K Downes
Clune

6.

A NUMERICAL METHOD FOR REACTOR SITE EVALUATION

FROM THE HAZARD-TO-PEOPLE VIEWPOINT

by

K. W. Downes and I. A. Singer[1]

INTRODUCTION

There may come a time when everyone will agree that reactors can never release their inventory of fission products. If this happens, the choice of a reactor site could be made independent of the surrounding population. In a similar manner, an absolute guarantee on the adequacy of a containment vessel located below ground level or shielded properly would allow the choice of a site to be independent of the surrounding population. A guaranteed containment vessel above ground would enable the site choice to be made without considering people living beyond one or two kilometers from the reactor (Reference I Appendix I). Until the time is reached when reactors cannot liberate their fission products, site selection will have to take into account the possible effects, to the surrounding population, from a major release.

The problem undertaken in this paper is the numerical rating of possible reactor sites from the hazard-to-people viewpoint. It is assumed that other considerations such as coolant and land availability, nearness to workers, and other economic factors have indicated a number of satisfactory sites which are then to be rated according to a hazard criteria.

The approach used for the problem stated above is to assume that the reactor runs for the life time of the fuel, and then all of the fission products are released as an ambient temperature, small sized cloud. No set sequence of events leading to this cloud is postulated because such a sequence would be intimately tied to the exact details of design, manufacture, and operation of the particular reactor in question. The justification of the choice of emitting 100% of the fission products is by reference to the work of G. Parker (Reference II), who got more than 50% of the fission products out of sample fuel elements by short time burning. As will be shown later, the rating of sites is insensitive to the choice of percentage release. Also, there is no way to prove that fission products, once liberated from the fuel, will not leave the site.

1. Brookhaven National Laboratory, Upton, New York, U. S. A.

F/10

A second assumption in the analysis is that the population density around the site can be approximated as a power of the distance. The justification for this is that all the sites checked so far can easily be fitted by a straight line on log-log paper. For sites with very asymmetric wind distributions, the population density should be weighted by the wind direction probability. This would be the same as calculating the release many times and taking the average of the effects.

The third assumption is that no warning is given to the surrounding population nor is anything done to reduce their exposure.

Using the above assumptions, a Hazard Index is calculated based on the sum of the mid-lethal dose times the number of people who would receive this or a greater dose plus the sum of the number of people who would be made sick times their doses. In order to calculate such an Index, the above sums are approximated in integral form. Since no account is taken of ground contamination, this Hazard Index is only indirectly related to the potential liability of a reactor accident.

MATHEMATICAL DERIVATION

A Sutton type equation (Reference III) for the dispersion of a cloud from a continuous point source at the ground is used.

$$D = \frac{2Q}{\pi C_y C_z u\, X^{2-n}} \exp -\left[\frac{y^2}{C_y^2\, X^{2-n}}\right] \exp -\left[\frac{z^2}{C_z^2\, X^{2-n}}\right] \qquad (1)$$

where:

D	- dosage	(curies - sec/m^3)
Q	- total release	(curies - measured at 24 hrs.)
C_y	- horizontal diffusion parameter	(meters $^{n/2}$)
C_z	- vertical diffusion parameter	(meters $^{n/2}$)
X	- distance downwind	(meters)
y	- distance crosswind	(meters)
z	- distance vertical	(meters)
n	- index of turbulence	(dimensionless)
u	- mean wind speed	(meters/sec)

let

$$X_D = \left[\frac{2Q}{\pi C_y C_z u\, D}\right]^{\frac{1}{2-n}} \qquad (2)$$

X_D - maximum distance of an isodose line at the ground ($z = 0$) (meters)

Then at ground level:

$$y = C_y\, X^{1-(n/2)} \left[\ln \left(\frac{X_D}{X} \right)^{2-n} \right]^{1/2} \tag{3}$$

We assume that the population as a function of distance can be written in the form:

$$\delta = a\, X^{\gamma} \tag{4}$$

δ	- population density	(people/meter^2)
a	- population density at 1 meter	(people/meter$^{2+\gamma}$)
γ	- slope of population density	(dimensionless)

Therefore, the number of people in an area dx dy is given by

$$dN\,(x,y) = a\, X^{\gamma}\, dx\, dy \tag{5}$$

$$dN\,(x) = 2y\, a\, X^{\gamma}\, dx \tag{5a}$$

Substituting (3) into (5a) and integrating produces:

$$N\,(D) = 2aC_y \int_0^{X_D} X^{\gamma+1-(n/2)} \left[\ln \left(\frac{X_D}{X} \right)^{2-n} \right]^{1/2} dx \tag{6}$$

N (D) - number of people within an area bounded by an isodose line. (people)

By letting $X = X_D \exp(-t)$, the solution of equation (6) is:

$$N\,(D) = a\, C_y\, (\pi)^{1/2} \left[\frac{2Q}{\pi C_y C_z u\, D} \right]^{\frac{\gamma+2-(n/2)}{2-n}} (2-n)^{1/2} \left[\gamma+2-(n/2) \right]^{-3/2} \tag{7}$$

The total hazard can now be estimated with the aid of equation (7) and knowledge of the human dose response curve by the following equation:

$$H_T = - \int_0^{\infty} h\ (D)\ dN\ (D) \tag{8}$$

H_T	- total hazard	(dimensionless)
h (D)	- human dose response function	(1/people)

With the present state of knowledge, the dose response factor must be estimated. It is hypothesized that this curve can be approximated by a double step function with a linear trend in between. (It is assumed that below a dose D_E there is no short term human effect. Above the mid-lethal dose, D_F, the effect is equal to D_F and between D_E and D_F, the effect is equal to the dose.) This reduces equation (8) to

$$-H_T = \int_{D_o}^{D_E} h_o dN\ (D) + \int_{D_E}^{D_F} D dN\ (D) + \int_{D_F}^{D_B} D_F\ dN\ (D) \tag{9}$$

D_B	- dose at site boundary.	(curies - sec/m^3)

h_o must be zero to satisfy our assumption of no hazard below dose D_E (Reference I Appendix L). It is only necessary to integrate to D_B rather than D , since the effect on site is not considered pertinent.

Thus,

$$-H_T = \int_{D_E}^{D_F} D dN\ (D) + \int_{D_F}^{D_B} D_F\ dN\ (D) \tag{10}$$

Equation (7) is in the form

$$N\ (D_i) = K\ D_i^{-A}$$

$$\text{Thus } dN\ (D_i) = K\ A\ D_i^{-A-1}\ dD \tag{11a}$$

where:

$$K = aC_y\ (\pi)^{1/2}\left[\frac{2Q}{\pi\ C_y C_z u}\right]^{\frac{\gamma+2-(n/2)}{2-n}}\ (2-n)^{1/2}\left[\gamma+2-(n/2)\right]^{-3/2}$$

$$A = \frac{\gamma + 2-(n/2)}{2-n}$$

substituting (11a) into (10):

$$H_T = \int_{D_F}^{D_E} -KAD^{-A}\ dD + \int_{D_B}^{D_F} D_F\left[-\ KAD^{-A-1}\right] dD \qquad (12)$$

$$H_T = D_F\ \ KD_F^{-A}\ \ -D_F\ \ KD_B^{-A}\ \ + \frac{KA}{A-1}\left[D_E^{-A+1}\ \ -D_F^{-A+1}\right] \qquad (13)$$

Let $H_1 = K\ D_F^{-A+1} = D_F\ N\ (D_F)$ (14a)

$$H_2 = -KD_B^{-A+1}\ -D_F\ \ N\ (B) \qquad (14b)$$

N (B) - number of people within an isodose line that extends to the site boundary. (people)

$$H_3 = \frac{K\ A}{A-1}\ D_E^{-A+1} = \frac{A}{A-1}\ D_E\ N\ (D_E) \qquad (14c)$$

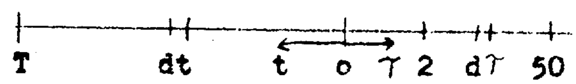
$$H_4 = -\frac{KA}{A-1}\ D_F^{-A+1} = -\ \frac{A}{A-1}\ \ D_F\ N\ (D_F) \qquad (14d)$$

Thus, the total hazard is simply

$$H_T = H_1 + H_2 + H_3 + H_4 \tag{15}$$

One further correction could be made to the above analysis because the mid-lethal dose was calculated only for a 180-day fuel life (Reference IV, Section E.) To convert these numbers for different fuel lives, the concept of effective power based on the Wigner Way approximation (Reference V) for the fission product decay was used.

Assuming that the dose to a person is mostly lung dosage and that this is roughly proportional to the integral of the dose rate from 2 to 50 hours after the accident



$$\text{Dose} = A\int_0^T dt \int_2^{50} (\tau + t)^{-1.2}\, d\tau \tag{16}$$

$$= A' \; (50 + T)^{.8} - (2 + T)^{.8} + 50^{.8} - 2^{.8} \tag{17}$$

for all times $T >> 50$ hours

$$\text{Dose} = A' \; (50 + T)^{.8} - (2 + T)^{.8} \tag{18}$$

expanding in a Taylor's series and keeping only the first two terms gives

$$\text{Dose} = A' T^{.8} \; (1 + \frac{40}{T}) - (1 + \frac{1.6}{T}) \tag{19}$$

$$D \quad A \quad T^{-.2} \tag{20}$$

Equation 20 normalized to 1 at $T = 180$ days gives.

$$R = \frac{P_{eff}}{P} = \left(\frac{180}{T \text{ (days)}}\right)^{-.2} \tag{21}$$

This equation is plotted on figure 2.

SAMPLE CALCULATIONS

According to Reference I Appendix E, the following diffusion parameters are typical for inversion conditions:

$n = 0.5$ $\quad\quad$ $C_z = 0.05\ m^{n/2}$

$u = 3.0\ m/sec$ $\quad\quad$ $C_y = 0.40\ ^{n/2}$

In a similar manner, Reference I Appendix D and Reference IV, are in agreement and give the following estimates:

$D_E = 100$ (curies -sec/m^3)

$D_F = 400$ (curies -sec/m^3)

$Q = 0.8\ P$ (curies - measured at 24 hours)
P = reactor thermal power (watts)

These values have been substituted into equation (2) and are plotted on Figure 1. The problem can then be classified into three regions (A, B and C).

REGION C

If the power of the reactor and the site radius is such that it falls into this region, then $D_E > D_F$ and $D_F > D_B$ in equation (10). Therefore, the hazard associated with both integrals have negative values. Since there can be no negative hazard, the Hazard Index for this region is zero.

REGION B

If the power of the reactor and the site radius is such that it falls into this region, then $D_E < D_F$ and $D_F > D_B$ in equation (10). Therefore, the hazard associated with the second integral in this equation becomes negative and assumed to be zero by the logic given in region A. The equation reduces to

$$-H_T = \int_{D_B}^{D_E} D\, dN\,(D) = \int_{D_B}^{D_E} -\ KAD^{-A}\ dD \qquad (22)$$

$$H_T = \frac{K\,A}{A+1}\left[D_B^{\;-AH} - 100^{\;-AH}\right] \tag{23}$$

$$H_T = \frac{\gamma + 1.75}{\gamma + 0.25}\; a'\; 8.6826 \times 10^{-3\gamma-7}\;\; 8.488P^{\frac{\gamma+1.75}{1.5}}\;\; \gamma + 1.75^{-3/2}$$

$$\left[-100^{\frac{-\gamma+0.25}{1.5}} + 8.488PB^{\;\gamma-0.25}\right] \tag{24}$$

a' - people per square kilometer at 1 kilometer
B - distance to site boundary (meters)

REGION A

If the power of the reactor and the site radius is such that it falls into this region, then $D_E < D_P$ and $D_P < D_B$ in equation (10) and equation (15) reduces to

$$H_T = H_1\left[1-\left(\frac{\gamma + 1.75}{\gamma + 0.25}\right)\left(1-(4)^{\frac{\gamma+0.25}{1.5}}\right)\right] - H_2 \tag{25}$$

where

$$H_1 = a'\; 3.473 \times 10^{-4-3\gamma}\;(\gamma + 1.75)^{-3/2}\left[2.122 \times 10^{-2}\; P\right]^{\frac{\gamma+1.75}{1.5}} \tag{25a}$$

$$H_2 = a'\; 3.473 \times 10^{-4-3\gamma}\;(\gamma+1.75)^{-3/2}\;\; B^{(\gamma + 1.75)} \tag{25b}$$

Equation (25a) is plotted on Figure 3 and equation (25b) is on Figure 4.

As a specific example on the use of the curves, let us consider the BNL reactor operating at 20 MW. The average age of the fuel in the reactor is about 180 days. Therefore from Figure 2, R = 1. From Figure 1, we see that this reactor-site combination lies in Region A and that the maximum interaction distance for D = 100 is approximately 14 Km. Figure 5 shows the population distribution around the site for which

$$\gamma = 0.93 \text{ and } a' = 6$$

From Figure 3 we get $H_1 + H_3 + H_4 = 7.2 \times 10^3$

From Figure 4 we get $H_2 = -50$

Therefore, $H = 7.2 \times 10^3 - 5 \times 10^1 = 7.15 \times 10^3$

Multiplying by $a' = 6$ gives a Hazard Index of approximately 4.3×10^4.

Another way of presenting the Hazard Index is to calculate an equivalent uniform population density. From Figure 3 for $\gamma = 0$, $P = 20$ MW, $H_1 + H_3 + H_4 = 1.5 \times 10^3$.

Similarly from Figure 4 for $\gamma = 0$, $P = 20$ MW, $H_2 = 80$.

$$a' = \frac{4.3 \times 10^4}{1.5 \times 10^3 - 80} = 30 \text{ people/km}^2$$

Thus, the BNL reactor-site combination is the same as a site with a uniform population distribution of approximately 30 people/km². As can be seen from the equations, this equivalent population density is a function of the reactor power.

OBSERVATIONS

It should be remembered that the problem undertaken in this study is to arrive at a Hazard order for various possible locations for the same reactor. This permits the use of many constants which, though not well known, tend to cancel out of the analysis. In this category are the doses, percentage release, reactor lifetime, etc. In each case, the only effect of a variation of the chosen number is to change the maximum radius of the population curve. This curve is very insensitive to changes in this radius, and hence the above constants need not be well known for the method to work.

While the example is shown for an inversion condition, it can be shown that H_T for a lapse is very much smaller. Thus, any time weighted H_T will tend to be proportional to H_T for the inversion case. Therefore, for the relative rating of sites, it is usually sufficient to only calculate the inversion case. An exception to this would be a site with a highly variable day-night population distribution.

Due to the general nature of the values used in the analysis, the numbers derived are only approximate. In this respect, variations of a few per cent among different sites is not significant.

REFERENCES

I. Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants. U. S. AEC Report WASH 740.

II. Parker, G. W., Experiments on the Release of Fission Products from Molten Reactor Fuels ORNL 57-6-87

III. Sutton, O. G., The Problem of Diffusion in the Lower Atmosphere, Quart. J. Roy. Meteorol. Soc. 73, 257 (1947).

IV. Marley, W. G., and Fry, T. M., Radiological Hazards from an Escape of Fission Products and the Implications in Power Reactor Location Proceedings of the Internation Conference on the Peaceful Uses of Atomic Energy Vol. 13, Page 104.

V. Way, K and Wigner, E. P. Radiation from Fission Products, Phys. Rev 70, 115 (1946).

Fig. I

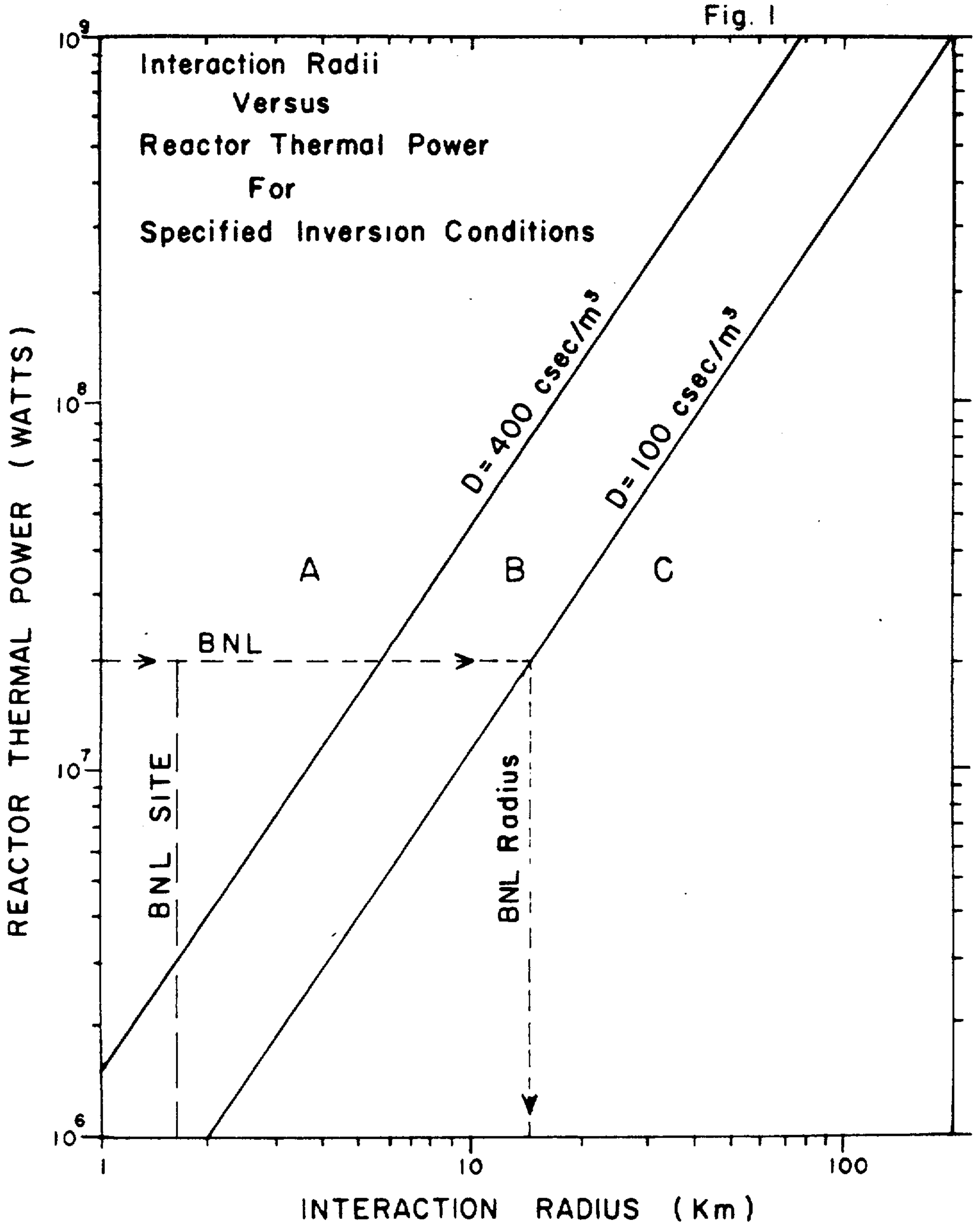
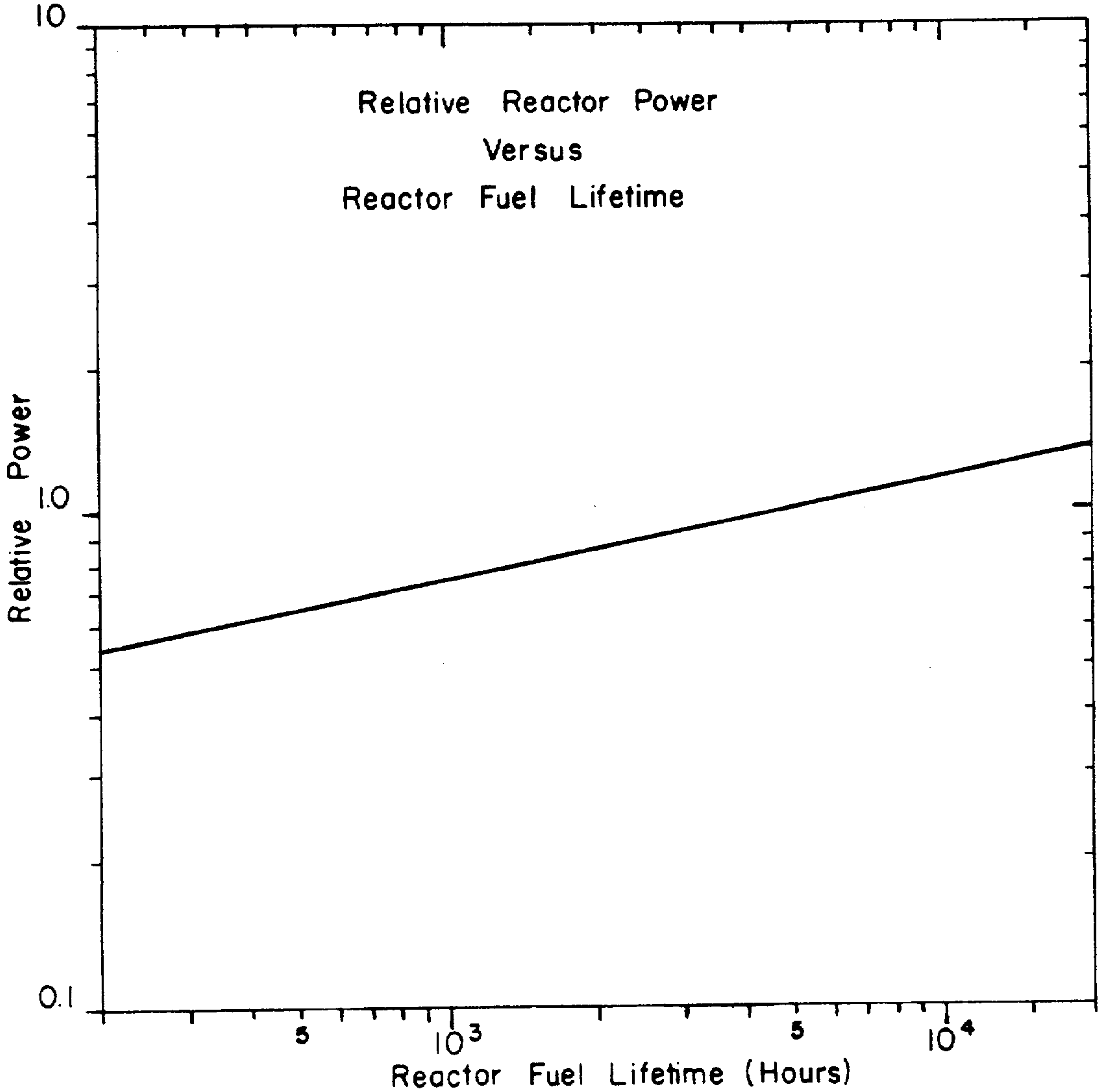
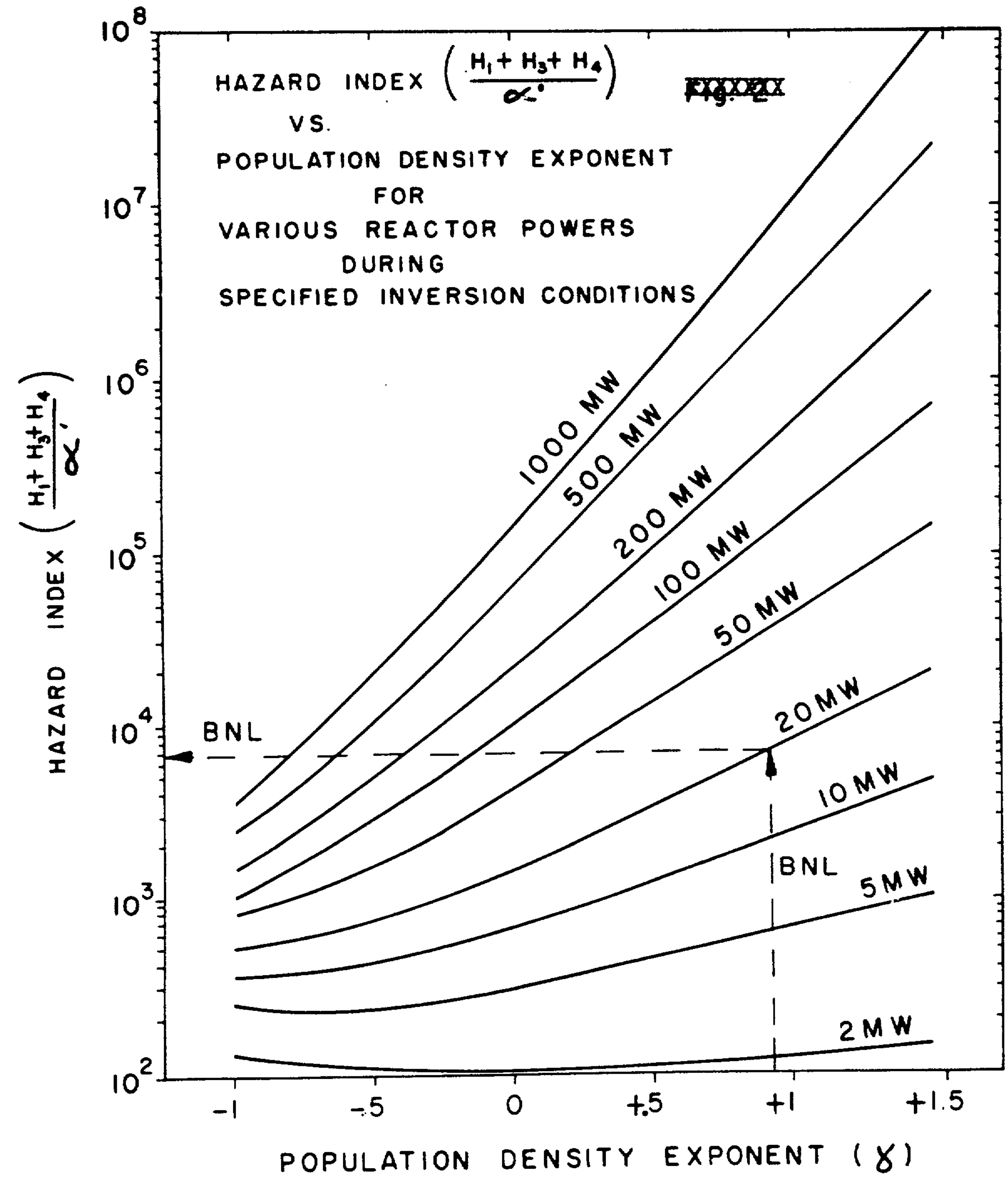

Interaction Radii
Versus
Reactor Thermal Power
For
Specified Inversion Conditions
D=400 csec/m³
D=100 csec/m³
A
B
C
BNL
BNL SITE
BNL Radius
REACTOR THERMAL POWER (WATTS)
10⁹
10⁸
10⁷
10⁶
1
10
100
INTERACTION RADIUS (Km)

Fig. 2



Relative Reactor Power
Versus
Reactor Fuel Lifetime
10
1.0
0.1
Relative Power
5
10^3
5
10^4
Reactor Fuel Lifetime (Hours)



HAZARD INDEX $\left(\frac{H_1+H_3+H_4}{\alpha'}\right)$
VS.
POPULATION DENSITY EXPONENT
FOR
VARIOUS REACTOR POWERS
DURING
SPECIFIED INVERSION CONDITIONS
1000 MW
500 MW
200 MW
100 MW
50 MW
20 MW
10 MW
5 MW
2 MW
BNL
BNL
10^8
10^7
10^6
10^5
10^4
10^3
10^2
HAZARD INDEX $\left(\frac{H_1+H_3+H_4}{\alpha'}\right)$
-1
-.5
0
+.5
+1
+1.5
POPULATION DENSITY EXPONENT (γ)

Figure 3.

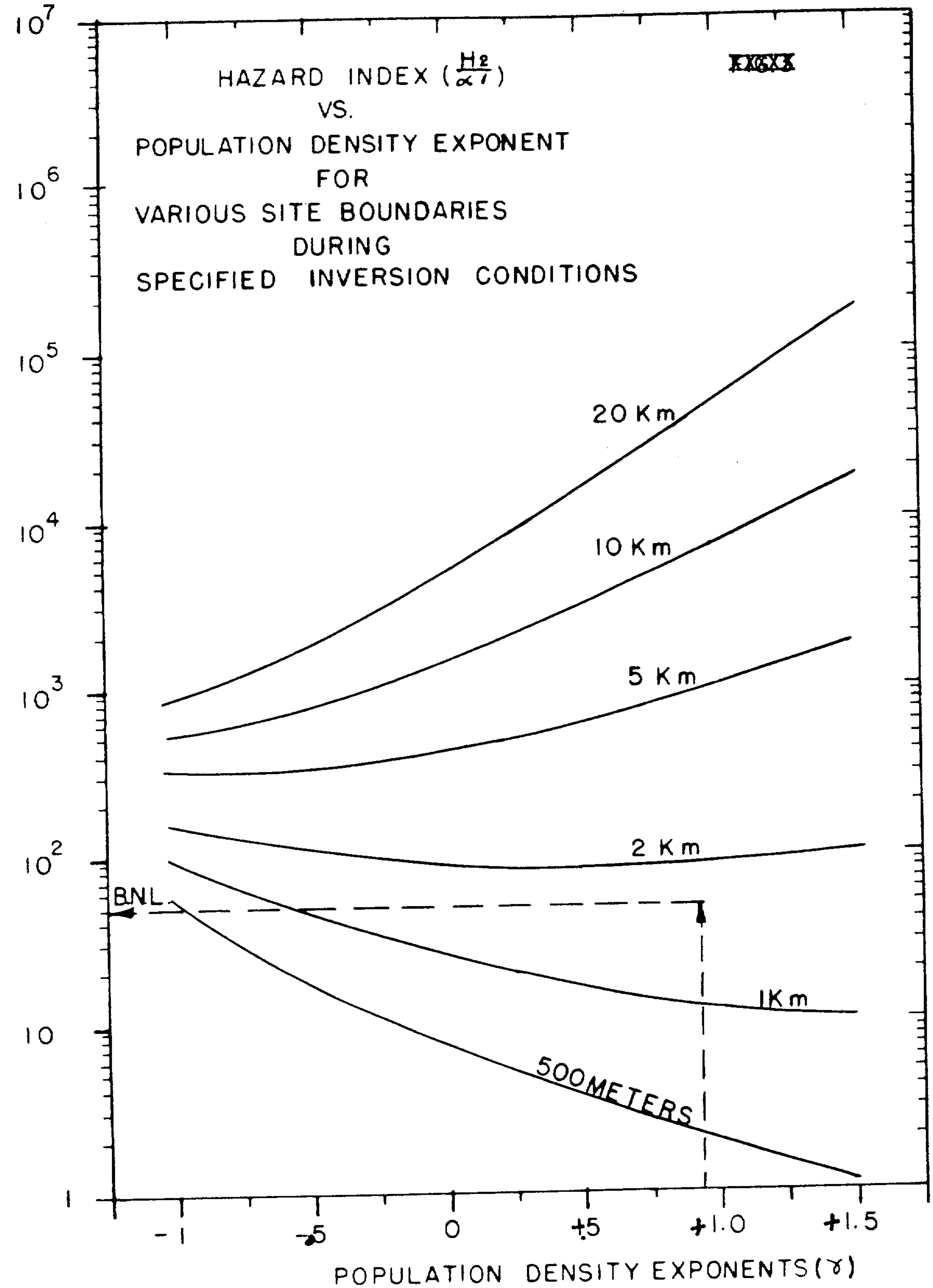

HAZARD INDEX ($\frac{H_2}{\alpha I}$)
VS.
POPULATION DENSITY EXPONENT
FOR
VARIOUS SITE BOUNDARIES
DURING
SPECIFIED INVERSION CONDITIONS
20 Km
10 Km
5 Km
2 Km
1Km
500METERS
BNL
10^7
10^6
10^5
10^4
10^3
10^2
10
1
-1
-.5
0
+.5
+1.0
+1.5
POPULATION DENSITY EXPONENTS(γ)

Figure 4.

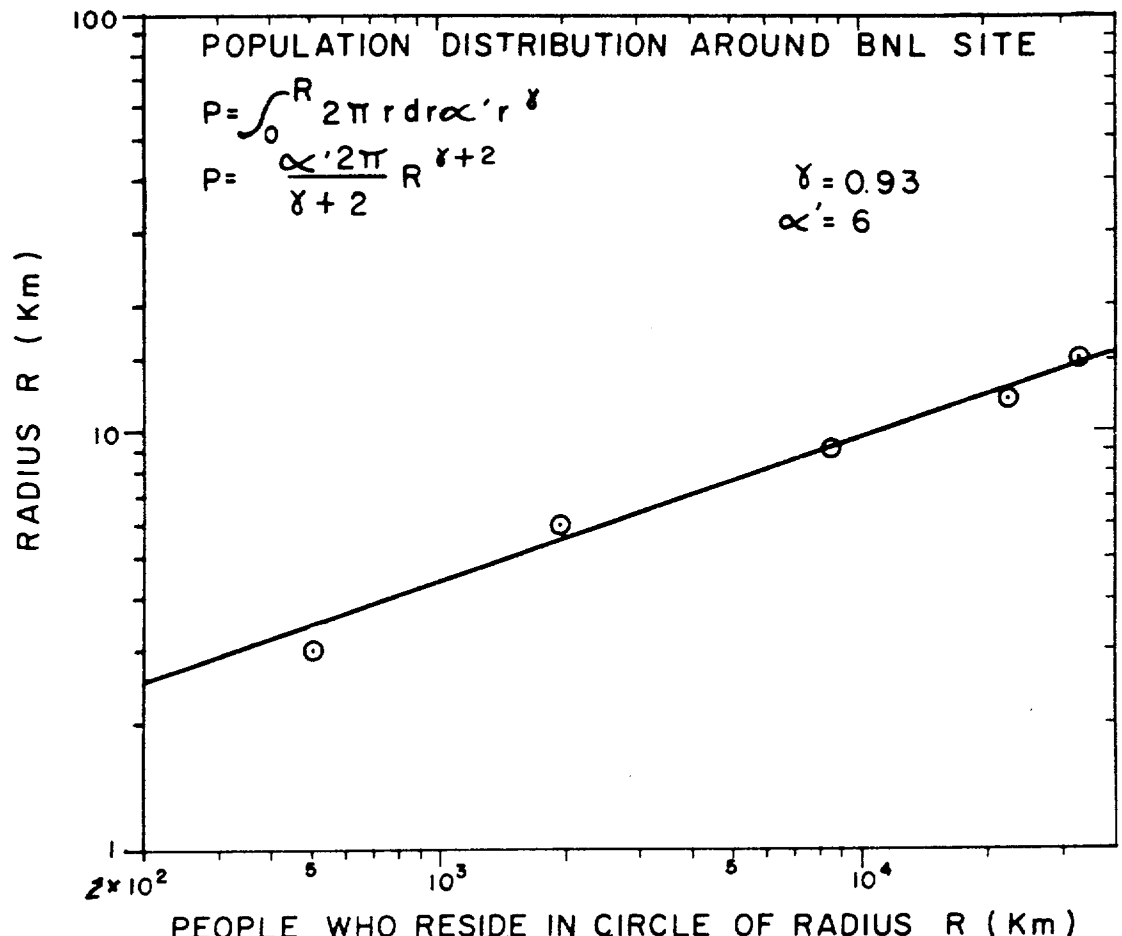

POPULATION DISTRIBUTION AROUND BNL SITE
$P = \int_0^R 2\pi r\,dr\,\alpha' r^{\gamma}$
$P = \frac{\alpha' 2\pi}{\gamma + 2} R^{\gamma + 2}$
$\gamma = 0.93$
$\alpha' = 6$
RADIUS R (Km)
100
10
1
2×10^2
5
10^3
5
10^4
PEOPLE WHO RESIDE IN CIRCLE OF RADIUS R (Km)

Figure 5.