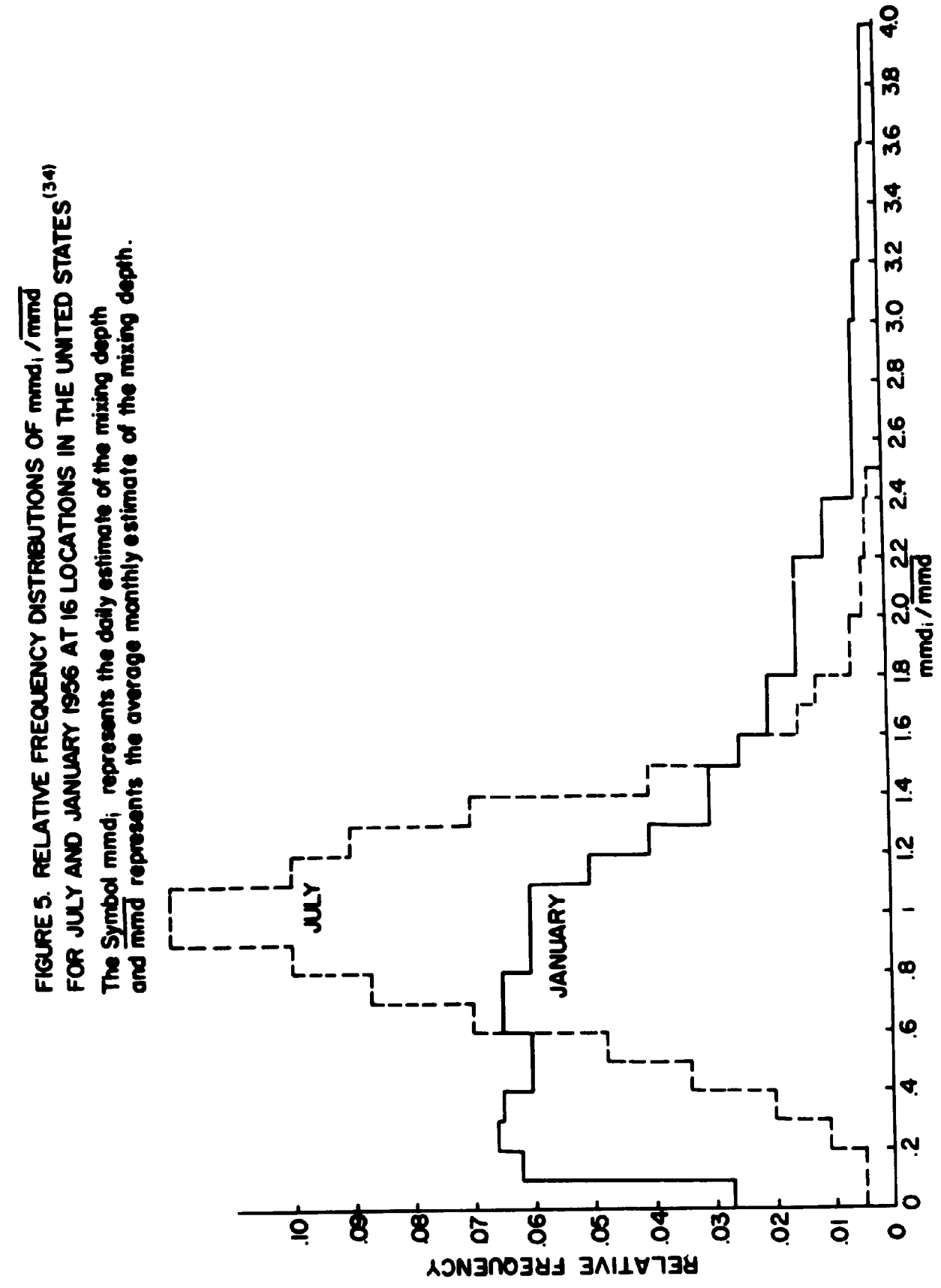


FIGURE 5. RELATIVE FREQUENCY DISTRIBUTIONS OF $mmd_i / \overline{mmd}$ FOR JULY AND JANUARY 1956 AT 16 LOCATIONS IN THE UNITED STATES[34]

The Symbol mmd_i represents the daily estimate of the mixing depth and $\overline{mmd}$ represents the average monthly estimate of the mixing depth.

average of the monthly mmd's from Buffalo, New York, Joliet, Illinois, and Sault St. Marie, Michigan,[33] are used to calculate the daily mixing depth for the Fermi site. These three locations were chosen because of their proximity to large bodies of water. The monthly mixing depths and the averages used for the Fermi site are shown in Table 5.

The frequency distribution determined for January was used for the months of December, January and February, while the frequency distribution for July was used for all the remaining months. This choice was based on values of $mmd_i/\overline{mmd}$ for Lansing, Michigan, for the months of January through October, 1964.[34] The statistic was found to have a skewed distribution for January and February while the distributions for the other months appeared to be symmetrical.

The mixing depths are applied to the vertical diffusion in unstable and near neutral atmospheres as well as in cases of lake breeze inversions as follows: Whenever a downwind distance, say x_1, is reached such that:

$$h + \text{effective stack height}^{*} = mmd_i \qquad (16)$$

the plume is made to expand vertically at a rate determined by the stability category F. Mathematically this is accomplished by multiplying σ_z determined from the equation governing the F category in Table 4 by the following relation

$$\frac{h(x_1) \text{ for stability categories A,B,C,D,E and lake breeze inversions}}{h(x_1) \text{ for the F stability category}}$$

---

*The effective stack height is discussed below.

TABLE 5

MEAN MAXIMUM MIXING DEPTHS[33] (METERS) FOR THREE LOCATIONS NEAR LARGE BODIES OF WATER

Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Buffalo	480	530	780	810	1070	1180	1440	1360	1190	530	700	510
Joliet	480	480	980	950	1040	1090	1380	1310	860	790	600	480
Sault St. Marie	340	340	510	600	800	730	900	840	730	350	400	340
Ave.	433	450	757	787	970	1000	1240	1170	927	557	567	443

In terms of Figure 4, the top of the plume $\underline{h}$ is found by drawing a line parallel to the h curve for the F category starting at the intersection of mmd_i and the h curve of the more unstable category. The mixing depths were applied in this manner for two reasons: First, in unstable atmospheres, where vigorous mixing is likely to occur, the vertical distribution changes from normal to uniform throughout the mixing depth;[24] this change of distribution has the effect of reducing the ground concentration. This process is approximated by allowing some vertical diffusion to take place above the mixing depth. Second, one might expect that vertical diffusion will not always be completely stopped at the top of the mixing depth, e.g., when the layer of air forming the lid has an isothermal temperature profile instead of a strong inversion.

It is worth noting that this method of applying the mixing depths cannot cause ground concentrations any greater than the maximum ground concentrations computed without consideration of a mixing depth. Therefore, a lower limit must be imposed on the value of the mixing depth because diffusion must be allowed to proceed without a consideration of the mixing depth until the maximum ground concentration occurs. If this limit were not imposed, the distance downwind to the point of maximum concentration would be greater with a mixing depth than without, which is not reasonable. The exact lower limit on the mixing depth is a function of the effective stack height and the degree of atmospheric stability.

In order to preserve continuity during lapse rate changes the following assumptions have been used: First, when the atmospheric stability changes from more stable to less stable the change is assumed to be instantaneous over the downwind range of interest. Mathematically, this

is accomplished by changing σ_z from the one representing the more stable atmosphere to the one representing the less stable atmosphere at the instant the stability changes. Second, when the atmosphere changes from less stable to more stable it is assumed that the vertical dimensions of the plume between the source and the sampler remain unchanged and that the plume moves intact at the average daily wind speed $\bar{u}$ until it passes the sampler. At the instant it passes the sampler the vertical dimension representing the more stable atmosphere is used until the lapse rate changes again. Mathematically this is accomplished by replacing x in the mathematical expressions for σ_ϕ shown in Table 4 with $(x - \bar{u}t)$ and allowing t to increase until the instant before $\bar{u}t = x$. At this instant the expression corresponding to the vertical dimension of the more stable lapse rate is used with x as the distance.

If the wind changes direction at the end of a 24 hour period, a plume is allowed to form in the new direction; the dimensions of the new plume are governed by a new 24 hour standard deviation and new hourly lapse rates. In the meantime, there is a segment of the old plume between the stack and the sampler which must be accounted for in order to preserve continuity. This is accomplished by freezing the horizontal dimensions of the old plume and allowing it to rotate toward the new wind direction. The shortest route from the old to the new wind direction is taken. Simultaneously the old plume is separated from the stack and allowed to move radially outward. The plume is not moved intact as in the case of vertical diffusion changes mentioned above. Rather, the horizontal plume dimension remains the same until the plume reaches the sampler, at which time the concentration instantaneously drops to zero.

These two processes (rotation and outward movement of the plume) are timed so that at the instant the new plume reaches the radial distance of the sampler, the centerline of the old plume coincides with that of the new, and the old plume has moved radially outward a distance equal to the distance of the sampler from the source. The vertical dimensions of the new plume and the trapped segment of the old plume are both determined by the lapse conditions of the new 24 hour period.

Mathematically the plume is swung by replacing y in equation 9 with the following expression:

$$y' = \pm y \pm \bar{u} t \tag{17}$$

where: y' = horizontal distance from the centerline of the old plume to the sampler at any time t (meters)

y = horizontal distance from the centerline of the old plume to the sampler at the beginning of the new 24 hour period, i.e. t = 0 (meters)

$\bar{u}$ = the average daily wind speed applicable to the new 24 hour period (m/sec)

t = time (sec.)

The horizontal distances from the plume are measured along an arc having a radius equal to the distance of the sampler from the stack.

The time for the old plume to swing to the centerline of the new plume is $t_{\theta_1-\theta_2}$ where:

$$t_{\theta_1-\theta_2} = \frac{|\theta_1-\theta_2| x}{\bar{u}} \tag{18}$$

where: θ_1 = angle between north and the centerline of the old plume (radians)

θ_2 = angle between north and the centerline of the new plume (radians)

x = radial distance from the stack to the sampler (meters)

The sign of y in equation 18 is determined by the position of the sampler relative to the centerline of the old plume; to the left (looking out from the source) is negative; to the right is positive. The sign of $\bar{u}t$ is determined by the sign of y' at $t_{\theta_1-\theta_2}$, i.e., the position of the sampler relative to the centerline of the new plume.

If the air containing the contaminant is hot or if it has a significant escape velocity, the plume will rise above the opening of the stack. This has the effect of increasing the stack height. Holland[35] has suggested a formula for computing the rise of a plume. This formula, which is reported to be conservative and applicable in average weather conditions, gives the rise of a plume above the stack as:

$$\Delta H = \frac{1.5\ v_e di}{\bar{u}} + \frac{10.\ Q_H}{\bar{u}} \qquad (19)$$

where: ΔH = rise of the plume (meters)

di = diameter of the stack opening (meters)

v_e = vertical velocity of the plume (m/sec)

Q_H = heat emission rate (MW)

Other formulae have been proposed which give much higher values of ΔH than those computed from equation 19.[36] Furthermore, these later estimates of ΔH appear to be more accurate than those estimated by equation 19. However, the means of applying ΔH to the diffusion formula must also be considered. The plume travels downwind as it is rising and also diffuses as it travels. The maximum rise may not be reached even at distances of several thousand meters.[18] The way, most commonly used, to apply the rise of the plume is to add it to the real stack height giving what is usually referred to as an effective stack height. This procedure assumes that the plume rises vertically to its maximum height without any downwind travel or diffusion. Therefore, while equation 19 may underestimate the maximum rise of the plume, its application in the present diffusion formula may not be overly conservative.

In the solution of the model the stack height $\underline{H}$ is replaced by the effective stack height H_e where:

$$H_e = H + \Delta H \tag{20}$$

All the heights in equation 20 are expressed in meters.

To summarize, the time-integrated air concentration at any point resulting from the release of Q μCi/sec, neglecting ground deposition and radioactive decay is given by the following expression:

$$\chi_{tic}(x,y,z) = \int_0^t \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} e^{\frac{-y^2}{2\sigma_y^2}} \left(e^{-\frac{(z-H_e)^2}{2\sigma_z^2}} + e^{-\frac{(z-H_e)^2}{2\sigma_z^2}} \right) dt \tag{21}$$

where: $\chi_{tic}(x,y,z)$ = time integrated air concentration ($\mu Ci\text{-}sec/m^3$)

Q = source strength ($\mu Ci/sec$)

σ_y = standard deviation in the y direction (m)

1. given by equation 10 for 0 to 1 hour
2. given by equation 15 for 1 to 24 hours
3. at the end of the 24 hour period σ_y is held constant at its 24 hour value from equation 15 until the plume swings to a new direction

σ_z = standard deviation in the z direction (m), given by the expressions in Table 4 multiplied by x. The procedures for calculating σ_z during changes of atmospheric stability are given above.

$\bar{u}$ = average daily wind speed (m/sec)

y = the distance measured along the circumference of a circle of radius x from the centerline of the plume to the sampler (m). y is constant except when the plume is swinging from one direction to another. During the swing of the plume, y takes on values calculated from equation 17.

z = the vertical distance from the sampler to the centerline of the plume. (m)

H_e = the effective stack height given by equations 19 and 20

The average concentration over the time period t is given by the following equation:

$$\bar{\chi} = \chi_{tic}/t \tag{22}$$

Where: $\bar{\chi}$ = average air concentration over the period t ($\mu Ci/m^3$)

t = averaging time in seconds

2. Deposition of the contaminant

The quantity of a contaminant deposited on a surface is given by the following expression:

$$DEP_d = v_d \chi_{tic}(x,y,o) \tag{23}$$

Where: DEP_d = dry deposition ($\mu Ci/m^2$)

v_d = deposition velocity (m/sec)

$\chi_{tic}(x,y,o)$ = time integrated concentration given by equation 21. $(\frac{\mu Ci\text{-}sec}{m^3})$

Experimental evidence indicates that a realistic deposition velocity for iodine-131 onto grass lies in the range from 0.3 to 0.7 cm/sec. In a

study at Idaho Falls[37] the deposition velocity for iodine-131 vapor was measured in the range from 0.37 to 0.72 cm/sec, with a median value of 0.51 cm/sec. These values were measured in a moderately unstable atmosphere and with an average grass cover of 150 wet gms/m^2. Measurements after the Windscale accident indicated deposition velocities onto pasture grass in the range from 0.3 to 0.4 cm/sec.[38] Cline et al.[39] have reported a mean deposition velocity for iodine-131 vapor onto various types of grasses to be 0.5 cm/sec. On the basis of these studies the deposition velocity of iodine-131 onto pasture grass is assumed to be 0.5 cm/sec in this study.

Peirson and Keane[40] have reported a value of 0.26 cm/sec for the deposition velocity of radioactive fallout particles onto grass. The value 0.25 cm/sec is used in this investigation.

The values of the deposition velocity of micron size particles and iodine-131 onto precipitation collectors used in this research are based on observations made in this laboratory and by others.[41] Table 6 summarizes the values for the deposition velocities used in this investigation.

High efficiency filters are used in most nuclear power plants to clean gases before they are released to the atmosphere. This is true of the Fermi Plant.[42] These filters are 99.9+% efficient for 0.3 micron diameter particles.[42,43] It seems likely that under normal operating conditions, most of the particulate radioactivity emitted to the atmosphere will be on particles with diameters less than 1 micron.

To the best of my knowledge, there is no theory which predicts any scavenging whatever of submicron particles from the atmosphere by

TABLE 6

ASSUMED VALUES OF THE DEPOSITION VELOCITY v_d ONTO GRASS AND PRECIPITATION COLLECTORS

Type of Radioactivity	Deposition Velocity (cm/sec) Pasture Grass	Precipitation Collectors
Iodine-131	0.50	0.2
Sub-Micron Particles	0.25	0.1

falling raindrops. Field measurements tend to confirm this.[44] Using the probabilities of collision of large raindrops with smaller raindrops computed by Langmuir,[45] and the raindrop size distributions of Best,[46] Chamberlain[47] has computed the efficiencies of various rainfall rates for scavenging various size particles from the atmosphere. His efficiencies when plotted against particle size for various rainfall rates show a definite cutoff point in the particle size below which the scavenging efficiency is zero. For a particle density as high as 4 gms/cc this cutoff point is 1.5 microns for all rainfall rates. The field experiments of Engelmann[44] show that a cutoff point for particles with a density of 4 gm/cc exists between 0.8 and 3.2 microns.

It appears therefore that little if any of the submicron particles themselves will be rained out in the vicinity of the site. Eventually, these particles may be deposited by any one or combination of several processes. They may coagulate with other small particles or larger particles and then be scavenged by rain. They may become entrained in a rain cloud and by mechanisms not well understood be brought to the ground in rain. These processes are time dependent, and it is assumed for the purposes of this research that they do not cause deposition of the submicron particles within the radius of interest around a nuclear facility.

Chamberlain has developed a theory for calculating the scavenging of gaseous iodine-131 from the atmosphere by falling raindrops.[47] His theory has been confirmed within an order of magnitude by observations on the scavenging of SO_2 vapor in Britain.[48] The scavenging efficiency as a function of the rate of rainfall is expressed in the following series of equations. These equations agree to within a few percent with Chamberlain's graphical presentation.[49]

$$EFF_r = RR \times 10^{-4} \qquad 0<RR\leq 0.5 \tag{24a}$$

$$EFF_r = (0.2 + 0.6\ RR) \times 10^{-4} \qquad 0.5<RR\leq 1 \tag{24b}$$

$$EFF_r = (0.5 + 0.3\ RR) \times 10^{-4} \qquad 1<RR\leq 3 \tag{24c}$$

$$EFF_r = (0.8 + 0.2\ RR) \times 10^{-4} \qquad 3<RR\leq 10 \tag{24d}$$

where: EFF_r = scavenging efficiency (sec^{-1})

RR = rate of rainfall (mm/hr)

The product of the efficiency EFF_r and the quantity of the contaminant over the area of interest is the deposition rate on the area. The quantity of the contaminant over the area of interest is the integral of equation 9 with respect to z from 0 to ∞. The stack height $\underline{H}$ in equation 9 may be disregarded in the integration because it does not affect the quantity of the contaminant in the plume. The result is:

$$\int_0^\infty \chi(x,y,z)dz = \frac{Q}{\bar{u}\ \sigma_y (2\pi)^{1/2}}\ e^{-1/2(y^2/\sigma_y{}^2)} \tag{25}$$

The deposition rate at (x,y,o) is:

$$\frac{d\ DEP_r}{dt} = \frac{E\ Q}{\bar{u}\ \sigma_y (2\pi)^{1/2}}\ e^{-1/2(y^2/\sigma_y{}^2)} \tag{26}$$

The total deposition is:

$$DEP_r = \int_{T_o}^{T_r} \frac{E\ Q}{\bar{u}\ \sigma_y (2\pi)^{1/2}}\ e^{-1/2(y^2/\sigma_y{}^2)}\ dt \qquad (27)$$

where: T_o = time at which the rain starts

$T_r - T_o$ = duration of rainfall (sec)

Strictly speaking, the upper limit of the integral in equation 25 should be a distance equal to the height of the rain cloud base. However since the dimensions of the plume are usually small compared to this height, and the fact that two or three standard deviations σ_z include over 95% of the activity in the plume, the upper limit of ∞ is not unreasonable.

3. Corrections due to cloud depletion resulting from deposition.

For clarity the methods used to calculate the depletion of the contaminant within the plume due to dry and wet processes are considered first under steady state conditions. The methods used for non-steady state conditions are included when discussing the total cloud depletion expressions. In general, the correction for cloud depletion is made by substituting reduced source strengths for the original source strength Q in equation 21.

The concentration of a contaminant in a plume is reduced by dry deposition. A method developed by Chamberlain[47] is used to account

for the effect of cloud depletion on the air concentration. It is assumed that the shape of the vertical distribution is unaltered by deposition. This should be a permissible assumption for deposition velocities up to $0.01\ \bar{u}$.[17] Even with a value of $\bar{u}$ as low as 1 m/sec (a rare occurrence for a daily average velocity) the deposition velocities in Table 7 do not invalidate the assumption. If it is assumed that deposition is independent of the cross wind distribution (an apparently valid assumption) the effect of deposition on the air concentration within the plume can be analyzed with the cross wind integrated concentration, which simplifies the mathematics considerably.

Setting z = 0 and integrating equation 9 with respect to y from $-\infty$ to $+\infty$ one obtains the following expression for the cross wind integrated concentration (χ_{cic}).

$$\chi_{cic} = \left(\frac{2}{\pi}\right)^{1/2} \frac{Q}{\sigma_z \bar{u}}\ e^{-1/2(H^2/\sigma_z^2)} \tag{28}$$

In order that continuity be maintained the following equation must be satisfied:

$$\int_o^\infty \chi(x,z)\ \bar{u}\ dz = Q - \int_o^x \chi_{cic}\ v_d\ dx \tag{29}$$

where: Q = source strength (μCi/sec)

The integral on the left side of equation 29 is the reduced source strength $Q(x)_d$ at x due to dry deposition over the distance x. If equation 29 is differentiated with respect to x, the following expression is obtained for the rate of change of the source strength with respect to x:

$$\frac{d\,Q(x)_d}{dx} = - \chi_{cic}\ v_d \tag{30}$$

Equation 30 is solved for $Q(x)_d$ with the following result:

$$Q(x)_d = Q\ e^{-\left(\frac{2}{\pi}\right)^{1/2} \frac{v_d}{\bar{u}} \int_o^x \frac{e^{-1/2(H^2/\sigma_y^2)}}{\sigma_z}\, dx} \tag{31}$$

Finally $Q(x)_d$ is substituted for Q in equation 21 to account for the decrease in air concentration due to dry deposition.

Just as in the case of dry deposition, the deposition due to rain scavenging reduces the amount of contaminant in the plume. Chamberlain uses the same method to account for the effect of rain scavenging on air concentration as for the effect of dry deposition.[47] The rate at which the contaminant is washed from the whole plume is:

$$EFF_r \int_o^\infty \chi_{cic}\, dz = \frac{EFF_r\ Q(x)_r}{\bar{u}} = - \frac{d\ Q(x)_r}{dx} \tag{32}$$

where: $Q(x)_r$ = reduced source strength due to rain (μCi/sec)

Solving equation 32 for $Q(x)_r$:

$$Q(x)_r = Q\ e^{- EFF_r x/\bar{u}} \tag{33}$$

In the steady state condition the total cloud depletion Q(x) at some point x from the stack, is a function of x only and is given by the following equation:

$$Q(x) = Q\, e^{-EFF_r x/\bar{u} + (\frac{2}{\pi})^{1/2} \frac{v_d}{\bar{u}} \int_o^x \frac{e^{-1/2(H^2/\sigma_z^2)}}{\sigma_z} dx} \qquad (34)$$

In reality the steady state is rare, and the cloud depletion is a function of time as well as of distance. The reduced source strength due to rain (henceforth referred to as $Q(x,t)_r$) is largest at the beginning of the rain, diminishes to a steady state level at a time t (= $x/\bar{u}$, the travel time from the stack to the point of interest x) and then increases to the pre-rain level after the rain stops. If the beginning of the rainfall period is taken as t = o and the duration of the rainfall is T_r, the mathematical expressions describing $Q(x,t)_r$ are the following:

$$Q(x,t)_r = Q\, e^{-EFF_r t} \qquad 0 \leq t < x/\bar{u} \qquad (35a)$$

$$Q(x,t)_r = Q\, e^{-EFF_r x/\bar{u}} \qquad x/\bar{u} \leq t < T_r \qquad (35b)$$

$$Q(x,t)_r = Q\, e^{-E(x/\bar{u}-t+T_r)} \qquad T_r \leq t \leq T_r + x/\bar{u} \qquad (35c)$$

In the case of cloud depletion due to dry deposition (see equation 31), σ_z can be a function of time as well as a function of x. Therefore, for the non-steady state condition, $Q(x)_d$ is replaced by $Q(x,t)_d$.

Since the changes in the atmospheric stability are assumed to occur instantaneously, a numerical method is used to compute the non-steady state cloud depletion due to dry deposition.

Small increments in distance are related to small increments in time by the velocity as shown in the next equation:

$$\Delta x = \bar{u}\ \Delta t \tag{36}$$

The reduced source strength from dry deposition at a distance x at any time t may be written as follows:

$$Q(x,t)_d = Q\ e^{-\left(\frac{2}{\pi}\right)^{1/2} \frac{v_d}{\bar{u}} \sum_{i=1}^{N} \frac{e^{-1/2\ H^2/\sigma_z(x_i,t_{(M-N+i)})^2}}{\sigma_z(x_i,t_{(M-N+i)})} \Delta x} \tag{37}$$

where: N = is the nearest integer to $x/\Delta x$

M = is the nearest integer to $t/\Delta t = t\bar{u}/\Delta x$

The numerical integration of equation 37 is carried out using Simpson's rule.[50] Each time x is increased by Δx there is a corresponding increment in $t = \Delta t$, which by equation 36 equals $\Delta x/\bar{u}$. If the lapse rate changes at the time $t = (M-N)\Delta t + i\Delta t$, then the value of σ_y at $x = i\Delta x$ corresponding to the new lapse rate is included in the integration. Therefore, even though the lapse rates change instantaneously the reduced source strength changes relatively slowly with time.

For the non-steady state condition the reduced source strength $Q(x,t)$ due to both dry deposition and rain scavenging is equal to the product of equation 37 and 35 divided by Q

$$Q(x,t) = Q(x,t)_d \quad Q(x,t)_r/Q \tag{38}$$

4. Correction due to radioactive decay

Radioactive decay is dependent only on time. In general, if $D(x/\bar{u})$ is the decay correction factor, it is multiplied by $Q(x,t)$ to obtain yet another reduced source strength which includes radioactive decay, $Q(x,t,D)$, where:

$$Q(x,t,D) = Q(x,t) \quad D(x/\bar{u}) \tag{39}$$

Table 7 shows the decay correction factors used in this study. The decay rates for the beta and gamma activity of the noble gases are explained below in Section II B 4.

If the wind speed $\bar{u}$ changes from one day to the next the decay correction factor applied at x also will change. The rate of change will be linear over the time it takes the old plume to swing to the position of the new plume, $t_{\theta_1-\theta_2}$ (see equation 18). The following equation expresses the decay correction factor $D(x/\bar{u})$ used during the swing of the plume.

$$D(x/\bar{u}) = D(x/\bar{u}_1) - \frac{t}{t_{\theta_1-\theta_2}} \left[D(x/\bar{u}_1) - D(x/\bar{u}_2) \right] \tag{40}$$

TABLE 7

DECAY CORRECTION FACTORS $D(x/\bar{u})$

Type of Radioactivity	$D(x/\bar{u})$
Particulate	1
Iodine-131	$e^{-\lambda_I x/\bar{u}}$ ($\lambda_I = 1 \times 10^{-6} sec^{-1}$)
Noble gas beta	for $x/\bar{u} \leq 1800$ sec $e^{-\lambda_b x/\bar{u}}$ ($\lambda_b = 0.00136 sec^{-1}$) for $x/\bar{u} > 1800$ sec $5.51\ (x/\bar{u})^{-.259}$
Noble gas gamma	for $x/\bar{u} \geq 300$ sec $0.55 + 0.0004\ x/\bar{u}$ for 300 sec $< x/\bar{u} \leq$ 1200 sec 0.67 for 1200 sec $< x/\bar{u} \leq$ 3600 sec $4.35\ (x/\bar{u})^{-.265}$ for 3600 sec $< x/\bar{u} \leq$ 1440 min $12.1\ (x/\bar{u})^{-.388}$

where: $D(x/\bar{u}_1)$ = decay correction factor for day 1

$D(x/\bar{u}_2)$ = decay correction factor for day 2

t = time during the swing of the plume

$0 \leq t \leq t_{\theta_1-\theta_2}$ (sec)

$t_{\theta_1-\theta_2}$ = time to complete plume swing (sec)

5. Radioactive decay on collectors during sampling.

The radioactivity collected by air and deposition samplers decays as it is being collected. The following equation describes the rate of change of the radioactivity on the filter of an air sampler:

$$\frac{dA}{dt} = SR \quad \chi(x,y,z) - \lambda A \tag{41}$$

where: A = radioactivity on the collector at any time t (μCi)

$\chi(x,y,z)$ = concentration of radioactivity being collected at any time t ($\mu Ci/m^3$)

SR = sampling rate (m^3/sec)

λ = radiological decay constant of nuclide being collected (sec^{-1})

Equation 41 may be solved for A at some time t_1 with the following result:

$$A = SR \left[e^{-\lambda t_1} \int_0^{t_1} e^{\lambda t} \chi(x,y,z)dt \right] \tag{42}$$

The same analysis holds for the decay of a radionuclide deposited on precipitation samplers by dry processes by replacing the air sampling rate SR with the deposition velocity v_d. The radioactivity A is then expressed in $\mu Ci/m^2$.

The expression in brackets is the decay-corrected, time-integrated air concentration. The integral is solved numerically using Simpson's Rule.(50)

The decay of a radionuclide deposited on precipitation collectors by rainfall is approximated by multiplying the days deposit by $e^{-\lambda t_1}$; where t_1 is measured from the midpoint of the rainfall interval to the end of the collection period.

6. Beta exposures from noble gases.

The range of beta particles in air is on the order of a few meters. Therefore, since the change in the radioactivity concentration is small over this distance it can be assumed that the beta exposure at a point is a function of the radioactivity concentration at the point. The beta exposure is a function of the radioactivity concentration and the average beta energy as shown in the next equation.(51)

$$EXP_\beta = 2.3 \times 10^{-4} \bar{E}_\beta \chi_{tic} \quad (43)$$

where: EXP_β = beta exposure (mrad)

$\bar{E}_\beta$ = average beta energy (mev)

χ_{tic} = time integrated air concentration of beta radioactivity ($\mu Ci\text{-sec}/m^3$)

One curie of a noble gas is defined here as 3.7×10^{10} disintegrations per second of the noble gas radionuclides listed in Table 8. These radionuclides were chosen because of their relatively high fission yields. The inclusion of other noble gas radionuclides would not add significantly to either the beta or the gamma dose. The relative abundance of each radionuclide was calculated on the assumption that equilibrium had been reached in the reactor and that the absorption cross sections were negligible. For the purposes of this investigation, the assumption of negligible absorption cross section is valid even for xenon-135 because the Enrico Fermi reactor employs a fast neutron flux. It is assumed that daughter products of the noble gases are not present at the mouth of the stack, i.e., that the filter is 100% efficient for collecting them. The decay of the beta radioactivity is shown in Table 7.

The average beta energy of the noble gas mixture in Table 8 changes with time according to the equation:

$$\bar{E}_{\beta} = 0.156 \ e^{-0.00055t} + 0.236 \ e^{-0.000187t} + 0.284 \ e^{-0.000017t} \qquad (44)$$

where: $t = x/\bar{u}$ (sec)

Equation 44 is a good approximation for decay times up to 24 hours.

7. Gamma exposure from noble gases.

The gamma radioactivity dA_{υ} in a small volume of the plume centered at the point x, y, z is given by the following expression:

TABLE 8

THE COMPOSITION OF THE NOBLE GAS MIXTURE

Radionuclide	Half Life	Fission Yield (%)	Relative* Abundance
Kr-85m	4.4 hrs.	1.1	0.0423
Kr-87	78 min.	0.97	0.0373
Kr-88 Rb-88	2.77 hrs. 18 min.	0.93 Daught. of Kr-88	0.0358
Kr-89 Rb-89	3.2 min. 15 min.	4.59 Daught. of Kr-89	0.177
Xe-133	5.27 da.	6.62	0.254
Xe-135	9.13 hrs.	6.30	0.242
Xe-138 Cs-138	17 min. 32.2 min.	5.49 Daught. of Xe-138	0.211
		TOTAL	1.00

*The relative abundance is computed assuming equilibrium for each parent radionuclide and zero absorption cross section.

$$dA_\nu = \chi(x,y,z)\ D(x/\bar{u})\ dx\ dy\ dz \tag{45}$$

where: dA_ν = gamma radioactivity (μCi)

$D(x/\bar{u})$ = decay correction factor from Table 7

The energy released per unit time from the small volume is:

$$\frac{dE}{dt} = dA_\nu \quad 3.7 \times 10^{10} \quad \bar{E}_\nu\,(x/\bar{u}) \tag{46}$$

where: $\frac{dE}{dt}$ = energy emission rate (MeV/sec)

3.7×10^{10} = conversion from μCi to dps

$\bar{E}_\nu(x/\bar{u})$ = average gamma energy per disintegration after traveling the distance x (MeV/dis)

The energy is dissipated in its travel from the small volume to the receptor on the ground by the inverse square law and air absorption. When multiple scattering is considered, the following equation expresses the energy flux incident on the receptor a distance r from the small volume of radioactivity:

$$d\phi = \frac{dE}{dt} \quad \frac{B(\bar{E}_\nu)\ e^{-\mu_T(\bar{E}_\nu)\ r}}{4\pi r^2} \tag{47}$$

where: $d\phi$ = energy flux (MeV/m^2-sec)

$B(\bar{E}_\nu)$ = build up factor due to multiple scattering of the gamma rays

$\mu_T(\bar{E}_\nu)$ = total linear absorption coefficient (m^{-1})

r = distance from small volume to receptor (m)

The method of calculating r is illustrated in Figure 6. Both the build up factor and the absorption coefficient are dependent on the energy of the gamma photon and therefore on the travel time from the stack to the point x. The gamma dose rate in mrad/sec is the quantity of the incident energy flux absorbed per unit mass of the receptor in ergs divided by 0.1 ergs of absorbed energy/gram/mrad and is given by the following expression:

$$d\,EXP_{\nu} = \frac{d\,\phi \quad \mu_a \quad 1.6 \times 10^{-3}}{\rho} \tag{48}$$

where: EXP_{ν} = exposure rate in mrad/sec

μ_a = linear absorption coefficient (cm^{-1})

ρ = density of the absorbing material (gm/m^3)

The total gamma exposure to the receptor is obtained by integrating equation 48 over the whole plume. The integration is carried out by dividing the plume into small cubes and summing the doses to the receptor from each cube. The side of each cube is set equal to one standard deviation of the y or z dimension of the plume, whichever is smaller. The integration is carried out to $\pm$ 4 standard deviations in both the y and the z directions. The integration is begun at x and carried out toward the stack until the distance equivalent to one second of travel time is reached. At this point the integration is resumed slightly downwind of x and carried out to a distance of 3x. These limits of the integration have been found to be equivalent for all practical purposes to from 0 to ∞ in the x and z directions and $-\infty$ to $+\infty$ in the y direction.

FIGURE 6. ILLUSTRATION OF THE METHOD USED TO CALCULATE THE DISTANCE r FROM THE CENTER s OF A CUBE OF RADIOACTIVITY TO THE RECEPTOR p.

THE FOLLOWING EXPRESSION IS USED TO CALCULATE r:

$$r = r_1^2 + pq^2 - 2r_1\, pq\, \cos(<oqp)$$

(from the law of cosines[50])

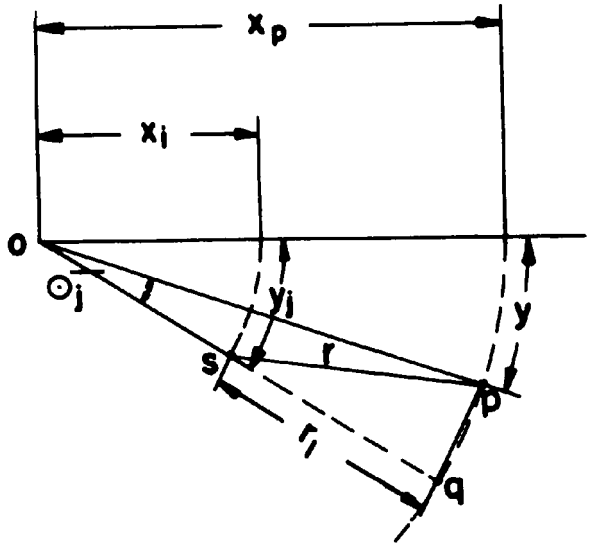
where: $r_1 = x_p - x_i$

$$pq = 2X_p \sin(\odot_j/2)$$

$$<oqp = \frac{\pi - \odot_j}{2}$$

$$\odot_j = \left| y/x_p - y_j/x_i \right|$$

See the figure below for a description of the symbols:



r = Distance from the center of a cube of radioactivity s to the receptor p.

In order to hold computing time to a minimum and still obtain reliable gamma exposure estimates, interim integration limits are used. Integration is allowed to proceed in the $\pm$ x directions until the dose from a y and z integrated slab is less than 10^{-3} of the already accumulated dose. When the dose from each cube contributes less than 10^{-6} of the already accumulated dose the integration is stopped in the $\pm$ y direction. Integration in the z direction is started at $-4\sigma_z$ or at 0 if $4\sigma_z$ is greater than the stack height and allowed to proceed upward to $+4\sigma_z$.

When the cube from which the dose is being computed is near the receptor the point source approximation is not valid, and the dose from a volume source is more applicable. If the distance from the receptor to the center of the cube is equal to or less than 1.5s (where s is the length of the cube's side) then the radioactivity in the cube is assumed to be uniformly distributed in a sphere of diameter s. The energy flux at any point r from the center of a sphere with radius $c = s/2$ is given by the following expression.[52]

$$d\phi = \frac{1.91 \times 3.7 \times 10^{10}}{4} \chi(x,y,z)\, D(x/\bar{u})\bar{E}_{\nu}(x/\bar{u}) \left[2c + \frac{c^2 - r^2}{r} \ln\left|\frac{c+r}{c-r}\right| \right] \quad (49)$$

The exposure at the receptor from the radioactivity in the sphere is obtained by substituting equation 49 into 48. The factor 1.91 is included in equation 49 to account for the greater amount of the contaminant in the cube of side s.

The following expression is used to estimate the build up factor for values of $\mu_T r$ less than or equal to 0.5.

$$B(\bar{E}_\nu) = [0.75(\mu_T r)^{1.57}+1.4]\ \bar{E}_\nu^{-[0.606(\mu_T r)^{0.42}-0.35]} \quad (50)$$

For values of $\mu_T r$ that are greater than 0.5 the following expression is used to compute $B(\bar{E}_\nu)$[53]

$$B(\bar{E}_\nu) = 1 + \mu_T r + \frac{(\mu_T r)^2}{\bar{E}_\nu^{2.4}} \quad (51)$$

Equation 50 computes $B(\bar{E}_\nu)$ to within $\pm$ 15% of the values calculated by Goldstein and Wilkins [54] for a single calculation and to within less than $\pm$ 7% for the average of many calculations. Because equation 50 over estimates $B(\bar{E}_\nu)$ by + 40% at $\mu_T r = 0$ equation 51[53] is used to calculate $B(\bar{E}_\nu)$ below $\mu_T R = 0.5$.

It is assumed that the receptor has a density of 1 gm/cc and that μ_a for water is applicable to absorption in the receptor. While μ_a is relatively constant with energy for water (and air), μ_T is not. The following set of equations was derived to compute μ_T as a function of the gamma energy:

$$\mu_T = 0.074\ \bar{E}_\nu^{-0.32} \qquad \bar{E}_\nu < 0.2\text{MeV} \quad (52a)$$

$$\mu_T = 0.065\ \bar{E}_\nu^{-0.414} \qquad 0.2 < E_\nu \leq 0.9\text{MeV} \quad (52b)$$

$$\mu_T = 0.063\ \bar{E}_\nu^{-0.498} \qquad 0.9\ \text{MeV} < \bar{E}_\nu \quad (52c)$$

These equations compute μ_T to within a few percent for gamma energies above 0.1 MeV.

The average energy of the gamma radiation emitted by the noble gas mixture changes with time. The following equations give the average gamma energy as a function of the travel time from the stack.

$$\bar{E}_\nu = 0.5 \qquad x/\bar{u} \leq 3300 \text{ sec} \qquad (53a)$$

$$\bar{E}_\nu = 3.84(x/\bar{u})^{-0.252} \qquad x/\bar{u} > 3300 \text{ sec} \qquad (53b)$$

where $\bar{E}_\nu$ = average gamma energy (MeV)

Table 9 compares the exposures computed by this method and those reported by Holland.[53] Holland's method employs a combination of analytical and numerical solutions. His method uses the fewest assumptions of any other method I know of. The bases for the comparison are listed in the table. For the purposes of this investigation the agreement is good.

Because of the great amount of computer time required, gamma exposures are not calculated as a function of time and then integrated with respect to time as is done for the air concentration and therefore for the beta exposure. The average dimensions of the plume for the 24 hour period are used to compute the gamma exposure instead. To attain the necessary sensitivity, the measurement period for the gamma exposure in an environmental survey must be longer than a day, and the use of the average daily plume dimensions does not materially affect the results when averaged over a period of a week or so.

TABLE 9

A COMPARISON OF THE GAMMA EXPOSURES COMPUTED BY HOLLAND[53]

AND THOSE FROM THE PRESENT METHOD*

Distance	Holland	The Present Method
30 meters	170 mr	149 mrad
300	19.6	18.6
3000	0.388	0.393
30000	0.000745	0.000904

*The exposures are calculated for a release of $4.8 \times 10^{16}\ t^{-1.21}$ MeV/sec (t in sec) of fission products with an average gamma energy of 0.7 MeV. Diffusion is calculated using Sutton's equation with $C_y = C_z = 0.15$ and $n = 0.25$. $\bar{u} = 5$ m/sec.

8. Iodine-131 in the milk of cows.

There is a great deal of experimental evidence which indicates that iodine-131 is removed from vegetation at a rate faster than would be dictated by its 8.05 day half life. Thompson[55] has summarized the results of twenty four measurements of the effective half life of iodine-131 on vegetation. The mean of these measurements was 5.0 days with a standard deviation of the mean of 0.12 days. The lowest value reported was 3.0 days and the highest value was 6.0 days. The types of vegetation used in the various experiments ranged from desert sagebrush to lush pasture grass. The physical state of the iodine-131 used in the experiments ranged from vapor to a combination of vapor and particles. In some experiments the iodine-131 was deposited by rain and in some cases it was deposited dry. An effective half life of five days for iodine-131 indicates a removal half life of 13 days. Thompson also reported the results of measurements of removal half lives of other fission product radionuclides. These ranged from 9 to 27 days with most values being between 13 and 14 days.

The process or processes by which the iodine-131 is removed from vegetation are not known. Marter[56] has attributed a measured 5 day effective half life to the dilution by new growth because laboratory tests showed that "little or no" iodine-131 was removed by the equivalent of an inch of rain. On the other hand the work reported by Cline, et al.[39] showed conclusively that processes other than new growth can remove iodine-131 from vegetation. On the assumption that the rate of wash-off was linear with the amount of rainfall, elimination constants

for wash-off of radioactivity by rain have been reported.[40,55,57] However, the experimental methods used in two of these determinations[40,57] pre-supposed that rain was the only removal mechanism. Had wind speed been chosen to measure the effect of wind action as the removal mechanism, the results might well have been the same. Effective half lives of 5.5 days and less have been measured in the absence of rain. It must be concluded that the important mechanisms for removal are still unknown, but it seems likely that whatever they are they act in an either-or fashion. This is indicated by the fairly consistent effective half-lives obtained under the many different source and weather conditions. For the purposes of this investigation it is assumed that the iodine-131 deposited on vegetation decays with a 5 day effective half-life.

The next equation describes the rate of change of the radioactivity per unit area on grass:

$$\frac{dA'_g}{dt} = a\frac{d\ DEP_r}{dt} + \frac{d\ DEP_d}{dt} - \lambda_{eff} A'_g - \frac{A'_g}{Y} J \qquad (54)$$

where: A'_g = iodine-131 per unit area on grass ($\mu Ci/m^2$)

$\frac{d\ DEP_r}{dt}$ = deposition rate of iodine-131 in rain ($\mu Ci/m^2/day$) computed by dividing DEP_r by 1 day.

a = fraction of radioactivity in rain which adheres to the grass

$\frac{d\ DEP_d}{dt}$ = deposition rate of iodine-131 on grass due to dry processes ($\mu Ci/m^2/day$) computed by dividing DEP_d by 1 day.

λ_{eff} = effective decay constant, 0.693/5 = 0.139 $days^{-1}$

Y = the stand of grass on the pasture (gms/m^2)

J = consumption rate of the grass by the dairy herd ($gms/m^2/day$).

The stand of grass on the pasture Y is a function of the growth rate K and the consumption rate J according to the next equation:

$$\frac{dY}{dt} = K - J \tag{55}$$

where: $\frac{dY}{dt}$ = rate of change of the stand of grass on the pasture ($gms/m^2/day$)

K = growth rate ($gms/m^2/day$)

Solving equation 55 for Y one obtains the following expression:

$$Y = Y_o + (K - J)\, t \tag{56}$$

where: Y_o = stand of grass at t = 0

The concentration of radioactivity in grass A_g is related to the radioactivity per unit area on grass A'_g according to the next expression:

$$A_g = A'_g/Y \tag{57}$$

Probably the most important factor determining the value of the retention factor a in equation 54 is the surface area of grass available to intercept rain per unit area of ground. The intensity of rainfall as far as it affects the relative sizes of the raindrops may also be

important. A crude measure of the area of grass available to intercept rain is the weight of grass per unit area. Therefore, as a first approximation a is assumed to be proportional to Y. That is,

$$a = k\, Y_s \tag{58}$$

where: k = a proportionality constant (m^2/gm)

It should be noted that the linear relationship between a and Y may not be valid at very high or very low values of Y.[58] The values of a, Y and k measured by various investigators are shown in Table 10 with the values of k used in this research.

Substituting equation 57 and 58 into equation 54 one obtains the following expression for the rate of change of the concentration of radioactivity in grass:

$$\frac{dA_g}{dt} = k\,\frac{dD_r}{dt} + \frac{1}{Y_s}\,\frac{dD_d}{dt} - \left(\lambda_{eff} + \frac{K}{Y}\right) A_g \tag{59}$$

where: A_g = iodine-131 concentration in grass at any time t ($\mu Ci/gm$)

Equation 59 is strictly applicable to a growth process which dilutes the radioactivity uniformly throughout the entire stand of grass. In general cows eat grass down to a certain level, leaving a stand on the pasture at all times. For grass, which grows from the bottom up, the radioactivity concentration at the level to which the cows graze will reflect past deposition (and also decay) until a complete turnover of grass below this level has been achieved. However,

TABLE 10

VALUES OF THE RAIN RETENTION FACTOR a ESTIMATED BY VARIOUS INVESTIGATORS FOR FALLOUT RADIONUCLIDES

The corresponding values of the grass cover Y and the ratio a/Y =k are also included

Y (dry gms/m^2)	a	k (m^2/dry gm)	Radionuclide
41[58]	0.11	0.0027	Average of Ce-144, Sb-125, Ru-106, Cs-137, Sr-95, Mn-54
65[57]	0.20	0.0032	Ce-144
500[59]*	0.50	0.0010	Iodine-131
156[60]	0.29	0.0019	Average of Sr-89, Sr-90, Cs-137, Zr-95
200[60]	0.35	0.0019	"
270[60]	0.41	0.0015	"
	Average**	0.0020	

*In the original article, Y was reported in wet or natural weight. To convert to dry weight, it was assumed that 2/3 of the wet weight was water.

**The average value of k is used in this study.

since the deposition may be either continuous or intermittent and the turnover time is of the same order as the effective removal half life, the solutions of equation 59 are considered adequate for the purposes of this investigation.

It is assumed that when the cows are let out to pasture the stand of grass Y_o is 45 dry gms/m^2. This compares well with the value of 52 dry gms/m^2 in an Idaho Falls iodine-131 experiment already mentioned.[37]

A cow producing 24 liters of milk per day (typical of commercial dairy cows in the southeastern Michigan area) must eat about 5.9 Kg of pasture grass per day in addition to supplements such as grain and some form of food concentrate. It is assumed that the pasture can support 1 cow on each acre for a 120 day period. This is typical of a good pasture.[61] The growth rates necessary to meet these conditions are shown in Table 11 with other data pertinent to estimating the iodine-131 content of milk.

It is assumed that the following set of three simultaneous equations describes the flow of iodine-131 through the cow.

$$\frac{dC_{th}}{dt} = f_{th} A_g I - (\lambda_I + TH) C_{th} \qquad (60)$$

where: C_{th} = the quantity of iodine-131 in the cow's thyroid at any time t (μCi)

f_{th} = the fraction of the ingested iodine-131 reaching the thyroid

A_g = the concentration of iodine-131 in grass (μCi/gm)

TABLE 11

VALUES FOR THE PARAMETERS USED TO CALCULATE THE CONCENTRATION OF IODINE-131 IN THE MILK OF COWS

k	=	$0.002\ m^2/gm$
Y_o	=	45 dry gms/m^2
K	=	$1.68\ gms/m^2$/day for first 30 days
	=	$1.46\ gms/m^2$/day for second 30 days
	=	$1.12\ gms/m^2$/day for third 30 days
	=	$0.90\ gms/m^2$/day for fourth 30 days
I	=	5900 gms/cow/day
J	=	$1.46\ gms/m^2$/day
λ_{eff}	=	$0.139\ days^{-1}$

Milk output = 24 liters/cow/day

Area of pasture sustaining one cow for 120 days = 1 acre = $4050\ m^2$.

NOTE: All weights are expressed in dry measure.

I = rate of ingestion of contaminated grass (gm/day)

TH = biological decay constant for elimination of iodine-131 in the thyroid ($days^{-1}$)

$$\frac{dC_m}{dt} = (1 - f_{th})\, A_g I - (\lambda_I + M + U + F)\, C_m \qquad (61)$$

where: C_m = the quantity of non-protein bound iodine-131 in the cow's blood (μCi)

M = biological decay constant for elimination in milk ($days^{-1}$)

U = biological decay constant for elimination through urine ($days^{-1}$)

F = biological decay constant for elimination through feces ($days^{-1}$)

$$\frac{dC_b}{dt} = Th\, C_{th} - (\lambda_I + U + F)\, C_b \qquad (62)$$

where: C_b = the quantity of protein bound iodine-131 in the cow's blood (μCi)

Equations 60-62 agree qualitatively with most of the observed measurements of iodine-131 in the cow. The assumptions inherent in the equations are the following:

1) Protein bound iodine-131 in the blood does not contribute to the radioactivity in milk.[63]

2) The thyroid is the only source of protein bound iodine-131 in the blood. Organic iodine and protein bound iodine are taken here as being equivalent. It is known that the thyroid is a source of organic iodine (thyroxine),[64] and while the mammary glands are known to bind iodine in organic compounds, there appears to be little transfer of them back to the blood.[63]

3) The rates of elimination through the urine and feces are the same for both organic and inorganic iodine. This assumption is made for simplicity. However, it will be shown later that it is not critical in this study.

4) The total amount of iodine-131 in the milk of cows is linearly related to the milk output.[63,65,68] Thus M in equation 61 is proportional to the milk output.

5) The concentration of iodine-131 in milk is strongly dependent on the amount of stable iodine in the diet provided that the intake of stable iodine is low.[65,66] Measurements have shown[66] that the concentration of iodine-131 in milk increases with stable iodine intake up to 15 mg/day. The concentration remained relatively constant until the intake of stable iodine became very large (between 0.15 and 2 gm/day)[66] at which time the concentration of iodine-131 decreased drastically. Thus M also is proportional to the quantity of stable iodine in the diet.

6) The quantity of iodine-131 in the thyroid decreases as the intake of stable iodine increases,[65,66] and the decrease is due to

some process like isotopic dilution rather than a process which affects the functioning of the thyroid. In similar feeding experiments Bustad, et al. and Garner, et al. report maximum uptakes of iodine-131 in the thyroids of cows of 35% and 5% respectively of the original dose administered. However, both investigators measured an effective removal half life from the thyroid of 4.5 days.[66] Thus f_{th} also is dependent on the quantity of stable iodine in the diet.

The minimum daily requirement of iodine for dairy cows is between 2 and 3 mg/day.[62] For the purposes of this investigation, it is assumed that the cows eat 5 mg/day or about twice the minimum daily requirement. Furthermore, it is assumed that at equilibrium the cow delivers 0.5% of the daily intake of iodine-131 in each liter of milk. This assumption is discussed in Appendix A. Using these assumptions and the results of some experiments reported in the literature one is able to estimate values of the constants f_{th}, TH, M and (U + F). The values are shown in Table 12. The methods by which they were determined are described in Appendix A.

Once the value of f_{th} is known, only equation 61 is involved in the determination of the iodine-131 in cow's milk. It is rewritten here with the assumed values of the constants as follows:

$$\frac{dC_m}{dt} = 0.69\, A_g I - 0.661\, C_m \qquad (63)$$

Equation 63 is solved simultaneously with equation 59 by a Runge-Kutta method* of numerical analysis.[67] Once the value of C_m is

*This method of solving simultaneous linear differential equations is available as a subroutine at the University of Michigan Computing Center.

TABLE 12

VALUES OF THE PARAMETERS TO SATISFY THE CONDITION THAT THE CONCENTRATION OF IODINE-131 EQUALS 0.5% OF THE DAILY DOSE PER LITER OF MILK*

Constant	Value
f_{th}	0.31
TH	0.068 ($days^{-1}$)
M	0.115 ($days^{-1}$)
U + F	0.460 ($days^{-1}$)
λ_I	0.086 ($days^{-1}$)

*See Appendix A for details.

determined the concentration of radioactivity in the milk is computed by the following expression:

$$\text{Conc. of I-131 in milk} = \frac{M\ C_m}{\text{milk output (ml)}} \quad (\mu Ci/ml) \tag{64}$$

The value of C_m in equation 63 is an instantaneous one. In order to determine an average daily value of the concentration in milk, an average value of C_m is used, which is computed from 10 calculations of C_m at 2.4 hour intervals during the day.

It is interesting to note from equation 63 that the effective half life of non-protein bound iodine-131 in the cow is 1.05 days which agrees well with the values measured by many investigators.[66,68,37,69]

C. Sensitivity

In general the minimum detectable release rate MDR is found by dividing the experimentally determined MDL by the radioactivity or exposure level produced by a unit release rate, i.e.,

$$MDR = \frac{1}{R(Q=1)} \quad \overline{MDL} \tag{65}$$

where: MDR = minimum detectable release rate (μCi/sec or Ci/sec)

$R(Q=1)$ = radioactivity or exposure level produced by a unit release rate. (Units depend on sample media.)

For example, the sensitivity of air sampling to the continuous release of particulate radioactivity is given by:

$$MDR = \frac{1}{\bar{\chi}(Q = 1)} \overline{MDL} \tag{66}$$

where: MDR = minimum detectable release rate (μCi/sec)

$\overline{MDL}$ = average minimum detectable radioactivity level for a given air sampling period ($\mu Ci/m^3$)

$\bar{\chi}(Q=1)$ = radioactivity levels produced by a unit release averaged over the same period as the MDL ($\mu Ci/m^3$ per μCi/sec)

The average MDR for all sampling periods is the average of the MDR's calculated for each sampling period. In the case of air sampling the average sensitivity is defined mathematically as follows:

$$\overline{MDR} = \left\langle \frac{\overline{MDL}}{\bar{\chi}(Q=1)} \right\rangle_{av.} \tag{67}$$

where: MDR = average MDR of all sampling periods (μCi/sec)

Note that the $\overline{MDL}$ is the same in both the computation of MDR and of $\overline{MDR}$. The average MDL for all measurement periods is used throughout for simplicity. This is justifiable on the grounds that the weather data used to calculate $\bar{\chi}(Q=1)$ and the radioactivity measurements taken to find the MDL were not taken at the same time.

D. Probability of Detecting Various Releases

The probability of detecting a release from an elevated source is a function of the following things:

1) the vertical and horizontal dimensions of the plume
2) the distance from the stack to the samplers
3) the number and the spacing of the samplers around the stack
4) the distribution of the contaminant within the plume.

Although some thought was given to computing the theoretical probabilities of detecting various releases under certain ideal conditions, the idea was discarded in favor of an empirical approach. It was found that unless the theory was made rather comprehensive the theoretical results would not be relevant physically.

After solving the model already discussed with the input data to follow, the probabilities of detecting various releases were determined by the following expression:

$$P(\bar{\chi} \geq \bar{\chi}_i) = \frac{n(\bar{\chi} \geq \bar{\chi}_i)}{N} \tag{68}$$

where: $P(\bar{\chi} \geq \bar{\chi}_i)$ = probability of detecting a concentration greater than or equal to $\bar{\chi}_i$

$n(\bar{\chi} \geq \bar{\chi}_i)$ = number of days or weeks in which the concentration is greater than or equal to $\bar{\chi}_i$

N = total number of days or weeks of data

Cumulative frequency distributions for the detection of various releases are calculated using equation 68. Since the concentration $\bar{\chi}$ and the release rate Q are related, frequency distributions for detecting various release rates can be calculated.

III. EXPERIMENTAL METHODS

A. Inputs to the Mathematical Models

1. Micrometeorological data

Personnel of the Meteorological Department of the University of Michigan have measured continuously the micrometeorological parameters important to the dilution and dispersion of contaminants from the Enrico Fermi stack since December 1, 1956.[27] The parameters measured were:

1. wind direction at elevations of 25, 75 and 100 feet
2. wind speed at elevations of 25, 75 and 100 feet
3. temperature lapse rates between the 25 and 100 feet elevations
4. occurrence of precipitation

The data of wind direction, wind speed and lapse rate were made available[28] in the form of hourly averages from December 1956 to December 1961. The number of hours each day when precipitation was measured also was made available.[28] The amount of rainfall each day was taken from U.S. Weather Bureau data[70] from Monroe, Michigan, located about seven miles southwest of the site. For the purposes of this investigation the rainfall at Monroe is considered sufficiently representative of the rainfall at the reactor site. In only a few cases was rainfall indicated at one site and not at the other.

Based on these data the inputs to the model for each day are the following:

1) The average daily wind direction: In the original hourly data, the average wind direction was expressed as any one of the 16 cardinal points of the compass, i.e., N, NNE, NE, etc. Each of these points was assigned a number from 1 to 16 and the average of the 24 measurements was taken as the nearest whole number to the computed average. The average daily wind direction to the nearest degree was chosen at random from the 22.5° centered over the cardinal point.

2) The average daily wind speed: The average daily wind speed was taken as the average of the 24 hourly averages in the original data.

3) The 24 hour standard deviation of wind direction: The standard deviation of the 24 hourly average wind directions $[S_\theta]_{24}$ was computed according to the following equation:

$$[S_\theta]_{24} \approx [\sigma_\theta]_{24} = \left(\frac{\Sigma (\overline{wD} - wD_i)^2}{23} \right)^{1/2} \tag{69}$$

where: $\overline{wD}$ = average daily wind direction (not rounded to the nearest whole number)

wD_i = average hourly wind direction for the ith hour.

4) The number of hours of each of the 3 lapse conditions reported by Hewson (see Table 1): As already mentioned, atmospheric stability changes continuously with time, and Pasquill's 6 stability categories offer more definitions than do Hewson's 3 categories. Therefore, it is necessary to determine the time sequence of Pasquill's categories given the number of hours of Hewson's categories. First, the sequence of Hewson's 3 categories is determined by sampling at random a uniform distribution, and then the occurrence of Pasquill's categories within each of Hewson's is determined by sampling at random the frequency distributions shown in parentheses in Table 3. The very unstable conditions A and B are allowed to occur only during the warm months April through September.

5) The month of the year in which the particular day occurred. The month is needed to select the appropriate monthly mixing depth.

6) The duration of rainfall in hours which, when converted to seconds, equals $(T_r - T_o)$ in equation 27. Since σ_y in equation 27 is a non-linear function of time the quantity of deposition DEP_r is dependent on the value of T_o. The assumption is made that it is equally likely that the rain starts on any hour of those hours making up the difference between 24 and the duration of rainfall. The particular hour is selected by the random sampling of a uniform distribution.

7) The amount of rainfall: The rate of rainfall is computed by dividing the amount of rainfall by its duration.

Meterological data for the year 1958 are used in the model. Presumably due to equipment difficulties there were only 281 days in which complete data are available. Days of incomplete data are neglected and it is assumed that the 281 days are consecutive. Figures 7 and 8 show the wind rose of the 281 average daily wind directions and the average value of the 24 hour standard deviation of the hourly averaged wind directions corresponding to each daily wind direction. Table 13 shows the relative frequency of the various stability categories.

The concentration of iodine-131 in milk is of interest only in the late spring, summer and early autumn months. One hundred and twenty consecutive (consecutive within the 281 days of complete data) were used. The wind rose, the average 24 hour standard deviations and the relative frequency of Pasquill's stability categories for the 120 days were very much the same as those shown in Figure 7.

2. Sampling locations

The National Sanitation Foundation has performed an environmental survey in the vicinity of the Enrico Fermi site since 1958.[71] The sampling locations used in the model are those which have been in operation since June 1964. The polar coordinates of these locations, taking the stack as the origin, are shown in Table 14.

FIGURE 7. RELATIVE FREQUENCY OF DAILY AVERAGE WIND DIRECTIONS AT THE ENRICO FERMI ATOMIC POWER PLANT, 1958.

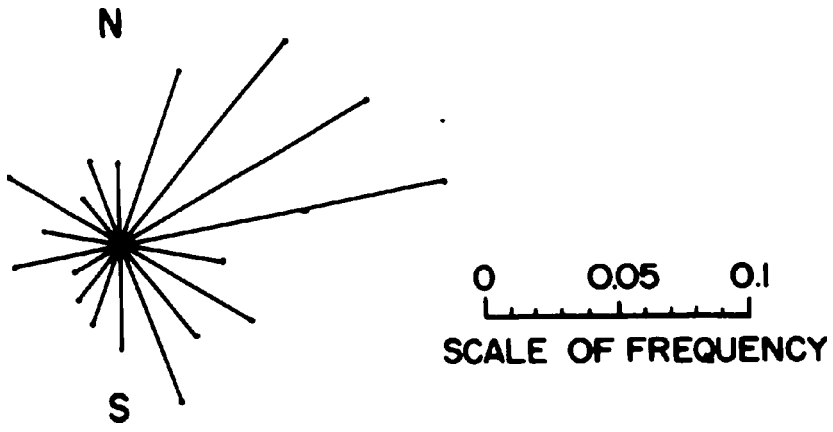


FIGURE 8. AVERAGE 24 HOUR STANDARD DEVIATIONS OF HOURLY AVERAGED WIND DIRECTIONS $[\sigma_\theta]_{24}$ AT THE ENRICO FERMI ATOMIC POWER PLANT, 1958

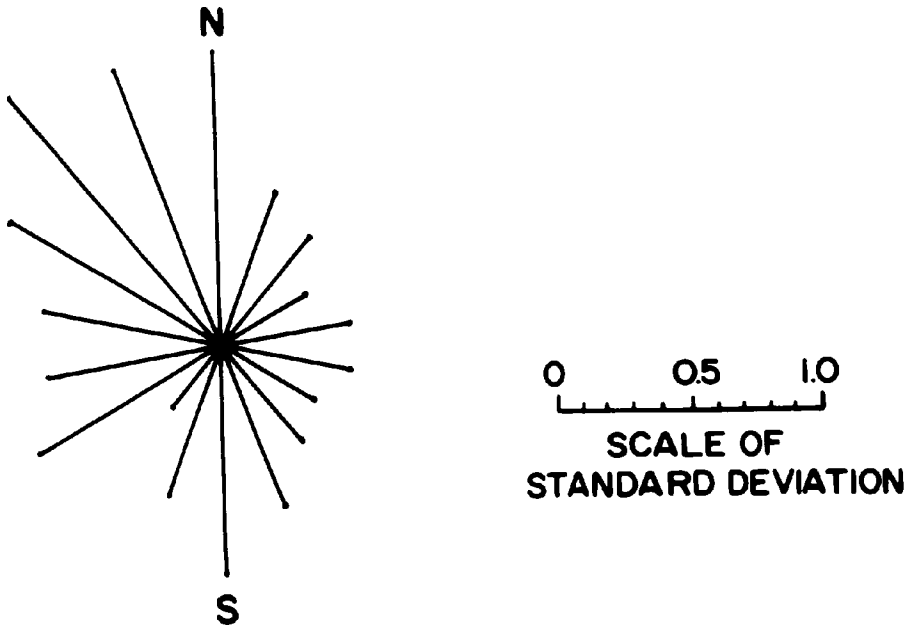


TABLE 13

RELATIVE FREQUENCY OF VARIOUS ATMOSPHERIC STABILITY CATEGORIES AT THE ENRICO FERMI ATOMIC POWER PLANT, 1958

A*	B*	C*	D*	E*	F*	La.I.**
0.0068	0.0376	0.300	0.333	0.107	0.175	0.0495

Strong Lapse***	Weak Lapse***	Inversion***
0.344	0.333	0.332

*Pasquill's stability categories (frequency is calculated)

**Lake breeze inversion (frequency is measured)

***Hewson's stability categories (frequency is measured)

TABLE 14

POLAR COORDINATES OF THE SAMPLING LOCATIONS USED IN THE ENVIRONMENTAL SURVEY FOR THE ENRICO FERMI ATOMIC POWER PLANT BEGINNING IN JUNE 1964

(These locations are used in the mathematical model)

Site Designation	Coordinates** Angular	Radial (m)
1 R*	90°	230
2 R	33°	4000
3 R	337°	1170
4 R	265°	785
5 R	195°	1170
1 B*	350°	16,100
2 B	318°	12,900
3 B	18°	22,500
4 B	250°	14,500
5 B (air only)	313°	53,100
6 B (deposition only)	70°	30,600

*Sites with the designation R are those on or near the reactor site. The designation B includes those sites used for background measurements.

**With the stack as the origin.

The National Sanitation Foundation does not collect milk as part of its survey because milk is collected in the area by the Michigan State Health Department. There are several small farms around the Fermi site, and for the purposes of this survey it is assumed that farms are located at sites 2R, 3R and 5R (see Table 14). Four of the five sites in the background area 1B, 2B, 4B and 6B were used to estimate the average levels of iodine-131 in the background area.

3. Stack release parameters

The parameters used to compute the effective stack height given by equation 19 and 20 are those derived from normal operating conditions at the Enrico Fermi Atomic Power Plant.[42] They are: stack height = 60 meters, heat emission = 0, escape velocity 10 m/sec, stack diameter 0.915 meter.

B. Counter Characteristics and Sample Sizes for Computing Minimum Detectable Radioactivity Levels in the Absence of Environmental Background

Table 15 shows the background counting rates and efficiencies of two counters which are commonly used in environmental surveying. Instruments with these characteristics are commercially available. The size of each sample counted also is included in Table 15. Four hundred cubic meters is approximately the maximum air volume which can be drawn through a 2 inch diameter membrane filter with an average pore size of 0.8 micron. The limiting factor in the sample size is the dust loading on the filter and/or relative humidity. A sample size of one liter is used for milk

TABLE 15

DATA PERTINENT TO THE CALCULATION OF THE MINIMUM DETECTABLE ACTIVITY MDA AND THE MINIMUM DETECTABLE RADIOACTIVITY LEVEL MDL IN THE ABSENCE OF BACKGROUND AT THE COLLECTION SITE

		Sample Size			
Type of Counter	Efficiency	Bkgd.*	Air	Milk	Deposition**
Low Background Beta Counter	40%	1 cpm	400 m^3	----	0.056 m^2
Gamma Spectrometer For Iodine-131	4.3%	21 cpm***	----	1 l.	----

*The background counting rates are determined with counting times of 50 and 100 minutes for the beta and the gamma counter respectively.

**Area of the precipitation collector.

***3" x 3" NaI(Tl) crystal surrounded by 4 inches of lead shielding.

because it is the size which has been used successfully in this laboratory for many years. The milk is counted in a Marinelli beaker over the 3" x 3" crystal. A sample size as large as 2 liters could be used with some reduction in the minimum detectable concentration of iodine-131 in milk. Sample sizes much larger than 2 liters however would not reduce the minimum detectable concentration because the counting efficiency decreases in proportion to the sample size. The area of the precipitation sampler is for a 10.5 inch diameter collector. This is probably one of the largest used for routine environmental monitoring.

C. The Environmental Survey Used to Determine Minimum Detectable Radioactivity Levels Above Environmental Background

1. Sampling locations

The data from the environmental survey for the Enrico Fermi Atomic Power Plant[71] are used to determine the minimum detectable radioactivity levels above environmental background. The survey to provide these data was put into operation on December 27, 1962. The sampling locations used until March, 1964 are shown in Figure 9. In March, 1964 the five precipitation samplers from the background group were moved on or close to the reactor site. It took from March to June 18, 1964 to move the five air samplers into position on or near the site and get them operating. Figure 10 shows the locations of the air and precipitation samplers used to measure releases from the reactor; Figure 11 shows the locations used for background measurement.

FIGURE 9. SAMPLING LOCATIONS FOR THE ENVIRONMENTAL SURVEY IN THE VICINITY OF THE ENRICO FERMI ATOMIC POWER PLANT, DECEMBER 1962 TO MARCH 1964.

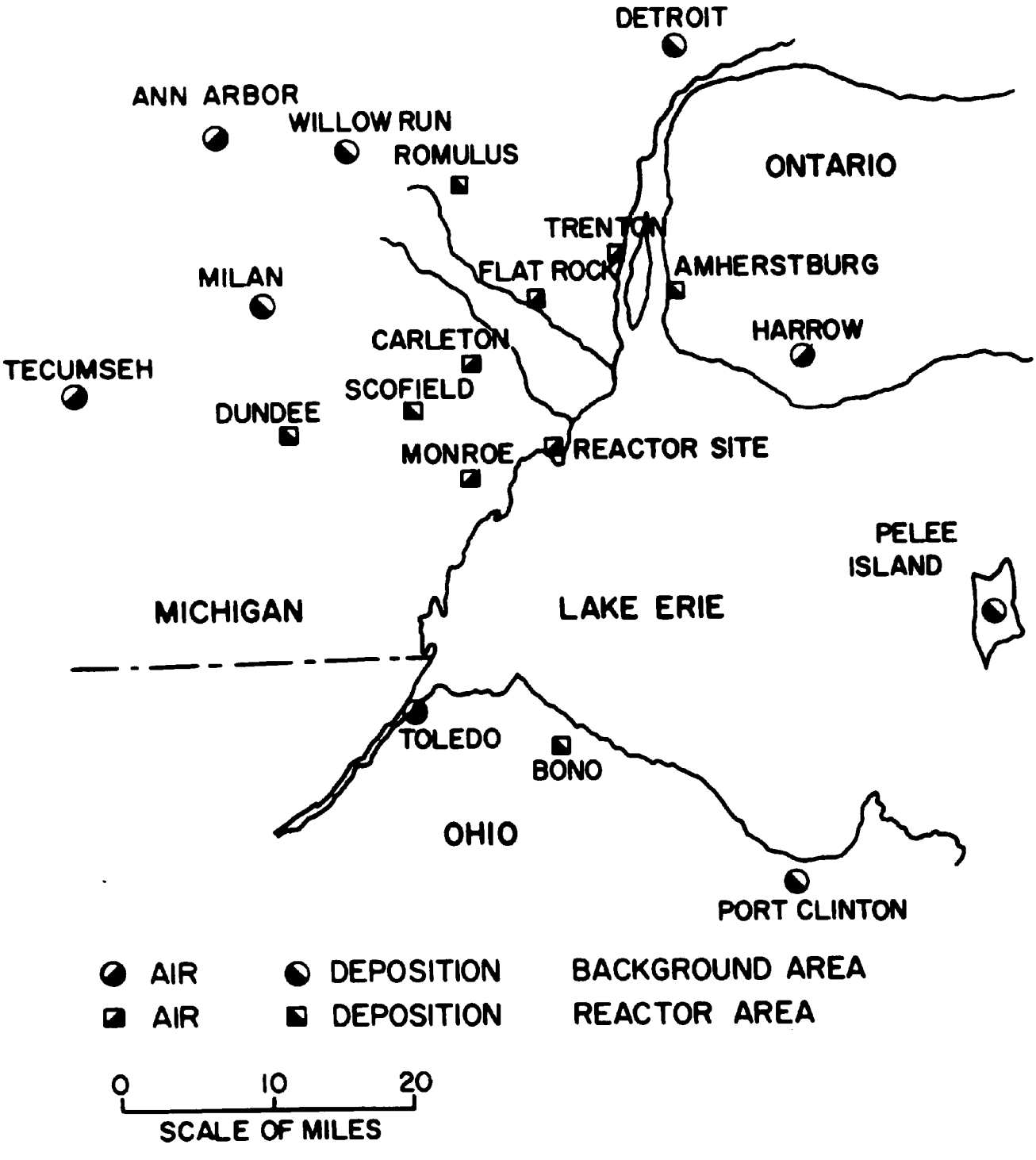


FIGURE 10. SAMPLING LOCATIONS ON OR NEAR THE ENRICO FERMI ATOMIC POWER PLANT SITE, FROM APRIL 1964.

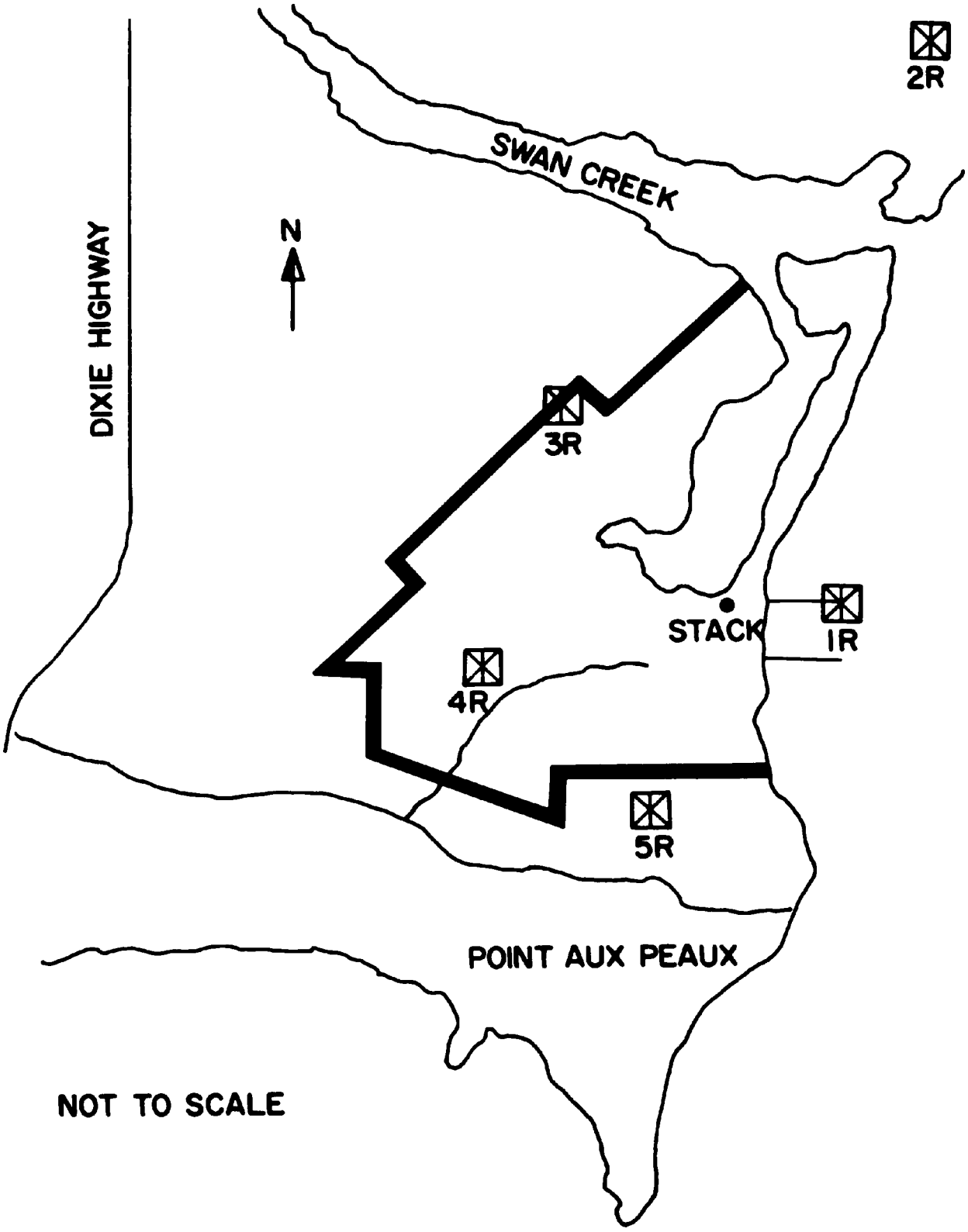
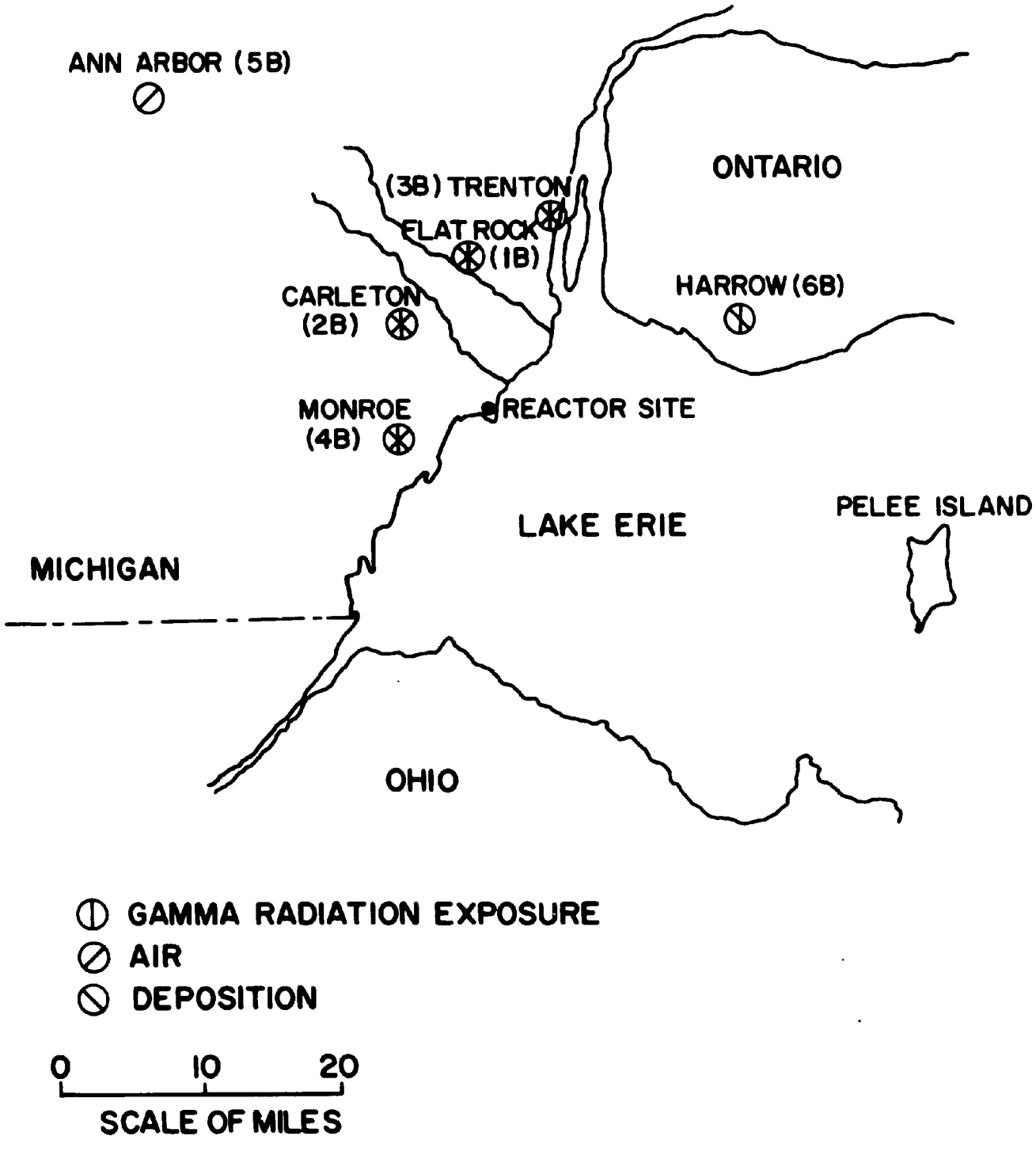


FIGURE II. SAMPLING LOCATIONS FOR THE MEASUREMENT OF BACKGROUND FOR THE ENVIRONMENTAL SURVEY IN THE VICINITY OF THE ENRICO FERMI ATOMIC POWER PLANT, FROM APRIL 1964.



2. Sampling techniques and methods of sample preparation and analysis

Filterable airborne radioactivity in air is collected on membrane filters* with an average pore size of 0.8 micron. This filter is backed with another membrane filter impregnated with activated charcoal to collect iodine-131 vapor. The efficiency of the first filter is greater than 95% for particles down to 0.01 micron.* The efficiency of the activated charcoal impregnated filter for iodine-131 collection is unknown because of its newness.* The filter contains 60% by weight of activated charcoal.* Air is drawn** through the two 2-inch diameter filters at the rate of about 0.007 m^3/sec (1.5 ft^3/min). The sampler was modified so that the air volume is measured at the exhaust of the air pump. Prior to this modification the air volume was measured between the pump and the air filter. The volume thus recorded had to be corrected for the pressure drop across the filter, and this introduced a potential source of error. With the volume meter at the exhaust end of the pump no pressure correction is needed. At the end of every other sampling period the volume meters at the background sampling sites are exchanged with those near the reactor. In this way, erroneous volume measurements are equally likely to occur in either group when averaged over a long period of time. Two week collection periods were used until June 18, 1964, at which time weekly sampling periods were used.

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*Gelman Instrument Company, Ann Arbor, Michigan.

**Gelman "Nuclear Air Sampler," Model No. 26001.

During collection, the filters are held in removable holders. At the end of the collection period the holders are replaced with other holders containing new filters. The holders are loaded and unloaded in the laboratory. Seven days after collection the filters are removed from their holder and placed in a stainless steel planchet and counted for beta radioactivity. After seven days the filter is recounted and the two counting rates are used to extrapolate graphically to the counting rate during the middle of the collection period.

Deposition by wet and dry processes is caught on a 10.5 inch diameter polyethylene funnel which drains into an 8-liter polyethylene jug. About 25 mg of zirconium carrier are added to the jug before it is put out for collection. This is done to minimize chemical absorption onto the walls of the jug. At the time of collection the funnel is washed with 50 ml of 6N nitric acid, the wash running into the jug. The collection period is 4 weeks.

The jug is returned to the laboratory where its contents are washed into a beaker with nitric and hydrochloric acid. The contents of the beaker are evaporated and ultimately the residue is transferred to a 2-inch diameter stainless steel planchet.

For the measurement of external gamma and beta exposures, a commercial film badge service* provides film badge dosimeters using Kodak Type 3 emulsion. The film badges are sealed in aluminized paper to exclude moisture. Two dosimeters are exposed at each location for a period of 4 weeks. The dosimeters are placed face up on a 2" x 6" lead brick to minimize exposure from the ground.

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*Radiation Detection Company, Palo Alto, California.

IV. RESULTS

A. Minimum Detectable Radioactivity Levels

1. In the absence of environmental background

The minimum detectable radioactivity levels for filterable airborne gross beta radioactivity, deposition of gross beta radioactivity on precipitation collectors and iodine-131 in milk are calculated using the data in Table 15 and equation 5. The results are shown, with the appropriate minimum detectable radioactivities, in Table 16. The minimum detectable exposures to external radiation in the absence of background have no useful meaning here and therefore are not included in this section.

2. In the presence of environmental background

Figures 12 and 13 show the average background levels ($\bar{x}_b$) of gross beta radioactivity measured by air samplers and precipitation collectors, respectively, from December 1962 to the middle of 1965. The minimum detectable radioactivity levels calculated from equation 6 are also shown for each sampling period. Figure 14 shows the average external gamma ray exposures measured in the background area from December, 1964 to September, 1965 and the MDL's for each sampling period. The suppliers of the film badge monitors report only gamma exposures and therefore beta exposures are not included. Significant differences between the levels

TABLE 16

MINIMUM DETECTABLE RADIOACTIVITY LEVELS IN THE ABSENCE OF ENVIRONMENTAL BACKGROUND

Medium	MDA*	MDL**
Filterable Airborne Radioactivity	1.5×10^{-6} µCi	3.5×10^{-15} µCi/cc
Deposition	1.5×10^{-6} µCi	2.7×10^{-9} µCi/cm^2 (0.07 mCi/mi^2)
Iodine-131 in Milk	3.7×10^{-5} µCi	3.7×10^{-8} µCi/ml

*Minimum Detectable Radioactivity

**Minimum Detectable Radioactivity Level

FIGURE 12. BACKGROUND CONCENTRATIONS OF LONG-LIVED, FILTERABLE GROSS BETA RADIOACTIVITY IN AIR $\bar{X}_b$ AND THE MINIMUM DETECTABLE CONCENTRATIONS IN THE VICINITY OF THE ENRICO FERMI ATOMIC POWER PLANT, JANUARY 1963 TO JULY 1965.

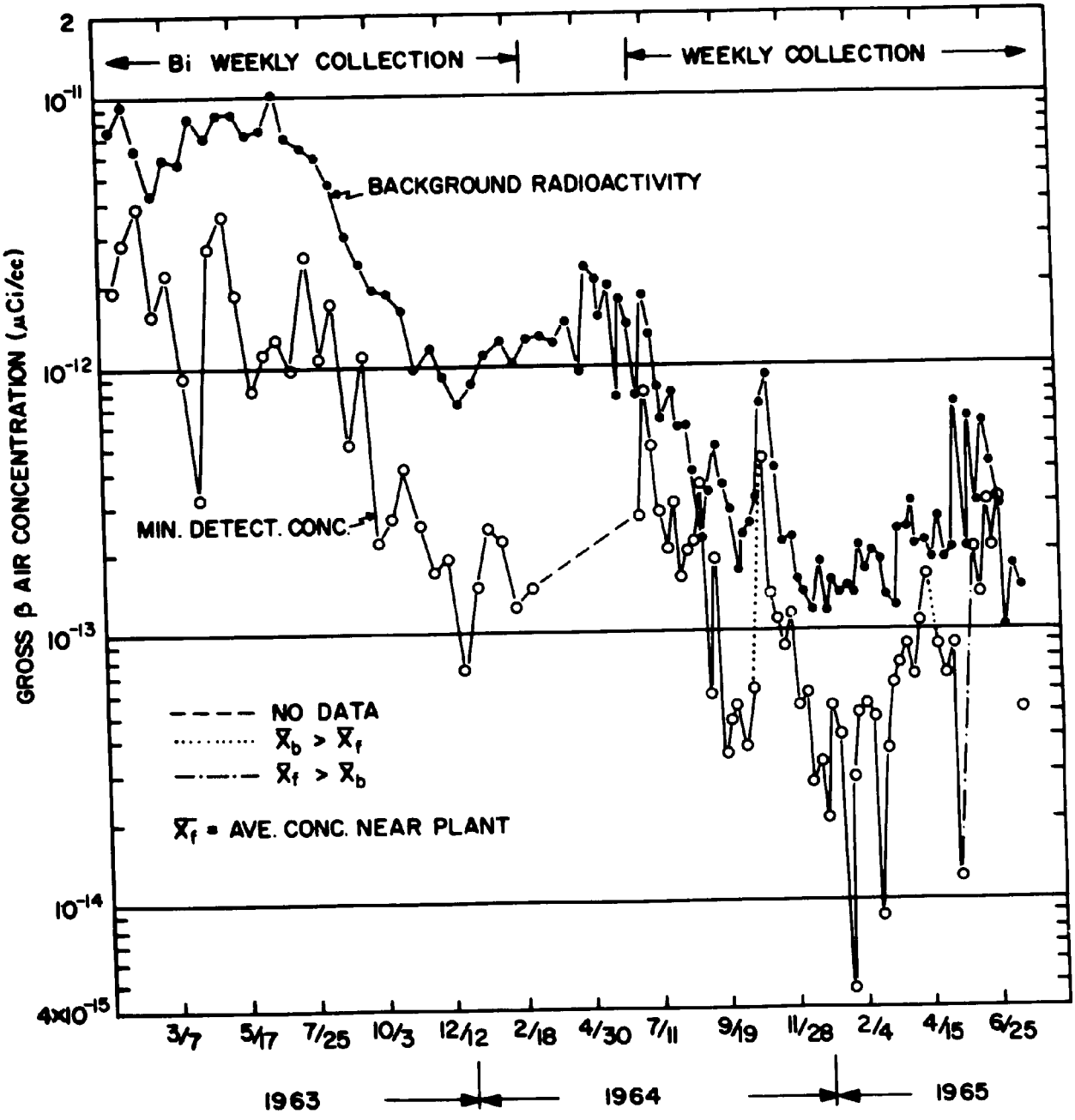


FIGURE 13. BACKGROUND DEPOSITION OF NON-VOLATILE GROSS BETA RADIOACTIVITY ONTO PRECIPITATION COLLECTORS AND THE MINIMUM DETECTABLE DEPOSITION IN THE VICINITY OF THE ENRICO FERMI ATOMIC POWER PLANT, JANUARY 1963 TO AUGUST 1965.

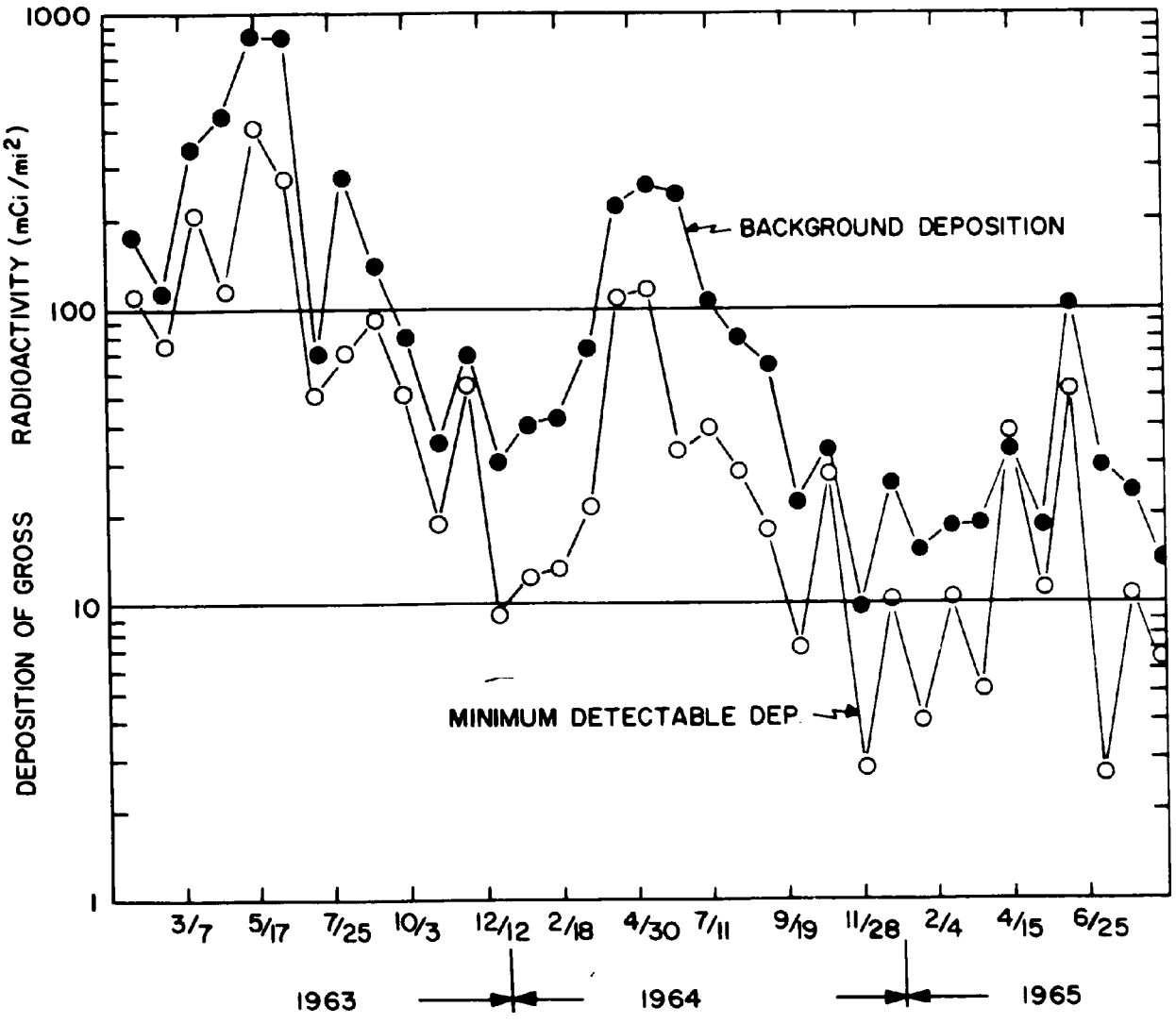
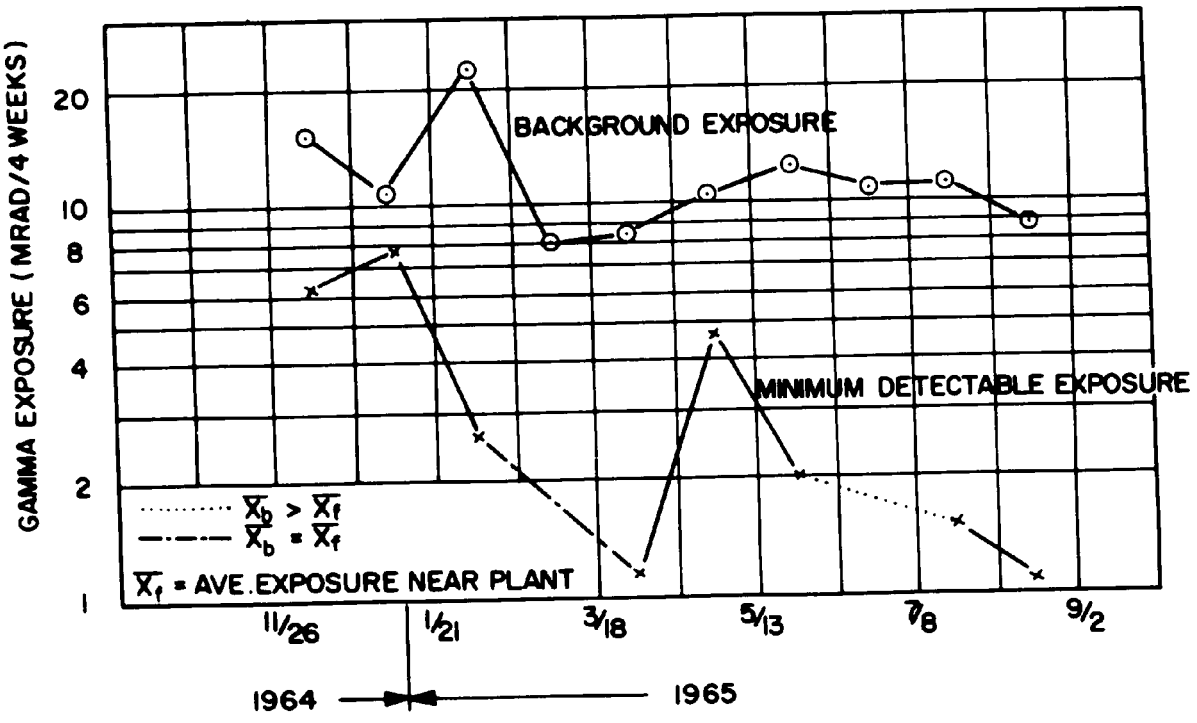


FIGURE 14. BACKGROUND GAMMA RADIATION EXPOSURE $\overline{X}_b$ AND THE MINIMUM DETECTABLE EXPOSURE IN THE VICINITY OF THE ENRICO FERMI ATOMIC POWER PLANT, DECEMBER 1964 TO AUGUST 1965.



in the background and the reactor areas are indicated in Figures 12 and 14 by either $\bar{x}_b > \bar{x}_f$ or $\bar{x}_b < \bar{x}_f$, whichever is found to occur.

The MDL, expressed as a fraction of background was found to decrease when individual measurements were averaged with time. Figure 15 shows a plot of the MDL's for airborne radioactivity, deposition and gamma radiation exposure as a function of the number of sampling periods used to calculate the average.

Tables 17 - 19 summarize the results of the MDL measurements for the survey around the Fermi Plant. The MDL's are listed for three levels of background radioactivity, high, medium and low, and for single measurement periods and for long term averages. The long term averages in Tables 17 - 19 do not necessarily have the same values as those in Figure 15. This is because the MDL's in Figure 15 represent the averages of all the measurements of each type. Values of the standard deviation expressed as a fraction of background are also included in Tables 17 and 18.

B. The Relationship Between Environmental Levels of Radioactivity and Stack Release Rates

1. For filterable airborne radioactivity.

The average weekly air concentrations of filterable radioactivity were calculated from equation 22 using the reduced source strength given by equation 37. It is assumed that the radioactivity is sufficiently long lived so that decay from the stack to the sampler is negligible. The results for the 5 sampling locations near the reactor (see Table 14) are shown in Figure 16 as running averages. The entry on each week is

FIGURE 15. MINIMUM DETECTABLE RADIOACTIVITY AND GAMMA RADIATION EXPOSURE LEVELS $\frac{MDL}{\overline{X_b}}$ EXPRESSED AS A PERCENT OF BACKGROUND $\overline{X_b}$ FOR VARIOUS AVERAGING PERIODS.

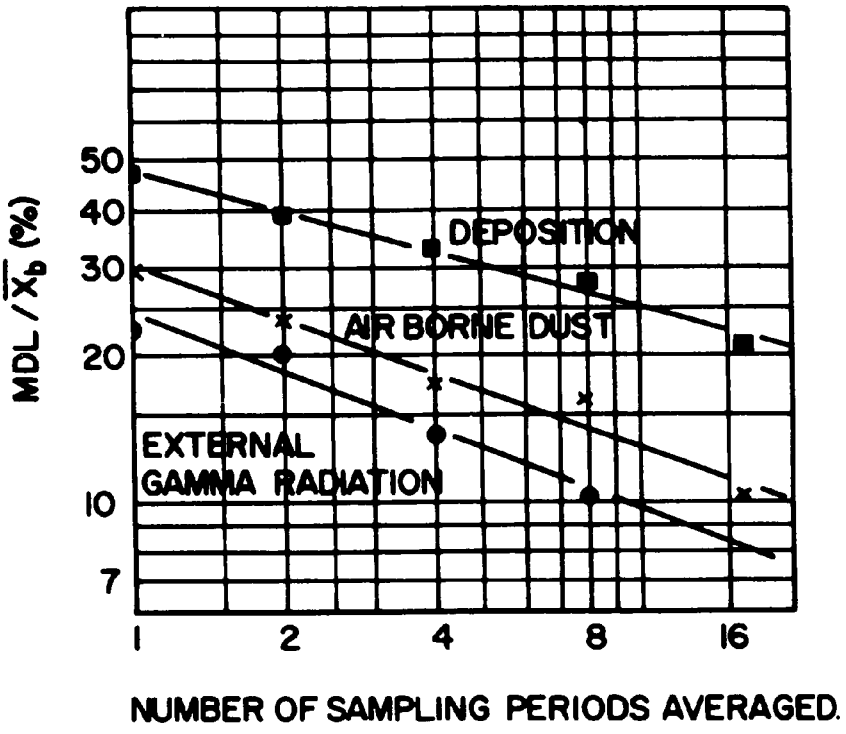


TABLE 17

AVERAGE MINIMUM DETECTABLE CONCENTRATIONS $\overline{MDL}$, AND STANDARD DEVIATIONS $\overline{S_p/\bar{x}_b}$ OF FILTERABLE AIRBORNE GROSS BETA RADIOACTIVITY FOR THREE LEVELS OF BACKGROUND $\bar{x}_b$

	Background Levels ($\bar{x}_b$)					
	High[1]		Medium[2]		Low[3]	
	Single Period[4]	62 week Average	Single Period	28 week Average	Single Period	29 week Average
Background (μCi/cc)	6.2×10^{-12}		4.9×10^{-13}		2.5×10^{-13}	
$\overline{MDL}$ (μCi/cc)	1.5×10^{-12}	3.3×10^{-13}	1.6×10^{-13}	3.9×10^{-14}	9×10^{-14}	4×10^{-14}
$\overline{MDL}/\bar{x}_b$	0.24	0.053	0.33	0.08	0.36	0.16
$\overline{(S_p/\bar{x}_b)}$[5]	0.12		0.16		0.21	

1. 31 - 2 week sampling periods from Dec. 27, 1962 to Mar. 5, 1964.
2. 28 - 1 week sampling periods from June 18, 1964 to Dec. 30, 1964.
3. 29 - 1 week sampling periods from Dec. 31, 1964 to July 22, 1965.
4. The MDL for a single sampling period is the average of all the MDL's for single sampling periods.
5. S_p = pooled sample standard deviation from equation 6.

TABLE 18

AVERAGE MINIMUM DETECTABLE DEPOSITIONS $\overline{MDL}$, AND STANDARD DEVIATIONS $\overline{S_p/\bar{x}_b}$ OF DEPOSITED GROSS BETA RADIOACTIVITY FOR THREE LEVELS OF BACKGROUND $\bar{x}_b$

	Background Levels ($\bar{x}_b$)					
	High[1]		Medium[2]		Low[3]	
	Single Period[4]	68 week Average	Single Period	36 week Average	Single Period	36 week Average
Background (mCi/mi^2/4 weeks)	227		94		32	
$\overline{MDL}$ (mCi/mi^2/4 weeks)	108	49	36	15	18	13
$\overline{MDL}/\bar{x}_b$	0.48	0.22	0.38	0.16	0.57	0.41
$\overline{(S_p/\bar{x}_b)}$[5]	0.23	--	0.28	--	0.29	--

1. 17 - 4 week sampling periods from Dec. 27, 1962 to April 16, 1964.
2. 9 - 4 week sampling periods from Apr. 16, 1964 to Dec. 23, 1964.
3. 9 - 4 week sampling periods from Dec. 23, 1964 to Sept. 22, 1965.
4. The $\overline{MDL}$ for a single sampling period is the average of all the MDL's for single sampling periods.
5. S_p = pooled sample standard deviation from equation 6.

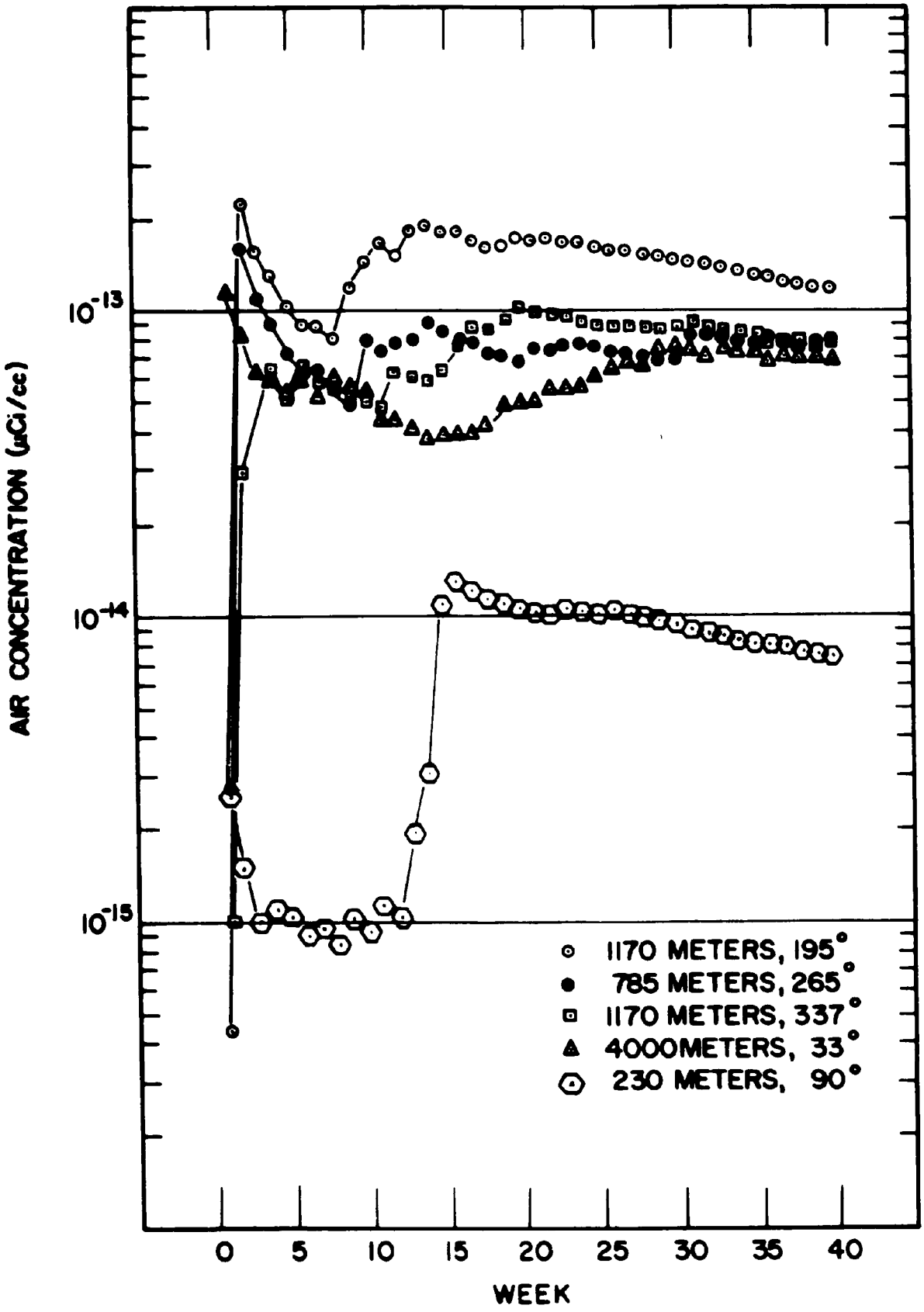
TABLE 19

AVERAGE MINIMUM DETECTABLE EXPOSURE $\overline{MDL}$ AND BACKGROUND EXPOSURE $\bar{x}_b$ OF GAMMA RADIATION TO FILM BADGE DOSIMETERS

	Single[1] Period	40 Week Average
Background (mrads/4 weeks)	11.9	
$\overline{MDL}$ (mrads/4 weeks)	2.7	1.0
$\overline{MDL}/\bar{x}_b$	23	8.7

1. The MDL for a single sampling period (4 weeks) is the average of all the MDL's for single sampling periods.

FIGURE 16. CALCULATED WEEKLY RUNNING AVERAGE AIRBORNE RADIOACTIVITY CONCENTRATIONS FOR A CONTINUOUS RELEASE OF 1μCi/sec FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT.



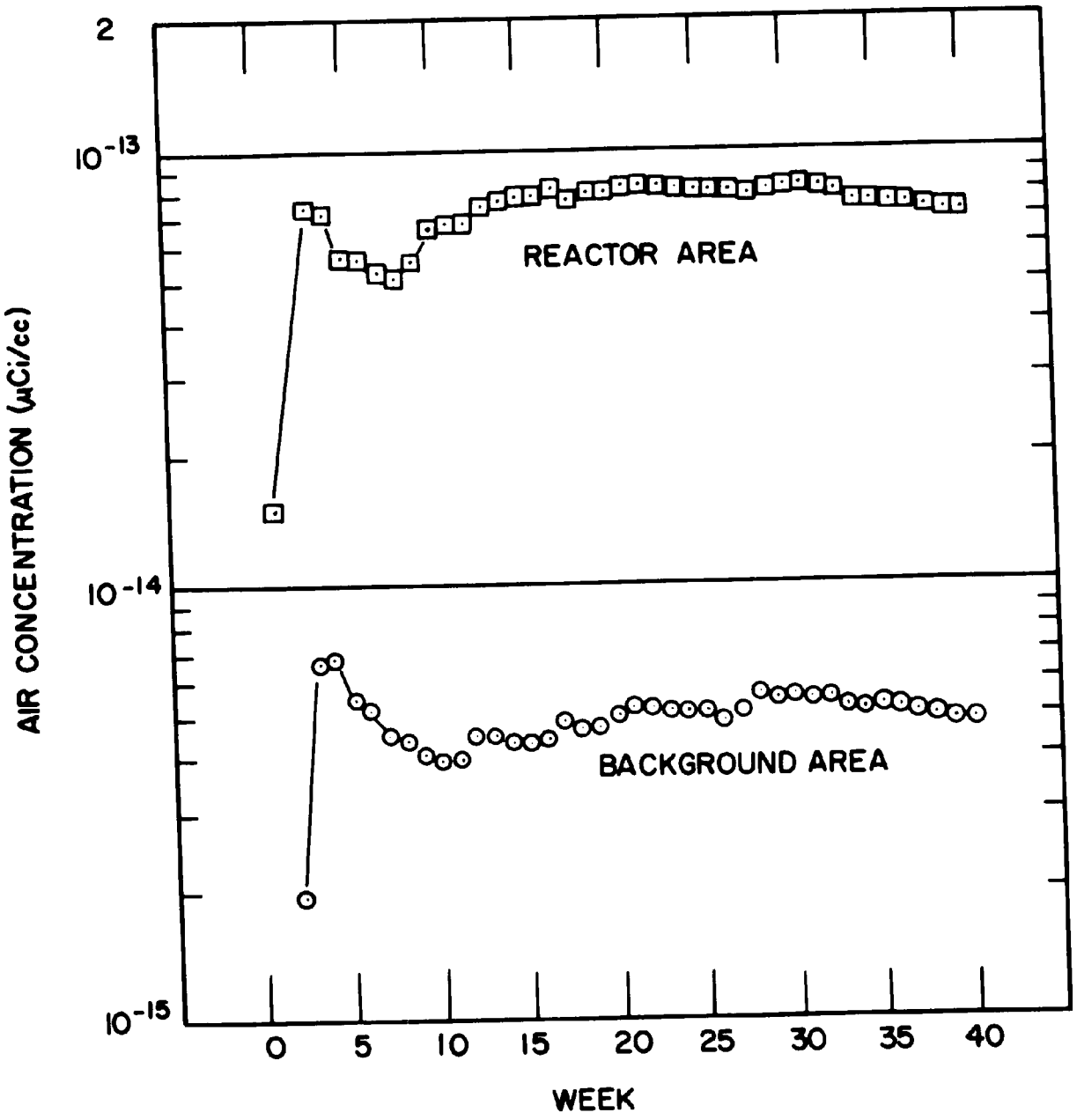
the average of the weekly concentrations up to and including that week. Only the first 40 weeks or 280 days of complete data were used in the calculations so that the days could be divided evenly into weeks. The 40-week average concentration at all 5 sites resulting from the continuous release of 1 μCi/sec is shown in Table 21 with the calculated maximum and minimum weekly averages for the 5 sites.

Figure 17 shows the running average weekly air concentration for the three locations in the background area which are nearest the Fermi site, 1B, 2B and 4B in Table 14. For comparison, the running weekly averages of the averages of all 5 sites near the reactor are included. The average weekly air concentration at the 3 nearest sites in the background area resulting from a release of 1 μCi/sec for the 40 week period is shown in Table 21 with the calculated maximum and minimum weekly average concentrations.

2. For deposition on precipitation collectors

The quantity of airborne radioactivity deposited on precipitation collectors is related to the air concentration by equations 22 and 23. The running average weekly deposition in $\mu Ci/cm^2$ and mCi/mi^2 is obtained by multiplying each value in figures 16 and 17 by 6.05×10^4 and 1.57×10^{12} respectively. The average weekly deposition on the 5 precipitation collectors near the reactor and on the 3 nearest collectors in the background area for the continuous release rate of 1 μCi/sec for the 40 week period are shown in Table 21 with the maximum and minimum values.

FIGURE 17. CALCULATED WEEKLY RUNNING AVERAGE AIRBORNE RADIOACTIVITY CONCENTRATIONS IN THE BACKGROUND AREA AND THE REACTOR AREA FOR A CONTINUOUS RELEASE OF 1μCi/sec FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT.



3. For iodine-131 concentrations in milk

Results of the calculations of the iodine-131 concentrations in milk are shown in Figures 18 and 19 for two sites close to the reactor. The results are shown as daily average concentrations. The average concentration over the 120 day period for the three sites near the reactor and the calculated maximum and minimum weekly concentrations are shown in Table 21. The average concentration over the 120 day period and the calculated maximum and minimum weekly concentrations for four sites in the background area are also shown in Table 21.

4. For exposures to beta and gamma radiation from noble gases

Table 20 shows the calculated weekly concentrations of noble gases and exposures to beta and gamma radiations for a continuous release of 1 Ci/sec from the stack of the Fermi Reactor averaged over the 280 days in 1958 in which complete weather data were available. The calculated average weekly maximum and minimum values for the three items are also shown for each location. Table 21 shows the overall average concentration of noble gases in the area near the reactor and the overall average exposures to beta and gamma radiation along with the calculated average weekly maximum and minimum exposures. Preliminary calculations of the beta and gamma exposures from noble gases in the background area indicated that the average levels would be at least a factor of 10 less than the exposures in the area near the reactor and therefore detailed calculations were not carried out.

FIGURE 18. CALCULATED AVERAGE DAILY IODINE - 131 CONCENTRATIONS IN THE MILK OF COWS ON PASTURE AT 4000 m AND 33° FOR THE CONTINUOUS RELEASE OF 1 μCi/sec FROM THE 60 m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT.

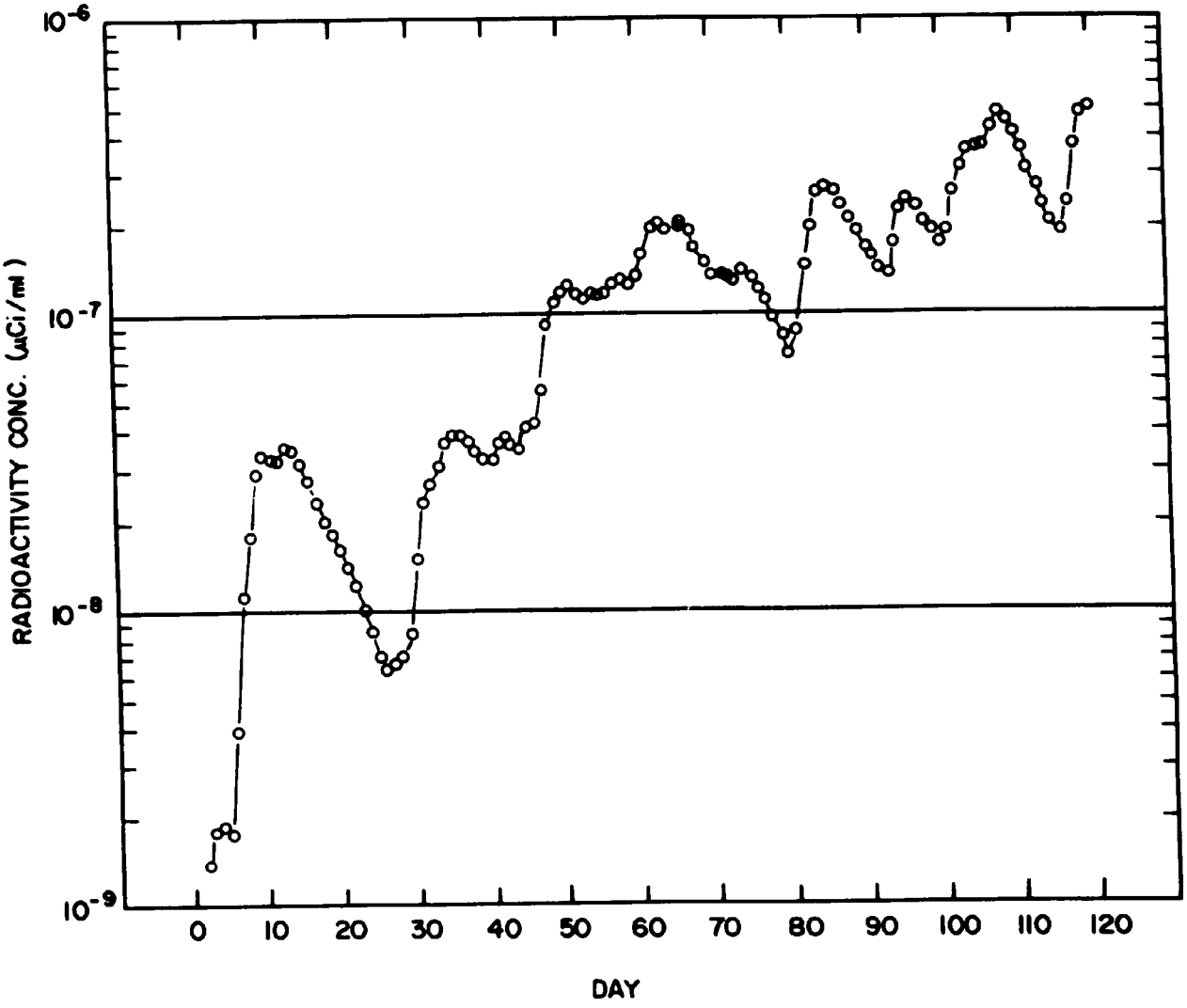


FIGURE 19. CALCULATED AVERAGE DAILY IODINE - 131 CONCENTRATIONS IN THE MILK OF COWS ON PASTURE AT 1170 m AND 337° FOR THE CONTINUOUS RELEASE OF 1 μCi/sec FROM THE 60 m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT.

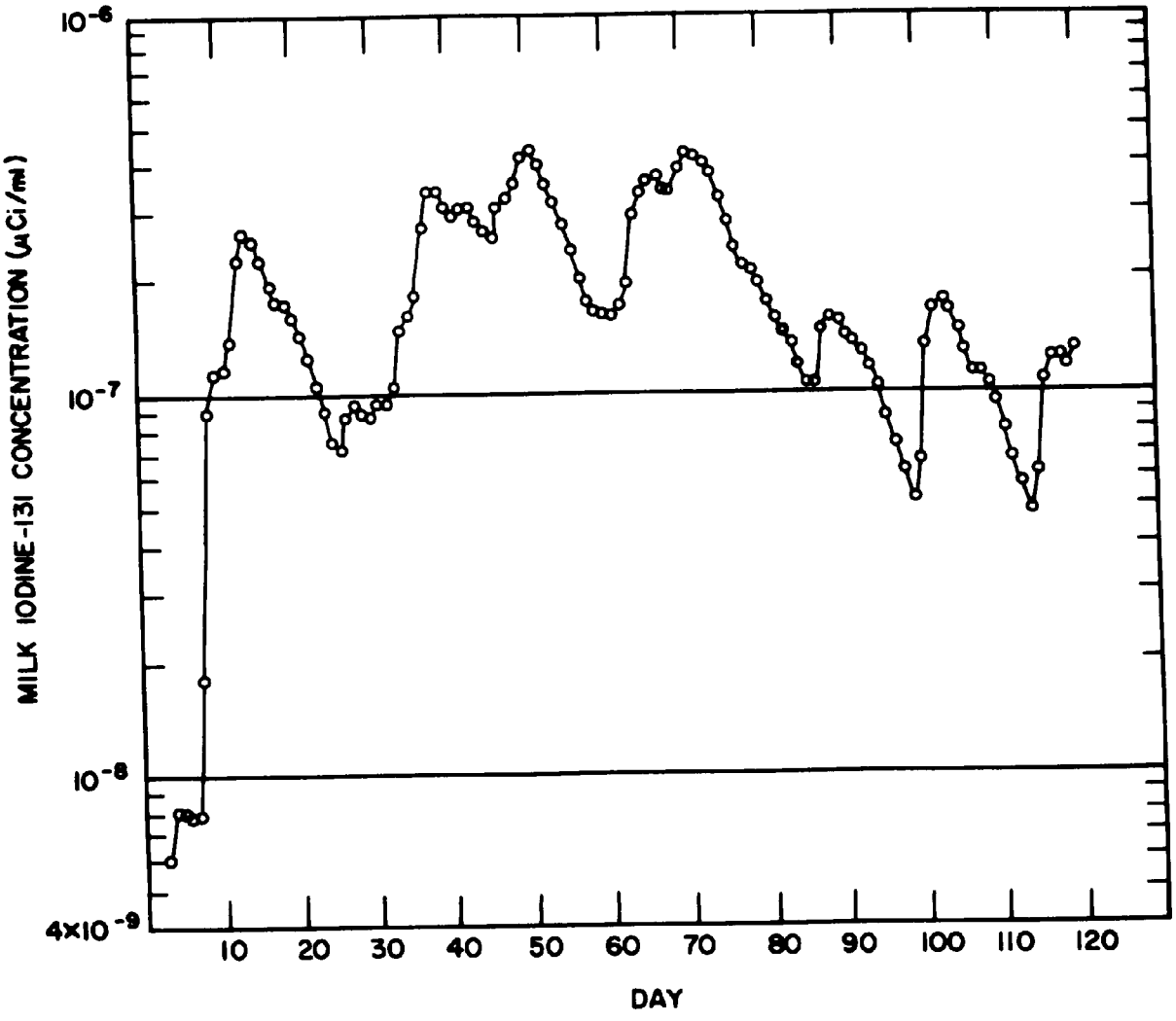


TABLE 20

CALCULATED CONCENTRATIONS OF NOBLE GASES AND RESULTING BETA AND GAMMA RADIATION EXPOSURES FOR THE CONTINUOUS RELEASE OF 1 Ci/sec FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

	1R	2R	3R	4R	5R
Concentration (μCi/cc)					
Minimum	$<10^{-12}$	0.13×10^{-8}	$<10^{-12}$	$<10^{-12}$	$<10^{-12}$
Average	0.73×10^{-8}	6.2×10^{-8}	7.6×10^{-8}	11.3×10^{-8}	8.5×10^{-8}
Maximum	12.0×10^{-8}	$21.\times10^{-8}$	$27.\times10^{-8}$	$56.\times10^{-8}$	$42.\times10^{-8}$
β Exposure (mrad/week)					
Minimum	$<10^{-4}$	0.11	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
Average	0.64	4.8	6.2	9.8	7.2
Maximum	11.	16.	22.	49.	35.
ν Exposure (mrad/week)					
Minimum	5.1	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
Average	55.	3.6	4.8	7.0	5.2
Maximum	226	10.	18.	25.	21.

*The locations in radial measure are: 1R - 230 meters, 90°; 2R - 4000 meters, 33°; 3R - 1170 meters, 337°; 4R - 785 meters, 265°; 5R - 1170 meters, 195°.

TABLE 21

CALCULATED AVERAGE RADIOACTIVITY AND EXPOSURE LEVELS IN THE BACKGROUND AND REACTOR AREAS FOR CONTINUOUS RELEASE FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

Type of Measurement	Release Rate	Calculated Weekly Radioactivity Level		
		Minimum	Average	Maximum
Airborne Radioactivity ($\mu Ci/cc$)[1]	1 $\mu Ci/sec$			
Reactor Area		0.65×10^{-14}	7.3×10^{-14}	17.2×10^{-14}
Background Area		0.07×10^{-15}	4.9×10^{-15}	18.6×10^{-15}
Deposition (mCi) ($mCi/mile^2/week$)	1 $\mu Ci/sec$			
Reactor Area		0.021	0.23	0.54
Background Area		0.0002	0.015	0.059
Iodine-131 in Milk ($\mu Ci/ml$)[2]	1 $\mu Ci/sec$			
Reactor Area[3]		0.93×10^{-7}	1.5×10^{-7}	2.1×10^{-7}
Background Area[3]		4.1×10^{-9}	8.8×10^{-9}	14.0×10^{-9}
Noble Gas Mixture[1,4]	1 Ci/sec			
Reactor Area				
Concentration ($\mu Ci/cc$)		1.0×10^{-9}	6.9×10^{-8}	$16. \times 10^{-7}$
Gamma Dose (mrad/week)		6.7	15.5	45.
Beta Dose (mrad/week)		0.65	5.7	13.

1. Based on 280 days in 1958 in which complete weather data were available.
2. Based on 120 days in the spring, summer and fall of 1958.
3. Maximum and minimum weekly averages.
4. See Table 8 for composition of mixture.

C. The Sensitivity of the Environmental Survey in the Vicinity of the Enrico Fermi Atomic Power Plant

To simplify the results the MDL's are assumed to be constant at their average levels at each of the three background levels considered. Only the variations in the calculated radioactivity levels which depend on meteorological parameters are used in determining the maximum and minimum sensitivities. The results are shown in Tables 22-25 for filterable airborne radioactivity, deposition of airborne radioactivity on precipitation collectors, exposures to the gamma radiations of noble gases, and iodine-131 concentrations in milk respectively. The MDR's are based on weekly sampling of air and milk and 4 week sampling of deposition and gamma exposure. The 4-week deposition and gamma exposure levels are obtained by multiplying the weekly levels in Table 21 by 4. The maximum and minimum values are for 4-week averages and as such are closer to the average than the 1 week values shown in Table 21. The iodine-131 concentrations in milk shown in Table 21 are divided by 2 to estimate the decay which would take place if a weekly composite of daily samples were collected and counted 4 to 5 days after collection. Estimates of the range of the MDR's for one collection period, based on the maximum and minimum levels in Table 21 also are included in Tables 22-25.

D. The Probability of Detecting Various Releases

The relative frequency of detecting continuous releases of long lived particulate material lasting a day and a week by air sampling were

TABLE 22

THE SENSITIVITY OF AIR SAMPLING[1] TO THE CONTINUOUS RELEASE OF LONG-LIVED[2]

FILTERABLE BETA RADIOACTIVITY FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

(Sensitivity is expressed as the minimum detectable release rate MDR.)

	Background Levels						
	High[3]		Medium[4]		Low[5]		None
	Length of Sampling or Averaging Period						
	2 Weeks	62 Week Average	1 Week	28 Week Average	1 Week	29 Week Average	1 Week
Minimum (μCi/sec)	11.3	---	1.2	---	0.52	---	0.02
Average (μCi/sec)	26.5	4.5	4.8	0.53	2.1	0.55	0.05
Maximum (μCi/sec)	96.3	---	33	---	14	---	0.54

1. See Table 14 for the locations of the five samplers used in the environmental survey.
2. "Long-lived" means long enough so that no appreciable decay takes place during collection and in the interval between collecting and counting.
3. High background - 6.2×10^{-12} μCi/cc.
4. Medium background - 4.9×10^{-13} μCi/cc.
5. Low background - 2.5×10^{-13} μCi/cc.

TABLE 23

THE SENSITIVITY OF DEPOSITION SAMPLING[1] TO THE CONTINUOUS RELEASE OF LONG-LIVED[2] BETA RADIOACTIVITY FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

(Sensitivity is expressed as the minimum detectable release rate MDR.)

	Background Levels						
	High[3]		Medium[4]		Low[5]		
	Length of Sampling or Averaging Period						
	4 Weeks	68 Week Average	4 Weeks	36 Week Average	4 Weeks	36 Week Average	4 Weeks
Minimum (μCi/sec)	157	---	52	---	26	---	0.15
Average (μCi/sec)	267	106	89	33	45	28	0.3
Maximum (μCi/sec)	432	---	144	---	72	---	0.7

1. See Table 14 for the locations of the five deposition samplers used in the environmental survey.
2. By "long-lived" is meant long enough so that no appreciable decay takes place during collection and in the interval between collection and counting.
3. High background - 227 mCi/mile^2/4 weeks.
4. Medium background - 94 mCi/mile^2/4 weeks.
5. Low background - 32 mCi/mile^2/4 weeks.

TABLE 24

THE SENSITIVITY OF FILM BADGE DOSIMETERS* TO THE GAMMA RADIATION OF NOBLE GASES** CONTINUOUSLY RELEASED FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

The background exposure to gamma radiation is about 12 mrad/4 weeks
(Sensitivity is expressed as the minimum detectable release rate MDR.)

	Length of Exposure or Averaging Period	
	4 Weeks	40 Week Average
Minimum (μCi/sec)	22,000	----
Average (μCi/sec)	46,000	16,000
Maximum (μCi/sec)	58,000	----

*See Table 14 for the locations of the five sites used to measure gamma exposures.

**See Table 8 for the composition of the noble gas mixture.

TABLE 25

THE SENSITIVITY OF WEEKLY MILK SAMPLING* TO THE CONTINUOUS RELEASE OF IODINE-131 FROM THE 60m STACK OF THE ENRICO FERMI ATOMIC POWER PLANT

It is assumed that the background concentration of iodine-131 is zero

(Sensitivity is expressed as the minimum detectable release rate MDR.)

Sensitivity (μCi/sec)		
Minimum	Average	Maximum
0.18	0.25	0.40

*See section III, A, 2 for a description of the sampling locations.

calculated from the data using equation 68. Figure 20 shows the results expressed as a cumulative frequency distribution. The relative frequencies are based on the ability of any one of the 5 samplers near the Fermi plant to detect the MDL in the absence of environmental background.

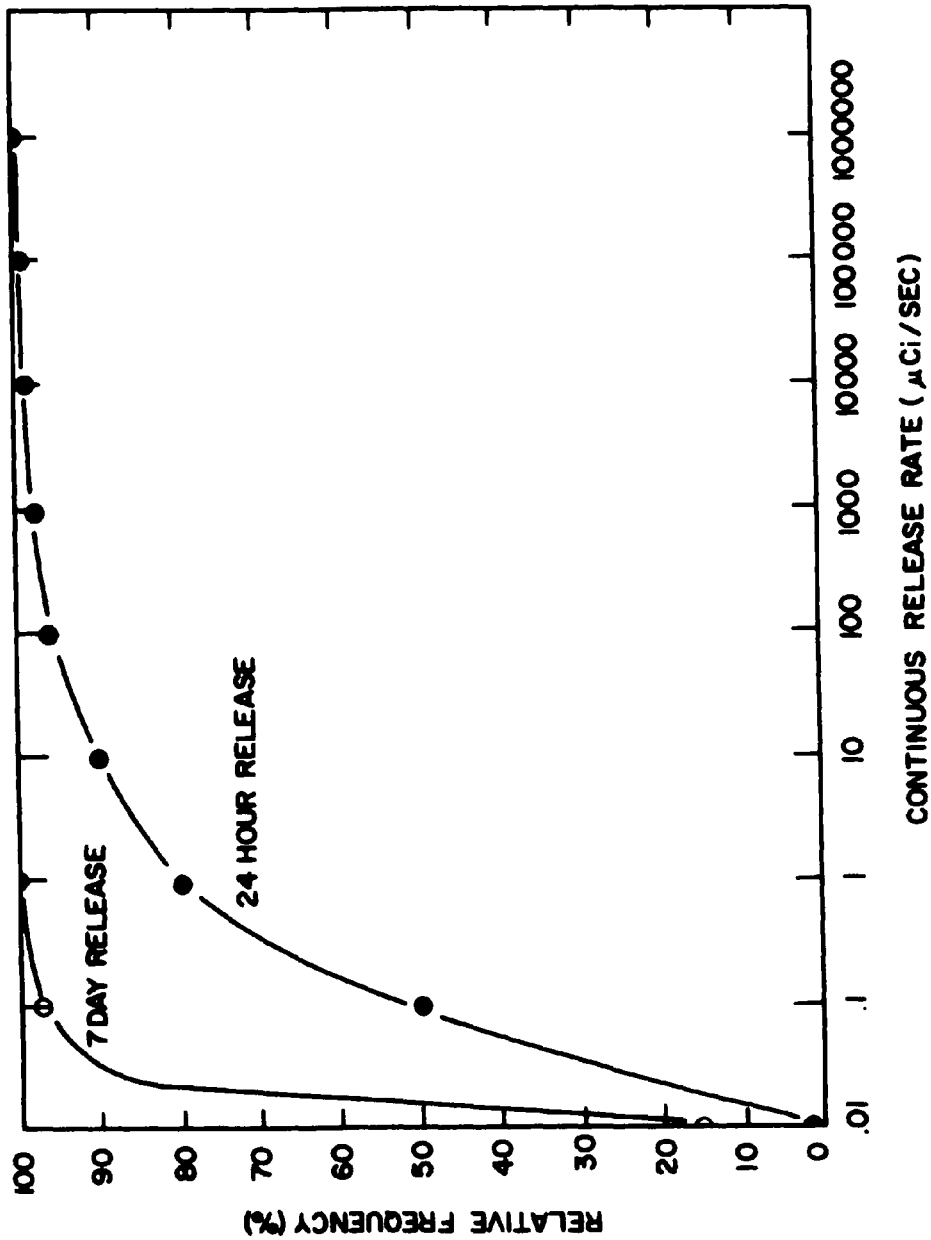


FIGURE 20. RELATIVE FREQUENCY OF DETECTING AT LEAST THE STATED RELEASE WITH ANY OF THE FIVE AIR SAMPLERS NEAR THE ENRICO FERMI ATOMIC POWER PLANT IN THE ABSENSE OF BACKGROUND RADIOACTIVITY.

V. DISCUSSION OF RESULTS

A. Validity of Assumptions

Prior to discussing the results per se it is well to discuss the validity of the assumptions on which the analyses of the experimental data rest. In order to use the t-test in testing the difference between two means, one assumes that the two populations from which the two samples are taken are normally distributed.[72] To check this assumption the data for each sampling period were plotted on normal probability paper. The majority of the data were found to lie in approximately straight lines. While the data from a few sampling periods showed a marked departure from a straight line there was no consistent trend toward any other curve. Therefore, the assumption of a normal distribution does not seem to be violated.

Another assumption on which the t-test is based is that the variances of the two populations are equal. To check this assumption each pair of sample variances was tested using the F ratio test.[73] The test was made at the 5% level of significance. The variances were declared significantly different 13% of the time. In about half the cases, significance resulted from an abnormally high or low radioactivity level in a single sample. Indication of unequal population variances in 13% of the comparisons is of little importance since the number of samples in each of the two sampling groups were equal, and therefore the requirement of equal variances is not critical.[74]

Probably the most important assumption used in this research is that the radioactivity level in the area around a nuclear facility is the same as that in the background area if the facility releases no radioactivity. During the period January 1963 to July 1965 the Enrico Fermi Reactor was run at a power level of no more than 1 MW. Therefore, for the purposes of this investigation the measurements reported here are considered to reflect pre-operational conditions. Figure 12 shows that in 3 out of 85 sampling periods the average airborne radioactivity level in the reactor area was not equal to that in the background area, the level in the background area being higher on 2 out of the 3 occasions. Since the significance level used for the two-sided test is 2 out of 100 and only 85 trials have been run, 3 differences are not considered enough to contradict the assumption. Figure 13 shows that out of 35 deposition sampling periods, none showed differences between the average radioactivity levels in the area near the reactor and those in the background area. Figure 14 shows that one out of 10 gamma exposure measuring periods showed a significantly greater exposure in the background area. However, 10 measurement periods are hardly adequate as a basis from which to contradict the assumption of equal exposures in the two areas.

It is assumed that the samplers in the background area do not measure any radioactivity other than background. Figure 17 shows that the average level measured by the three samplers in the background area nearest the Fermi reactor are about a factor of 15 lower than those in the area near the reactor. It was hoped that the difference between the radioactivity levels calculated for the two areas would be more substantial than a factor

of 15, and the calculations do suggest that, if it is feasible, the background samplers should be placed as far from the facility as possible. It is evident that no distance from the reactor really is beyond its sphere of influence. A reduction of a factor of 15 serves to raise the MDL only a few percent which is acceptable in view of some of the other uncertainties.

B. Measurements of the Minimum Detectable Radioactivity Levels.

It was hoped that the method of subtracting the current background radioactivity level from the level measured near a nuclear facility would free the environmental survey from its dependence on background. However, this was found not to be the case. Figures 12 and 13 show that the MDL follows the background radioactivity levels fairly closely, especially Figure 13, which shows the results of deposition measurements. Tables 17-19 show that, for a given duration of sampling, the value of the ratio $\overline{MDL}/\bar{x}_b$ is fairly constant for a given type of measurement, so that

$$MDL = G\,\bar{x}_b \tag{70}$$

The MDL is composed of two parts $(\bar{x}_f-\bar{x}_b)$ and $t_{theo}S_p(1/N_f+1/N_b)^{1/2}$. In the latter part only S_p is a variable. The values of $(\bar{x}_f-\bar{x}_b)$ were found to follow roughly the average background levels, but this follows from the finding that S_p follows the background levels quite closely, especially in the case of deposition measurements. The average value of

$S_p/\bar{x}_b$ for deposition measurements was 0.26 for single sampling periods. For single air sampling periods the average value of $S_p/\bar{x}_b$ was 0.16.

There are several factors which contribute to the magnitude of S_p. Among them are: 1) counting errors, 2) real differences in the radioactivity levels at the various locations, 3) imperfect sampling equipment and procedures, 4) laboratory handling and processing and 5) variability inherent in the background radioactivity itself.

The standard deviation due to the random nature of the nuclear disintegration process is equal to the square root of the total number of disintegrations. This variability is controllable and a standard deviation of less than 3% is not difficult to achieve in practice. Further, since the counting time may be varied to get the same total count from any sample, the percent standard deviation is held rather constant regardless of the radioactivity concentration. Therefore, this type of error would contribute to S_p so as to make S_p directly proportional to background radioactivity levels. The standard deviation due to counting represents the lowest possible value of S_p.

Radioactivity levels at distant locations probably would show real differences when averaged over short periods of time. Even over longer periods of time real differences may occur. In 1964 and up to mid 1965 there was a tendency for the deposition to be higher at Harrow, Ontario and Trenton, Michigan than at any of the other locations. While there was no more rainfall at these two sites than at the others, the solids content of the rain was always higher when the deposition of radioactivity was higher. In general, however, I expect that the magnitude of the variability due to location differences will be damped out

with time. No such persistant location differences were apparent for the radioactivity levels in air. In the case of deposition measurements, if it can be assumed that fallout radioactivity interacts with the tropospheric aerosol, then the variability introduced by location differences would tend to contribute to S_p so as to make S_p directly proportional to the background radioactivity levels. There is some evidence to support this assumption for stratospheric fallout at least.[75] Since the mass and number of fallout particles are negligible compared to the tropospheric aerosol, precipitation elements will interact primarily with the particles of the tropospheric aerosol. If there were a primary standard deviation measurable in terms of some property (e.g., the mass) of the tropospheric aerosol, then the standard deviation of the radioactivity would be higher or lower depending on the quantity of radioactivity which had interacted with the tropospheric aerosol. In the case of air concentrations of radioactivity, location differences also would contribute to S_p so as to make S_p directly proportional to the background radioactivity concentrations. If it is assumed that resuspension into the atmosphere from the ground does not contribute significantly to the air concentration, air mass movements would be the primary cause of location differences. Obviously, movements of air masses are independent of the quantity of radioactivity contained in the air masses. Therefore, the variability measured in terms of radioactivity would be high or low depending on the radioactivity concentration in the air mass. If the variability due to location differences dominated S_p one might expect that when the samplers were moved near or onto the reactor site $S_p/\bar{x}_b$ would decrease because the area covered by the samplers is much less than for

the previous sampling locations. Tables 17 and 18 show that the reverse happened. Therefore, it appears that while the contribution to S_p from location differences may not be insignificant it is not dominant.

The variability introduced by imperfect sampling and laboratory handling of samples would contribute to S_p so as to make S_p directly proportional to the average radioactivity levels. The variability introduced by leaking air hoses, or air volume meters that are out of calibration, is measured in units of air volume. If the air concentration of radioactivity were high, the variability in terms of radioactivity would be high. Low air concentrations would result in low variability. The same reasoning applies to variability introduced by imperfect sampling handling in the laboratory. A few drops of rain accidently spilled would result in a high or low error depending on the concentration of radioactivity in the rain. An occasional thumb print on an air filter would also lead to an error proportional to the total radioactivity on the filter. The relative contribution to S_p from this type of error is difficult to determine. However, I do not believe that it is a major contributor. Several improvements were made in the techniques of sampling and processing without any noticeable reduction in $S_p/\bar{x}_b$.

Except for some gaseous iodine-131, fallout radioactivity is associated with particles, and the variability inherent in collecting particles follows the Poisson distribution. It is a property of the Poisson distribution that the standard deviation of the number of particles collected on a filter is equal to the square root of the total number of particles collected. If each particle had the same quantity of radioactivity associated with it, it would be an easy matter to

determine the magnitude of the standard deviation resulting from this type of error. However, it has been shown that the radioactivity associated with a particle on a filter can vary by 6 to 9 order of magnitude depending on the age of the fallout.[76] During periods of fresh fallout 57% of the radioactivity in surface air may be associated with particles having a concentration of less than 0.025 particles per cubic meter.[76] In contrast, 91.5% of the radioactivity in older fallout may be associated with particles having a concentration of 2 to 3 x 10^4 particles per cubic meter.[76] Air measurements made in southeastern Michigan from November 1961 through June 1962 showed that the average value of the standard deviation expressed as a percent of the average radioactivity concentrations, varied from 22% during periods of fresh fallout (November 1961) to 8% during periods of older fallout (April-June 1962). When fallout gets very old and the levels become very low, there is an indication that the percent standard deviation may increase. Table 17 shows that the average value of $S_p/\bar{x}_b$ increased as the levels in air decreased. There is also an indication of this trend for the deposition measurements shown in Table 18. It should be pointed out that during the periods of medium and low background, fresh Chinese fallout was present in the area. This may be the cause of much of the increase in $S_p/\bar{x}_b$ during the medium background period. However, during the low fallout period there seemed to be a general increase in $S_p/\bar{x}_b$. It seems reasonable to me that the numbers of radioactive particles decreases as the fallout radioactivity becomes older, and that this accounts for the increasing values of $S_p/\bar{x}_b$ for very old fallout. There is little doubt that the high values of $S_p/\bar{x}_b$ during periods of fresh fallout are due

primarily to the presence of low concentrations of highly active particles. The relative contribution from this inherent type of variability to S_p during other periods is not known but I feel that it does make a significant contribution.

Table 17 shows that on the average the MDL for gross beta radioactivity in air during a period of high fallout was 1.5×10^{-12} μCi/cc for a single 2 week sampling period. The same results probably would apply if one week sampling periods were used. This level is 1/20 of the MPC given in 10CFR20 for exposure of persons in unrestricted areas to strontium-90. One is allowed to average the concentration in an unrestricted area over a period of one year. The MDL for one year can be estimated from the second column of Table 17. For the average of 31 two-week sampling periods the MDL was 3.3×10^{-13} μCi/cc or 1/100 of the MPC for strontium-90. The MDL for lower background levels were all well below the MDL for strontium-90.

It is the value of S_p which must be considered when attempting to extrapolate these results to other locations. I believe that the methods of sampling and analysis used in this research are superior to the average methods used in environmental surveying. However, there is no good reason why equivalent or better methods could not be used widely in practice. Once reasonably good methods of sampling and analysis are employed, the variability among the measured radioactivity levels are dependent on the physical properties of fallout and to a lesser extent on variations in weather conditions among the collection sites. Therefore, insofar as the physical properties of fallout are the same, and unusual topography or weather conditions are absent, I can see no reason

why the results of this research would not be applicable to other locations.

C. Measurements of the Minimum Detectable Exposure Level

The film badge dosimeter is used to measure the exposure rates to external radiation in the Enrico Fermi environmental survey. The film badge is inexpensive, rugged and easy to use. To the best of my knowledge it is the only dosimeter, capable of use in an environmental survey, which is sensitive to beta radiation. The supplier of the film badge for the Enrico Fermi environmental survey reports only gamma doses, but since there may be a significant exposure to beta rays it is worthwhile to discuss the response of the dosimeter to beta radiation.

The film badge contains several filters of various thicknesses and atomic numbers in addition to an open window all for the purpose of differentiating between the types and energies of radiation incident on the badge. The film will respond to gamma radiation under all the filters and the open window but will respond to beta radiation only under the open window.

Film badges used for environmental monitoring are wrapped in a heavy waterproof covering to keep out moisture, and the film itself is wrapped with several layers of paper. Thus the dosimeter may be insensitive to low energy beta rays. The thickness of the protective covering of the film badge used in the Fermi survey is 19 mg/cm^2. This covering together with the film wrapping totals about 43 mg/cm^2. Heard and Jones[77] measured the response of Kodak radiation monitoring film to beta radiation relative to the response to gamma radiation through 50 mg/cm^2 of a

plastic absorber in addition to the film wrappings. Their experimental results were fitted to the following mathematical expressions.

$$FR_{\beta/\nu} = 1.5 \qquad 0.8 < \bar{E}_\beta \qquad (71a)$$

$$FR_{\beta/\nu} = 2.1\ \bar{E}_\beta^{1.61} \qquad 0.27 < \bar{E}_\beta \leq 0.8 \qquad (71b)$$

$$FR_{\beta/\nu} = 9.1\ \bar{E}_\beta^{2.67} \qquad 0.1 < \bar{E}_\beta \leq 0.27 \qquad (71c)$$

where: $FR_{\beta/\nu}$ = film response to beta radiation relative to the response to gamma radiation

$\bar{E}_\beta$ = average energy of the beta radiation found by dividing the maximum energy of the beta radiation by 3 (MeV)

The average beta energy of the noble gas mixture depends on the time of travel from the stack to the dosimeter but for distances on the order of 1000 meters an average energy of 0.6 MeV is typical. According to equation 71b, the response of the film badge is about 0.92 of that due to gamma radiation. For the beta rays of krypton-85 ($\bar{E}_\beta \simeq 0.22$ MeV) the relative response would be only 0.17. The total thickness of absorber between the film and the source of radiation in the experiments of Heard and Jones was about 74 mg/cm^2 including the film wrappings. This is higher than that of the environmental film badge. However, this difference in absorber thickness is compensated for by the fact that the beta radiation from a cloud of radioactivity is not all normally incident to the surface; a major portion of the beta radiation will be incident at

an angle and thus must traverse a greater thickness before reaching the film.

It seems likely that if the badge is exposed to a cloud of radioactivity such as a plume from the stack of a nuclear facility, and it responds measurably to gamma radiation, there also will be some response to beta radiation. However, because of the uncertainties in extrapolating the results of Heard and Jones to the environmental monitoring film in question, the response of the film badge to beta radiation is not treated quantitatively in this study.

The maximum permissible exposure to persons in unrestricted areas is given in 10CFR20 as 500 mrem/year. This is equivalent to an average dose of 38.5 mrem in a four-week sampling period. Table 19 shows that the average MDL for a four-week period was 2.7 mrem. This is 7% of the maximum permissible exposure. For a 40-week period the MDL was 1 mrem/4 weeks. If this value is applied over the entire year the MDL for a year's exposure would be 13 mrem which is 2.7% of the maximum permissible exposure.

Because the film is protected from direct exposure to ground radioactivity by the 2 inch thick lead brick, the major portion of the exposure is from the atmosphere and therefore from cosmic rays. Barring some unusual topography, I can see no reason why the results of this research pertaining to the minimum detectable gamma ray exposures would not be applicable to other locations.

D. Calculated Relationships Between Stack Releases and Environmental Levels of Radioactivity

Some experimental justification has already been given for the equations relating stack releases to environmental levels of radioactivity. In fact, with one exception the equations may be considered empirical. The one exception is the washout efficiency for iodine-131 as a function of the rate of rainfall. The most involved relationship between stack releases and environmental levels is the relationship leading to iodine-131 in milk. The values of the parameters in the equations and the derivation of the equations are based on the results of several independent experiments. After the daily levels of iodine-131 in milk had been computed for the 120 day period the average milk concentration, the average grass concentration and the average air concentration were computed for each site. Table 26 shows the average iodine-131 ratios of grass to air, milk to grass and milk to air. For comparison the ratios reported by Soldat[78] for acute exposures to the iodine-131 from fallout and from a 1963 accident involving an iodine-131 release from one of Hanford's fuel reprocessing plants. Also included is the average air to grass ratio reported by Nelson based on 72 weeks of measurements around the Vallecitos Atomic Laboratory.[79] The average grass to air ratio computed in this study agrees well with the ratio measured at Vallecitos. The calculations made here and the measurements at Vallecitos are for chronic or intermittant exposure. One might expect that the grass to air ratio would be higher for a chronic exposure than for an acute exposure since in Soldat's evaluation of acute exposures all the ratios are based on the maximum concentrations measured. The average milk to grass ratio

TABLE 26.

A COMPARISON OF THE RATIOS OF AVERAGE IODINE-131 CONCENTRATIONS IN MILK (μCi/liter), GRASS (μCi/dry Kg) AND AIR (μCi/m^3) COMPUTED IN THIS STUDY AND THOSE MEASURED BY OTHER INVESTIGATORS

	Acute Exposure[78]		Chronic Exposure	
	Measured** Acc. Release Fuel Reprocessing Plant (1963)	Measured* Fallout (1961-1962)	Calculated This Study	Measured[79] Vallecitos
Grass				
Air	~40,000	~16,800	62,000	69,000** to 92,000
Milk				
Grass	~0.018	~0.038	0.029	---
Milk				
Air	~700	~600	1760	---

*The original ratios were given with the grass results expressed in μCi/wet kg. The results were converted to a dry weight basis given that 80% of the wet weight was water.[78]

**The ratio was given originally as 23,000 with the grass results expressed in μCi/wet kg. Since no dry weights were given it was assumed that from 2/3 to 3/4 of the wet weight was water.

computed in this research agrees to within a factor of 2 of those reported by Soldat. In fact, it is the average of the 2 ratios reported by Soldat. The ratio of milk to air is from 2 to 3 times higher than those reported by Soldat. In view of the many variables involved in the relationship between the iodine-131 in air and that in milk I think the agreement in Table 26 is very good.

The contribution to the iodine-131 concentration in grass from rain deposition was small compared to that from dry deposition. The reason for the much lower contribution from rain is that only a fraction of the deposition adheres to the grass as shown in Table 10.

It is interesting to compare the 281 day average air concentrations with those that would be predicted using a form of Sutton's equation given by Chamberlain[80] which is the following:

$$\bar{\chi} = 2.4 \times 10^{-3} \, Q/h^2 \qquad (72)$$

In the derivation of equation 72 it is assumed that virtual diffusion coefficients in the y and z direction are the same for short release or measurement times (i.e., $C_z = C_y$), and the swing of the wind over a long period of time results in a dilution factor of 1/20. It is also assumed that the average wind speed is 5 m/sec, and the concentration is measured at a distance from the stack where the maximum ground concentration occurs. For a 60-meter stack and a release rate of 1 μCi/sec, $\bar{\chi}$ is computed to be 6.7×10^{-13} μCi/cc. For comparison the average of the concentrations at 4 out of the 5 locations near the reactor is used. The average for the sampler at 230 meters is not used

because the sampler is so close to the stack. The average of the other 4 locations is 9×10^{-14} μCi/cc or from 7 to 8 times lower than that computed from equation 72. One reason why $\bar{\chi}$ computed from equation 72 is much higher than the one calculated in this study is the fact that a single fixed sampler cannot be at the distance of maximum concentration all the time, because this distance changes with atmospheric stability. This reason could account for a difference of a factor of 2 or 3. Another reason for the higher value from equation 72 lies in assuming that $C_y = C_z$. Hewson's recommended values of C_y and C_z in Tables 1 and 2 respectively show that C_z is equal, or almost equal, to C_y for the strong and weak lapse conditions, but that for inversion condition C_y is 5 times higher than C_z. This inequality of C_y and C_z would reduce $\bar{\chi}$ computed from equation 72 by a factor of five for inversion conditions. The two factors mentioned above probably would combine to reduce $\bar{\chi}$ from equation 72 by as much as a factor of 4 to 8. Of course, there are other uncertainties which would make $\bar{\chi}$ computed from equation 72 different than the $\bar{\chi}$ computed in this study. However, when the two factors discussed above are taken into consideration the agreement is fairly good.

Except for the gamma exposure calculations, the error introduced by using numerical methods is less than 5%. The arithmetic error on each gamma exposure calculation may be as high as 20 to 30% because of the approximations used in the numerical solution. An error was introduced inadvertently into the calculation of the effective stack height by using a stack diameter of 0.0915 meters instead of 0.915 meters. The maximum error in the calculated effective stack height from this

source is -10.5%. The average error is -4.1%. The average radioactivity levels at the locations near the reactor are on the order of 4% high from this source of error. The error is less for the levels in the background area.

The overall error in applying the calculated radioactivity levels to the levels which would result from the assumed releases is largest for short measurement periods and decreases as the measurement period increases. The error associated with a single calculation of the daily average air concentration at one sampling location probably ranges from many orders of magnitude to about a factor of 2 depending on the distance of the sampler from the centerline of the plume. The closer the sampler is to the centerline, the smaller the error. I believe that the error associated with the long term average concentration is less than 100%.

In order to extrapolate these results to other locations or indeed to the Fermi site at another time the values used for the parameters in the equations must be examined. Insofar as they are compatible with those of another location or those for the Fermi site at another time, the results of these calculations should apply elsewhere. As far as the air concentrations are concerned, it can be said that since the samplers are spaced fairly evenly around the reactor and at various distances from the reactor it would take a very drastic change in meteorological parameters such as the wind rose, average wind speed or the relative frequency of the various stability categories to alter appreciably the calculated long term average air concentrations.

E. Sensitivity

The only two sample media which measure the same type of release are air and deposition. Tables 22 and 23 show that air sampling is more than 10 times as sensitive as deposition sampling.

During the grazing season when there is no iodine-131 in the environment from other sources, iodine-131 sampling of milk is more sensitive in detecting iodine-131 releases than air sampling. If the MDR's for filterable gross beta radioactivity in air are multiplied by 2 to account for radioactive decay, they reflect the sensitivity limits of air sampling to the release of iodine-131. The factor of 2 for decay is due to the fact that the air filters are allowed to decay for seven days after they are collected. Note that milk sampling is about a factor of 10 more sensitive than air sampling even under low background conditions.

The least sensitive indicator of releases from the reactor is the gamma exposure measurement. However, this method can be made at least a factor of 3 more sensitive by moving all the film dosimeters to within 200 to 300 meters of the reactor. This would reduce the long term MDR to about 6,000 μCi/sec.

It is important to note that MDR's derived from this study are for continuous releases. This is most important to note for air and deposition measurements. Note in Figure 20 that it is possible for the Fermi reactor to release up to 1 Ci/sec for a 24 hour period without its being detected by the air samplers around the reactor. This is in the absence of environmental background, and much higher levels

could go undetected in the presence of background. However, Figure 20 also shows that this release rate would not go undetected if it were maintained for a week. In fact, if a release rate of 1 μCi/sec were maintained for a week the air samplers would detect it in the absence of background. It should also be noted that the minimum release rate which could be detected with near certainty if the release lasted only seconds or minutes would be much higher than 1 Ci/sec. Since gamma rays have an appreciable mean free path in air, the sensitivity of gamma exposure measurements is not as sensitive to the duration of release as air and deposition sampling. Milk is an integrating device for iodine-131 releases, and therefore milk sampling is not as much affected by the duration of release as air and deposition measurements.

The cumulative frequency distribution shown in Figure 20 is not applicable to sampling networks other than the one used in this study. The Fermi survey could do considerably better with regard to detecting releases if the sampler at 230 meters and 90° could be placed further from the reactor (which would mean out in Lake Erie) or its elevation raised 20 or 30 meters. In every case were the minimum detectable daily release rate exceeded 10 mCi/sec the atmosphere was stable with the wind blowing toward the quandrant centering on 90°.

VI. CONCLUSIONS

The following conclusions are drawn from an environmental survey consisting of five sampling stations close to a nuclear facility and an equal number of stations remote from the facility. Each station consists of an air particle sampler, a precipitation collector and two film badges. The conclusions regarding milk sampling are made for an environment in which the nuclear facility is the only source of iodine-131.

1. The minimum detectable radioactivity level MDL is proportional to background radioactivity in the environment $\bar{x}_b$, i.e.

$$MDL = G\,\bar{x}_b$$

The value of G decreases as the variation from the following sources is reduced: fractional counting error, imperfect sampling equipment and sample handling, differences in the background levels at specific locations, such as those resulting from topography and weather, and, in the case of particulate radioactivity, the inherent variability of background radioactivity. The value of G also decreases as the sampling time is increased.

2. The average values of G which can be expected in the environmental survey in the vicinity of the Enrico Fermi Atomic Power Plant are shown in the following table.

Expected Values of G

Air		Deposition		Gamma Radiation	
Length of Measurement Period					
1 or 2 Weeks	1 Year	4 Weeks	1 Year	4 Weeks	1 Year
0.3	0.1	0.5	0.25	0.25	0.1

The values of G for air and deposition sampling will be higher than those in the table if the background radioactivity is composed mainly of fresh fallout.

3. The MDL for iodine-131 in milk is dependent on the sample size and on the efficiency and background of the counter used to assay the milk. The MDL is 4×10^{-8} μCi/ml for a one liter sample and a 3" x 3" NaI(Tl) crystal and gamma spectrometer.

4. The minimum detectable release rate MDR is directly proportional to the MDL, i.e.,

$$MDR = \frac{1}{R(Q=1)} \times MDL$$

where R(Q=1) is the average radioactivity level measured near the facility produced by a unit release rate from the stack.

The value of R(Q=1) depends mainly on the average wind speed and the location of the samplers in relation to the wind rose and atmospheric stability. In addition to these factors the value of R(Q=1) for iodine-131 in milk depends on values of several transfer coefficients from air to milk.

5. The average values of R(Q=1) which can be expected for a continuous releases from the stack of the Enrico Fermi Atomic Power Plant are shown in the following table:

Expected Values of R(Q=1)

Air	Deposition	Gamma Radiation	^{131}I in Milk
7×10^{-14}	1	60	1.5×10^{-7}
$\left(\frac{\mu Ci}{cc} / \frac{\mu Ci}{sec}\right)$	$\left(\frac{mCi}{mile^2\text{-}4\ weeks} / \frac{\mu Ci}{sec}\right)$	$\left(\frac{mrad}{4\ weeks} / \frac{Ci}{sec}\right)$	$\left(\frac{\mu Ci}{ml} / \frac{\mu Ci}{sec}\right)$

6. The methods for determining the MDL are applicable to facilities where the background level in some remote area is the same as that near the facility. The values of G measured at such other locations should not differ greatly from those reported here.

7. The mathematical model for determining R(Q=1) is applicable to any location. The applicability to other locations of the actual values of R(Q=1) reported here will depend on how closely the input data match those used in this study.

REFERENCES

1. Morton, R. J., "Management and Disposal of Radioactive Wastes," Nuclear Safety (June 1960) 64-73.

2. Blatz, Hanson, "Are Surveys Necessary? NO," Nucleonics (Jan. 1959), 57.

3. Edelmann, Abraham, "Are Surveys Necessary? YES," Nucleonics (Jan. 1959), 57.

4. Pelletier, Charles A., "Environmental Surveys for Nuclear Facilities," Nucleonics (Jan. 1959), 56-59.

5. Harris, W. B., "Examining the Value of Reactor - Site Environmental Surveys, A United States View," Nucleonics (Aug. 1960), 66-67.

6. Dunster, H. J., "Examining the Value of Reactor - Site Environmental Surveys, A United Kingdom View," Nucleonics (Aug. 1960), 67.

7. Kenneke, Albert P., Nehemias, John V., Whipple, G. Hoyt, "Reactor Site Surveys," a letter to the Editor of Nucleonics, Nucleonics, (Dec. 1960), 6.

8. Pelletier, Charles A., Whipple, G. Hoyt, "Pre-Operational Environmental Survey for the Enrico Fermi Atomic Power Plant: 1958-1962," American Industrial Hygiene Association Journal, 24, 122-179, 1963.

9. Radiological Health Handbook, United States Department of Health, Education, and Welfare, PB 121784R, 196, 126-132.

10. Dixon, Wilfrid J. and Massey, Frank J., Jr., Introduction to Statistical Analysis. New York: McGraw-Hill Book Company, Inc., 1951, 97-101.

11. Ibid., 108-109.

12. Ibid., 104.

13. Hodgman, Charles D., Editor in Chief, Handbook of Chemistry and Physics. Cleveland: Chemical Rubber Publishing Company, 1958-59, 215-217.

14. Pasquill, F., Atmospheric Diffusion. London: D. Van Nostrand Company Ltd. 1962, 184-185.

15. Ibid., 185-193.

16. Ibid., 95-101.

17. Ibid., 231-235.

18. Stewart, N. G., Gale, H. J. and Brooks, R. N., 1954, "The Atmospheric Diffusion of Gases Discharged from the Chimney of the Harwell Pile," International Journal of Air and Water Pollution, 1, 87-102, 1958.

19. Sutton, O. G., Micrometeorology. New York: McGraw-Hill Book Company, Inc., 1953, 110 and 287.

20. Ibid., 138-139.

21. Ibid., 283-287.

22. Smith, F. B., "The Diffusion of Smoke from a Continuous Elevated Point-Source into a Turbulent Atmosphere," Journal of Fluid Mechanics, 2, 49-76, 1957.

23. Gifford, F. A., Jr., "Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Model," Nuclear Safety, 56-59, (Dec. 1960).

24. Pasquill, F., "The Estimation of the Dispersion of Windborne Material," The Meteorogolical Magazine. 90:33-49 (1961).

25. Gifford, F. A., Jr., "Atmospheric Dispersion," Nuclear Safety. 56-62 (Mar. 1960).

26. Hewson, Wendell E., Gill, Gerald C. and Walke, Gerald J., Progress Report No. 3 - Smoke Plume Photography Study Big Rock Point Nuclear Plant, Charlevoix, Michigan, College of Engineering, The University of Michigan, 04015-3-P, (Dec. 1963).

27. Hewson, Wendell E., Gill, Gerald C. and Bierly, Eugene W., Final Report, Meteorological Analysis, College of Engineering, The University of Michigan, 2515-6-F (Jan. 1961).

28. These data were supplied through the courtesy of Gerald C. Gill, Professor of Meteorology and the Department of Meteorology and Oceanography, The University of Michigan.

29. These data were supplied through the courtesy of Paul Giever, Research Associate in Industrial Health, Industrial Health Department, The University of Michigan.

30. Hewson, Wendell E., Gill, Gerald C., and Bierly, Eugene W. Atmospheric Diffusion Study at the Enrico Fermi Nuclear Reactor Site, First Technical Report, A quantitative Analysis of Diffusion, College of Engineering, The University of Michigan, (July 1960).

31. Bryant, Pamela M., "Methods of Estimation of the Dispersion of Windborne Material and Data to Assist in Their Application," AHSB (RP) R 42, 1964.

32. _____. "Derivation of Working Limits for Continuous Release Rates of Iodine-131 to Atmosphere in a Milk Producing Area," Health Physics. 10, 249-57 (April 1964).

33. Holzworth, George C., "Estimates of Mean Maximum Mixing Depths in the Contiguous United States," Monthly Weather Review 92:235-242 (May, 1964).

34. These data were supplied through the courtesy of George C. Holzworth and the United States Weather Bureau Research Station, Cincinnati, Ohio.

35. Holland, J. Z., "A Meteorological Survey of the Oak Ridge Area." ORO - 99 (1953).

36. Bryant, Pamela M., Addendum to Part I Section 6 of Reference 31, AHSB (RP) R 42 Addendum.

37. Hawley, C. A., Jr., Sill, C. W., Voelz, G. L. and Islitzer, N. F., "Controlled Environmental Radioiodine Tests, National Reactor Testing Station," IDO-12035 (June 1964).

38. Chamberlain, A. C., "Transport of Particles Across Boundry Layers," The Third Conference on Nuclear Reactor Chemistry, Gatlinburg, Tennessee, October 9-11, 1962. TID-7641, 1-14.

39. Cline, J. F., Wilson, D. O. and Hungate, F. P., "Effect of Physical and Biological Conditions on Deposition and Retention of ^{131}I on Plants," Health Physics. 11, 713-717 (Aug. 1965).

40. Pierson, D. H. and Keane, J. R., "Characteristics of Early Fallout from the Russian Nuclear Explosions of 1961," Nature. 196, 801-807 (Dec. 1962).

41. Pelletier, Charles A., Whipple, G. Hoyt and Wedlick, Harold L. "The Use of Surface Air and Rainfall Measurements to Predict the Deposition of Fallout Radionuclides," The Second Atomic Energy Commission Conference on Fallout, Germantown, Maryland, November, 1964. Proceedings to be published in TID-7116.

42. Personal communication with John G. Feldes, Health Physicist for the Enrico Fermi Atomic Power Plant.

43. Silverman, Leslie, "Economic Aspects of Air and Gas Cleaning for Nuclear Energy Processes," Disposal of Radioactives Wastes, Volume 1. International Atomic Energy Agency, Vienna I, Austria, 139-179 (1960).

44. Engelmann, R. J., "Rain Scavenging of Particulates," HW-79382 (Dec. 1963).

45. Langmuir, Irving, "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing," Journal of Meterology, 5, 175-192 (Oct. 1958).

46. Best, A. C., "The Size Distribution of Raindrops," Quarterly Journal of the Royal Meteorological Society. 76, 16-36 (1950).

47. Chamberlain, A. C., "Aspects of Travel and Deposition of Aerosol and Vapour Clouds," AERE HP/R 1261 (1955).

48. Pasquill, F., Atmospheric Diffusion. London: D Van Nostrand Company Ltd. 1962, 239.

49. Chamberlain, A. C., "Washout of Iodine Vapor From Air," Aspects of the Deposition of Radioactive and Other Gases and Particles. Edited by E. G. Richardson, 1961.

50. Burington, Richard Stevens, Handbook of Mathematical Tables and Formulas, Sandusky, Ohio: Handbook Publishers, Inc. 1950.

51. Loevinger, R., Japha, E. M. and Brownell, G. L., "Discrete Radioisotope Sources," Radiation Dosimetry. Edited by Hine, Gerald J. and Brownell, Gordon L., New York: Academic Press, Inc., 1956, 733.

52. Souttar, H. S., "On Fields of Radiation from Radon Seeds," British Journal of Radiology. New Series 4, 1931, 681-689.

53. Holland, J. Z., "Radiation From Clouds of Reactor Debris," A/Conf.8/P./572 (Jun. 1955).

54. Goldstein, H. and Wilkins, J. E., Jr., Calculations of the Penetration of Gamma Rays. NYO-3075 (1954).

55. Thompson, S. E., "Effective Half-Life of Fallout Radionuclides on Plants with Special Emphasis on Iodine-131." UCRL12388 (Jan. 1965).

56. Marter, W. L., "Radioiodine Release Incident at the Savannah River Plant," Health Physics. 9, 1105-1109 (Dec. 1963).

57. Whipple, G. Hoyt, Pelletier, Charles A. and Wedlick, Harold L. "Investigations Into the Cycling and Recycling of Certain Radionuclides Through the Milk Food Chain," Progress Report No. 2. to the United States Atomic Energy Commission, Contract No. AT(11-1)-1333.

58. English, R. A., "Foliar Retention of Fallout," A research report in partial fulfillment of the requirements for a master's degree in the Department of Environmental Health, The University of Michigan. (Apr. 1965).

59. Hull, A. P., "Vegetation Retention and Vegetation - Milk Ratios of Fallout I^{131}," Health Physics. 9, 1173-1177 (Dec. 1963).

60. Morgan, A., "The Direct Uptake of Fission Products on Ryegrass," AERE-R 3181 (1959).

61. Reaves, Paul M. and Henderson, H. O., Dairy Cattle Feeding and Management. New York: John Wiley and Sons, Inc. 1963, 51.

62. Ibid., 39.

63. Miller, J. K., Swanson, E. W. and Cragle, R. G., "Relation of Milk Secretion to Iodine in Milk--An Abstract." Health Physics, 9, 1247 (Dec. 1963).

64. Van Middlesworth, L., "Factors Influencing the Thyroid Uptake of Iodine Isotopes From Nuclear Fission - A Review." Health Physics. 9:1197-1211 (Dec. 1963).

65. Lengemann, F. W. and Comar, C. L., "Metabolism of I^{131} by Dairy Cows During Long Term Daily Administration of the Radioisotope." Health Physics. 10, 55-59 (Feb. 1964).

66. Bustad, L. K., Wood, D. H., Ellefson, E. E., Ragan, H. A. and McClellan, R. O., "I^{131} in Milk and Thyroid of Dairy Cattle Following a Single Contamination Event and Prolonged Daily Administration," Health Physics, 9, 1231-1234. (Dec. 1963).

67. Macon, Nathaniel. Numerical Analysis. New York: John Wiley and Sons, Inc. 1963, 138-140.

68. Squire, Helen M., Middleton, L. J., Sansom, B. F. and Coid, R. C., "The Metabolism in Dairy Cows of Fission Products," The Entry of Fission Products into Food Chains, Edited by Loutit, J. F. and Russell, R. Scott. New York: Permagon Press, 1961: 69-91.

69. Herbst, W., "Radiobiological Problems of Aerosols. Properties and Hazards of Radioactive Aerosols Produced by Atomic Technique 1. Radioiodine Survey," AEC-tr-6550 (Written in 1963, translated in 1965).

70. "Climatological Data, Michigan," United States Department of Commerce, Environmental Sciences Services Administration, Weather Bureau.

71. Progress reports to The Power Reactor Development Company are available from the National Sanitation Foundation, 109 S. Observatory Road, Ann Arbor, Michigan.

72. Dixon, Wilfrid, J. and Massey, Frank J., Jr., Introduction to Statistical Analysis. New York: McGraw-Hill Book Company, Inc. 1951, 98-99.

73. Ibid., 84-91.

74. Li, Jerome C. R., Introduction to Statistical Inference. Ann Arbor, Michigan. Edwards Brothers.

75. Shalmon, Eliahu, Deposition of Some Radionuclides on Tropospheric Aerosols - A Ph.D. Thesis written at the University of Michigan, 1964.

76. Pelletier, Charles A., Wegst, Audrey V. and Whipple, G. Hoyt, "Concentrations of Radioactive Particles in Surface Air, November, 1962 through March, 1963." Health Physics, 10, 917-921 (Dec. 1964).

77. Heard, M. J. and Jones, B. E., "A New Film Holder for Personnel Dosimetry." HERE-M 1178 (1963).

78. Soldat, J. K., "Environmental Evaluation of an Acute Release of ^{131}I to the Atmosphere." Health Physics. 11, 1009-1015 (Oct. 1965).

79. Nelson, S. C., "Environmental Radioactivity in the Vicinity of the Vallecitos Atomic Laboratory - I, 1956 through 1963." APIO - 1013 - 1, Class T, (Mar. 1965).

80. Chamberlain, A. C., "Dispersion of Activity From Chimney Stacks," Atomic Energy Waste, edited by E. Glueckauf, New York. Interscience Publishers (1961) 316-318.

APPENDIX A

METHODS OF CALCULATING THE VALUES OF THE CONSTANTS IN THE EQUATIONS RELATING THE IODINE-131 CONTENT IN COW'S MILK TO THE INTAKE OF IODINE-131 ON PASTURE GRASS

The minimum daily requirement for iodine intake for the cow is between 2 and 3 mg/day.[61] It is assumed in this research that the cows ingest 5 mg of iodine per day. It is also assumed that the cows in this research produce 24 liters of milk per day.

1. Estimation of f_{th} and TH Equations 60 and 61.

Assuming equilibrium, equation 60 can be solved for f_{th} with the following result:

$$f_{th} = \frac{C_{th}}{A_v I} (\lambda_I + TH) \qquad (A1)$$

with a stable iodine diet of 5 mg per day Bustad et al.,[66] report a value for the ratio $C_{th}/A_v I \simeq 2$. If it is assumed that the effective removal half life is 4.5 days,[66] $(\lambda + TH) = 0.154$. It follows then that f_{th} in equation A1 is equal to 0.31.

Giving Engleman as a reference, Van Middlesworth gives a biological half life for iodine in the cow's thyroid of 16 days.[64] With this value, and equation A1, f_{th} is calculated to be 0.26. The small difference between the two values of f_{th} shows that f_{th} is not strongly

dependent on the assumed biological half life of iodine in the cow's thyroid. The biological half life corresponding to an effective half life of 4.5 days is 10.2 days. The values of f_{th} and TH used in this research are 0.31 and 0.068 respectively.

2. Estimation of M and (U + F)

From graphs presented by Bustad et al.[66] concentrations of iodine-131 in milk were estimated to be about 0.5 and 1% of the daily dose per liter of milk for stable iodine intakes of 5 and 15 mg/day respectively. Lengemann and Comar[65] report a concentration of about 1% of the daily dose per liter of milk for a stable iodine intake of 15 mg/day. Lengemann and Comar[65] also reports concentrations from other sources which are in good agreement with the above values.

It is assumed in this study that the concentration in milk is 0.5% of the daily dose per liter of milk. In terms of equation 61, this assumption is expressed mathematically as follows:

$$\frac{MC_m}{(OP)} = 0.005 \; A_v \; I \qquad \text{(A2)}$$

where: (OP) = milk output (liters/day)

Solving equation A2 for C_m:

$$C_m = \frac{0.005 \; A_v \; I \; (OP)}{M} \qquad \text{(A3)}$$

The work reported by Lengemann and Comar[65] showed that the amount of iodine-131 eliminated in the milk was about 25% of that eliminated in the feces and urine each day. This is expressed mathematically as follows:

$$\frac{M}{(U + F)} = 0.25 \tag{A4}$$

Equations A3 and A4 can be substituted into equation 61 (assuming equilibrium) and solved for M with the following results:

$$M = \frac{\lambda\ (OP)\ 0.005}{[(1-f_{th}) - 0.005\ (OP)\ (1 + \frac{U + F}{M})]} \tag{A5}$$

with $f_{th} = 0.31$

$OP = 24$ liters/day

$M/(U + F) = 0.25$

Equations A5 and A4 give values of M and (U + F) of 0.115 and 0.460 $days^{-1}$ respectively.

It is interesting to note that this mathematical analysis of iodine-131 in the cow has led to certain restrictions on the values that the constants can assume. In order for the analysis to be meaningful equation A6 must be satisfied.

$$1 - f_{th} < 0.005\ (OP)\ (1 + \frac{U + F}{M}) \tag{A6}$$

APPENDIX B

EXPLANATION OF SYMBOLS AND ABBREVIATIONS

a	= fraction of radioactivity in rain which adheres to grass
A	= radioactivity (μCi)
A_g	= radioactivity concentration in grass (μCi/dry gm)
A'_g	= radioactivity per unit area on grass (μCi/m^2)
dA_γ	= gamma radioactivity in an infinitesimally small volume (μCi)
$B(\bar{E}_\gamma)$	= buildup factor for gamma rays in air
c	= radius of sphere (m)
C_b	= quantity of protein bound iodine-131 in the blood of cows (μCi)
C_m	= quantity of non-protein bound iodine-131 in the blood of cows (μCi)
C_{th}	= quantity of iodine-131 in the thyroid of cows (μCi)
cpm	= counts per minute
cps	= counts per second
Ci	= curie
μCi	= microcurie
mCi	= millicurie

C_y = virtual diffusion coefficient in y direction ($m^{n/2}$)

C_z = virtual diffusion coefficient in z direction ($m^{n/2}$)

d = a variable exponent of τ in equation 15

di = diameter of stack (m)

DEP_d = dry deposition ($\mu Ci/m^2$)

DEP_r = deposition due to rain ($\mu Ci/m^2$)

$D(x/\bar{u})$ = correction factor for radioactive decay

dps = disintegration per second

dpm = disintegration per minute

$\bar{E}_\beta$ = average energy of beta radiation (MeV)

$\bar{E}_\nu$ = average energy of gamma radiation (MeV)

dE/dt = rate of energy release (MeV/sec)

EFF_c = counting efficiency (dpm/cpm)

EFF_r = rain scavenging efficiency (sec^{-1})

ERR_Z = counting error at the Z confidence level

EXP_β = exposure to beta radiation (mrad)

EXP_ν = exposure to gamma radiation (mrad)

f_{th} = fraction of ingested iodine-131 reaching thyroid

F = biological decay constant for elimination of iodine-131 in feces ($days^{-1}$)

FC_Z = fractional counting error at the Z confidence level

$FR_{\beta/\nu}$ = film response to beta radiation relative to gamma radiation

G = proportionality parameter between MDL and $\bar{x}_b$

h = the height at which the concentration of a contaminant in a plume equals 10% of the concentration at the centerline (m)

H = stack height (m)

H_e = effective stack height (m)

ΔH = rise of the plume above the stack (m)

I = ingestion rate of grass by cows (dry gm/day)

J = consumption rate of grass by cows (dry gm/m^2-day)

k = ratio of retention factor $\underline{a}$ to stand of grass on pasture $\underline{Y}$ (m^2/dry gm)

K = rate of growth of pasture grass (dry gms/m^2-day)

M = biological decay constant for elimination of iodine-131 in milk ($days^{-1}$)

MDA = minimum detectable activity (μCi)

MDL = minimum detectable radioactivity level

MDR = minimum detectable release rate

mmd = maximum mixing depth (m)

mmd_i = daily maximum mixing depth (m)

$\overline{mmd}$ = average monthly maximum mixing depth (m)

n = atmospheric stability parameter

n' = slope of log-log plot of σ_θ Vs averaging time $x/4\bar{u}$.

N = total number of days or weeks of data

$n(\bar{\chi} \geq \bar{\chi}_i)$ = number of days or weeks in which $\bar{\chi}$ is greater than or equal to $\bar{\chi}_i$

n_b = background counting rate (cpm)

n_x = net sample counting rate (cpm)

n_x(minimum) = minimum detectable net sample counting rate (cpm)

N_b = number of samples collected in background area

N_f = number of samples collected in area near the facility

$P(\bar{\chi} \geq \bar{\chi}_i)$ = probability of detecting a concentration greater than or equal to $\bar{\chi}_i$

Q = stack emission rate (μCi/sec or Ci/sec)

$Q(x)_d$ = stack emission rate corrected for steady state dry deposition (μCi/sec)

$Q(x)_r$ = stack emission rate corrected for steady state deposition due to rain scavenging (μCi/sec)

$Q(x)$ = stack emission rate corrected for total steady state deposition (μCi/sec)

$Q(x,t)_d$ = stack emission rate corrected for non-steady state dry deposition (μCi/sec)

$Q(x,t)_r$ = stack emission rate corrected for non-steady state deposition due to rain scavenging (μCi/sec)

$Q(x,t)$ = stack emission rate corrected for total non-steady state deposition (μCi/sec)

$Q(x,t,D)$ = stack emission rate corrected for total non-steady state deposition and radioactive decay

Q_H = stack emission rate of heat (M_w)

r = distance of center of cube of radioactivity to a receptor (m)

$R(Q = 1)$ = radioactivity or exposure level produced in the environment by a unit release rate (units depending on sample media; in the case of air concentrations, μCi/m^3 per μCi/sec)

RR = rate of rainfall (mm/hr)

s = length of the side of a cube of radioactivity (m)

SS = sample size (units depending on sample media)

S_b^2 = the sample variance in the radioactivity levels of the observations in the background area (units depending on sample media)

S_f^2 = the sample variance in the radioactivity levels of the observations in the area near the facility (units depending on sample media)

S_p = pooled sample standard deviation (units depending on sample media)

SR = sampling rate (units depending on sample media)

$[S_\theta]_{24}$ = estimate of the 24-hour standard deviation of wind direction (radians)

t = time (sec), also the computed t-statistic on page 9.

t_b = background counting time (min)

t_s = sample counting time (min)

t_{theo} = theoretical t statistic

$t_{\theta_1-\theta_2}$ = time for the old plume to swing to the centerline of the new plume (sec)

T_o = time at which rainfall starts (sec)

T_r = time at which rainfall ends (sec)

TH = biological decay constant for elimination of iodine-131 from the thyroid of cows ($days^{-1}$)

$\bar{u}$ = average daily wind speed (m/sec)

U = biological decay constant for elimination of iodine-131 in urine of cows ($days^{-1}$)

v_d = deposition velocity (cm/sec)

v_e = escape velocity from stack (m/sec)

$\overline{WD}$ = average daily wind direction

WD_i = average hourly wind direction

x = downwind distance from stack (m)

$\bar{x}_b$ = average radioactivity level in background area (units depending on sample media)

$\bar{x}_f$ = average radioactivity level in area near facility (units depending on sample media)

y = horizontal distance from centerline of plume measured along an arc of radius x (m)

y' = horizontal distance from the centerline of the old plume to the sampler at any time t measured along an arc of radius x, where x is downwind distance of sampler (m)

Y = stand of grass on a pasture (dry gms/m^2)

z = vertical distance from the centerline of the plume (m)

Z = a statistic, the value of which depends on the confidence level with which one wishes to declare the counting error

λ = general decay constant (sec^{-1})

λ_β = decay constant for beta radioactivity of noble gas mixture after 1800 sec of decay (sec^{-1})

λ_{eff} = effective decay constant for iodine-131 on grass ($days^{-1}$)

λ_I = decay constant for iodine-131 (sec^{-1} or $days^{-1}$)

μ_a = true linear absorption coefficient (cm^{-1})

$\mu_T(\bar{E}_\gamma)$ or μ_T = total absorption coefficient (cm^{-1})

ρ = density of air (gms/cc)

σ_y, σ_z = standard deviation of the distribution of the contaminant within a plume in the y and z directions respectively

σ_θ, σ_ϕ = standard deviation of the wind directions in the y and z directions respectively

τ = sampling time (sec)

ϕ = energy flux of gamma radiation (MeV/m^2-sec)

χ = instantaneous concentration ($\mu Ci/m^3$)

$\bar{\chi}$ = average concentration ($\mu Ci/m^3$)

χ_{cic} = cross-wind integrated concentration ($\mu Ci/m^2$)

χ_{tic} = time integrated concentration (μCi-sec/m^3)

$\bar{\chi}$ (Q = 1) = concentration produced by a unit release rate ($\mu Ci/m^3$ per μCi/sec)