International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

The Cost-Effectiveness of Remote Nuclear Reactor Siting

Niehaus, F., Cohen, J.J. and Otway, H.J.

IIASA Research Memorandum
April 1976

Niehaus, F., Cohen, J.J. and Otway, H.J. (1976) The Cost-Effectiveness of Remote Nuclear Reactor Siting. IIASA Research Memorandum. Copyright © April 1976 by the author(s). http://pure.iiasa.ac.at/650/

RM-76-34

THE COST-EFFECTIVENESS OF REMOTE NUCLEAR REACTOR SITING

Friedrich Niehaus*
Jerry J. Cohen**
and
Harry J. Otway***

April 1976

---

*Seconded by the Federal Republic of Germany to the Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011 Vienna, Austria.

**Seconded by the United States of America to the Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011, Vienna, Austria.

***Project Leader, Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011 Vienna, Austria.

PREFACE

Risks have emerged as a major constraint to the introduction and development of technological systems. The work of the Joint IAEA/IIASA Research Project (IAEA = International Atomic Energy Agency) is directed toward gaining an improved understanding of how societies judge the acceptability of new technologies and how objective information on risks, and the anticipated responses to them, may be considered in decision-making. A conceptual framework is being used for risk assessment studies which includes in addition to the consideration of physical risks, the perception of risk situations and the resulting psychological and sociological levels of risk.

This paper treats the cost-effectiveness of the physical risk reduction achieved through the remote siting of nuclear power plants.

ABSTRACT

This paper attempts to gain insights into the cost-effectiveness of remote nuclear power plant siting as a means of minimizing potential radiation exposure. A simplified approach was used in which the reduction in population dose as a function of increasing distance between the nuclear power plant and the densely populated area it serves is evaluated against the resulting increase in power transmission cost. The model only considers power transmission costs as an economic variable; other advantages, such as the use of secondary heat, are not included.

These calculations indicate that, based upon the guideline value of $1,000/man-rem, remote siting of nuclear power facilities would not seem to be a cost-effective way to control potential radiation exposures. But only the biological effects of potential radiation exposure were considered; if other risk aspects were to be included remote siting might be justified.

The Cost-Effectiveness of Remote Nuclear Reactor Siting[1]

Friedrich Niehaus[2]
Jerry J. Cohen[3]
and
Harry J. Otway[4]

In recent years there have been increasing concerns expressed about the potential adverse effects of technological developments. This is especially true with regard to energy systems where the nuclear energy debate has concentrated upon the associated risks; in fact, risks have emerged as one of the major constraints affecting decision-making in this area. The concepts of risk assessment have been outlined in an earlier publication (Otway and Pahner, 1976) which also summarised an extensive, interdisciplinary research programme on this topic.

In this research risk situations are considered to be characterised by a number of "levels". The first level is that of the physical risks presented by a particular facility or technology; the next level is that of how these risks are

---

[1] The views expressed in this paper are those of the authors, and do not necessarily reflect those of the Project Sponsors.

[2] Seconded by the Federal Republic of Germany to the Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011 Vienna, Austria.

[3] Seconded by the United States of America to the Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011 Vienna, Austria.

[4] Project Leader, Joint IAEA/IIASA Research Project, International Atomic Energy Agency, P.O. Box 590, A-1011 Vienna, Austria.

perceived by individuals; the third level is the psychological effects upon individuals as they respond to these perceptions and the final level is the risks to social structures and cultural values as individuals express their concerns through their participation in interest groups which aggregate the individual attitudes.

The intent of this paper is to examine the cost-effectiveness of remote nuclear plant siting when only the first level of risk is considered, i.e., biological effects of radioactive release.

Background

Since the inception of the "nuclear age", the hazards of exposure to ionizing radiation have been recognized and efforts taken to control them by establishing numerical guidelines and standards (I.C.R.P., 1964; Nat. Bureau of Stds., 1959). Recognizing the absence of a safe threshold level for radiation exposure, control measures have been taken beyond these numerical requirements with the objective of keeping exposures "as low as practicable" (NBS, 1959), or "as low as readily achievable, economic and social considerations being taken into account" (ICRP, #9, 1966). Recently, increasing attention has been given to the cost-effectiveness of control measures and methodologies for such evaluations are being developed (USAEC, 1973; USEPA, 1973; USAEC, 1974). These cost-effectiveness evaluations are designed to determine whether the direct and indirect costs of controls are justified by the risk reduction achieved.

Economic Considerations

Safety expenditures generally follow the "law of diminishing returns"; that is, marginal risk-reduction decreases as total cost increases. This concept is illustrated in Fig. 1 where the costs of risk reduction are plotted against risk level. From this curve it can also be seen that regardless of the degree of risk reduction achieved at any given cost, it might be further reduced by still greater expenditure. It follows that, at some point, the cost-effectiveness (value received per unit expenditure) would go below some level of "acceptability". Recently, the U.S. Nuclear Regulatory Commission (USNRC, 1975) has suggested a guideline pertaining to waste effluent releases from nuclear reactors which states that a value of $1,000 per man-rem* reduction shall be used in cost-benefit analyses as an interim measure until establishment and adoption of better values or other appropriate criteria. It might be assumed that this marginal cost (or whatever marginal cost guideline is selected) might be uniformly applicable to all activities involving potential radiation exposure, or, more generally, to any risk to health and safety where equivalent harm might result (Wilson, 1975).

Recent papers (Hull, 1972; Cohen, 1975; Wilson, 1975) have indicated that marginal costs well in excess of $1,000 per man-rem have been spent in certain areas of nuclear safety. The question arises whether these are isolated

---

*The man-rem is a unit of measure for radiation doses to populations. It is the product of the average radiation dose (rem) to individuals and the number of persons exposed. It is usually applied in situations where large number of people receive small radiation doses.

examples or reflect general practice. If expenditures on nuclear safety are generally excessive relative to expenditures in other areas where equivalent harm might result, one might infer that objectives other than physical and biological safety are being met.

This study explores the cost-effectiveness of remoteness in the siting of nuclear power plants. The approach will be to construct a model which allows variation of distance between a hypothetical nuclear power plant (NPP) and the densely populated area (DPA) it serves. The parameters evaluated will be the adverse biological effects of potential radioactive releases and the transportation costs of electrical power.

General Considerations

Nuclear power plants have the advantage that their siting may be relatively independent of fuel supply sources. This is largely because the transport of large bulk quantities of fuel is not required as is often the case in fossil fueled plants. For example, in lignite fueled plants, fuel transportation costs are so high that plants are generally sited near a mining district. Also, large land areas for fuel storage are not required at nuclear plants.

Historically, nuclear power plants have been sited remotely from the densely populated areas where most power is used. Some reasons for this practice might include lower land costs, availability of cooling water supply and aesthetics, but the major and perhaps overriding consideration is the need to minimize the adverse consequences of potential radioactive releases to the environment, particularly those resulting from large-scale accidents.

One primary disadvantage of remote siting is the additional expense of transporting electrical power from the generating plant to population centers. In addition, remote siting eliminates the possibility of combined heat and power production for purposes such as space heating in urban areas.

The consequences of radioactive release from nuclear reactors can be categorized either as high-level, accidental releases or routine, low-level releases. The impacts of both release categories are dependent upon several factors, such as the release mechanism and meteorology, but they are also largely dependent on the population distribution surrounding the plant. The major consideration with regard to population distribution is the distance between the nuclear power plant (NPP) and the city or "densely populated area (DPA)" it serves. By evaluating the costs of siting at various distances an estimate of cost-effectiveness as a function of distance can be derived.

Population Distribution Model

To evaluate the effects of reactor siting as a function of remoteness (distance between NPP and DPA), a variable population distribution model was constructed. Our model is based largely upon demographic data from Central Europe where an increase of nuclear power installations is planned.

Specifically population data from the Federal Republic of Germany (FRG) are utilized (KFA-Juelich, 1974). The model, as illustrated in Fig. 2, consists of four regions:

1. Region I - The central city core, a five km radius circle;
2. Region II - The outer city, a five km annulus surrounding the central core;
3. Region III - The suburban area, a ten km annulus surrounding the city;
4. Region IV - An infinitely large rural area of average population density.

The assumed regional population densities, and power requirements, are shown in Fig. 2. In summary, the DPA consists of a circle of 20 km radius containing a population of 916,000 inhabitants consuming 740 MWe. The DPA is situated somewhere in a widespread rural area with an average population density of $248/km^2$. This figure is the average for the Federal Republic of Germany. Power needs are supplied by an NPP of 1,000 MW(e) capacity operating at an average load factor of 0.74. The distance between the DPA and NPP is the variable under study.

The Accident Case

The model plant (NPP) is assumed to be a 1,000 MWe light water reactor of a type analyzed in the recent U.S. Nuclear Safety Study, WASH-1400 (USERDA, 1975).

In WASH-1400 the consequences, and their probabilities, were calculated for 9 PWR and 6 BWR release categories which represent the spectrum of accidents studied. This analysis led to curves giving the probability of all consequences equal to or higher than a given value for the population distribution assumed. The average annual (expected value) population dose was determined to be 25.5 whole body man-rem for all accident categories studied. The reference accident (PWR-2, p. VI-10) which provides the basis for this study results in 3.1×10^{6} man-rem per accident and the probability of its occurrence is $5 \times 10^{-6} yr^{-1}$. Therefore, the expected value as calculated under the reference accident conditions is 15.5 man-rem/yr. This is roughly 61% of the sum of all categories and provides a basis for scaling the consequences of the reference accident to the overall accident risk for all light water reactors.

Dose Distribution

In WASH-1400, the dose distribution of the reference accident was given in Fig. VI-4 for the range of 1 to 10^{3} rem which covers the distance of about 10 to 400 km. This curve was extrapolated to closer distances from relationships given for stability category "F" meteorology conditions (Slade, 1968). The resulting dose as a function of distance is given in Fig. 3; population doses are calculated on the basis of this relationship. The dashed line in Fig. 3 indicates the assumed fenceline distance of the NPP at 300 m. No reduction in dose is assumed due to evacuation. The population dose calculations assume that the population distribution of the model remains constant.

Population Distribution Vs. Distance

The influence of variation in siting distance on population distribution is shown in Fig. 4. The solid curves give the cumulative population with distance from the reactor site as a function of distance between the NPP and DPA center. These curves are based upon the population distribution model previously discussed. It can be seen that the influence of the DPA on cumulative population distribution is almost negligible at distances greater than 50 km. At distances less than 30 km, the effect is significant.

For purposes of comparison some population distributions discussed in the WASH-1400 Report are shown by the dashed lines. These are based upon data from 66 U.S. reactors by analysis of 16 sectors radiating from each of the sites, a total of 1056 sectors being analyzed. The 1%, 10%, 50% curves denote those sectors having an average cumulative population of the indicated percentile of highest population distributions. This indicates that our model based upon European population data would fall somewhere between the 50th and 90th percentile of the analyzed U.S. nuclear reactor sites.

Population Dose Calculation

The cumulative population at various distances from the NPP can be calculated by:

$$P(r) = \int_0^r i(r)\cdot 2\pi r\cdot dr = \int_0^r p(r)dr \qquad (1)$$

where P = cumulative population (persons)

i = population density (persons/m^2)

r = distance (radius) (m)

p = population distribution (persons/m)

$$p(r) = \frac{dP(r)}{dr} = i(r)\cdot 2\pi r \qquad (2)$$

Therefore, p(r) gives the population distribution at a site in terms of people living in a unit ring. The population dose in a unit ring can be calculated by:

$$e(r) = p(r)\cdot D(r)\cdot \rho \qquad (3)$$

where e = population dose distribution (man-rem/m)

D = dose (rem)

ρ = angle involved (fraction of a circle)

The overall population dose E is then given by:

$$E = \int_0^r e(r)dr \qquad (4)$$

The probability of all angles between wind direction and a straight line between the NPP and the DPA center is assumed to be the same. The problem can, therefore, be easily solved by distributing the population at a given distance equally over the circumferences of concentric circles around the NPP.

As is shown in Fig. 5, the population distribution as defined in (2) can be calculated by:

$$p(r) = r \sum_{k=1}^{4} i_k \cdot \mathrm{arc}\beta_k \qquad (5)$$

where the β_k, if they exist, are given by:

$$\cos \beta_k = \frac{r^2 + d^2 - \ell_k{}^2}{2dr} \quad , \quad k = 1, 2, 3$$

and

$$\beta_4 = 360^\circ - \beta_3$$

Therefore, the calculations give the average of greater consequences with lower probabilities if the wind is blowing in the direction of the DPA and smaller consequences with greater probabilities if the wind does not. The calculated effects are the average of all wind directions and, therefore, independent of wind direction.

Determination of Effects

Potential adverse effects are initially calculated as total population dose (man-rem) without regard to the consequences. The number of acute deaths (near-term death resulting from very high exposure) are then determined according to the model given in WASH-1400 and shown in Fig. 6. All doses in excess of 600 rem are assumed to result in acute death while those receiving doses below 200 rem are assumed to survive for the near-term. The percentage of acute deaths at intermediate doses is linear between these values as indicated by the model. The remaining population dose to those persons whose exposure does not result in acute death may then be determined.

Aggregation of Effects

For purposes of analysis, we have aggregated acute deaths and population radiation dose (man-rem). The dose in men-rem would have the potential for causing fatal effects at some future time. To aggregate, we must identify a societal indifference level between the two adverse effects. This requires the estimation of a suitable trade-off level between acute deaths and man-rem at which one might be indifferent in the choice between the two, assuming that the choice must be made. Symbolically, the problem is to determine an equivalency factor (x) where:

$$1.0 \text{ Acute Death} \triangleq x \text{ Man-Rem}^{*} \quad .$$

Some factors which might be considered in determining a suitable indifference level are:

1. The trade-off between certain, imminent death (acute death) as opposed to potential death at some future time.

2. The trade-off between the certainty of one death as opposed to a statistical distribution of probabilities having a mean value of one death. The latter case might result in no deaths, one death,

---

[*] (The symbol $\triangleq$ will designate "is equivalent to".)

or possibly <u>more</u> than one death. In either case the expected value* would be one death. Linnerooth et al. (1975) discusses methodologies for decision-making under such circumstances.

3. Various sociological and psychological factors have been previously discussed by Rowe (1975), Otway and Pahner (1976), and Pahner (1975). Societal attitudes should be considered in such determinations. These attitudes might be evaluated by a study of revealed preferences as indicated by past societal decisions in similar areas, or by survey methods. Both approaches have certain advantages and disadvantages (Otway and Cohen, 1975).

We cannot rigorously determine a suitable indifference level; however, for these calculations we will assume that one acute death is equivalent to something between 10^3 and 10^4 sub-acute man-rem. This estimate is based on the BEIR Committee Report, and other recent studies (NRC-NAS, 1972; USEPA 520/4, 1974) which indicate roughly 10^{-4} to 10^{-3} potentially fatal health effects per man-rem. Calculations will be made at both extremes of this range in order to bound the "proper" value and to test the sensitivity of the results to the assumed equivalency factor.

---

*The expected value (E.V.) is the sum of the products of the probability of particular results given the occurrence of an event, times the number of events. For example, if the probability of a fatal effect as the result of one man-rem is 10^{-3}, then the E.V. for 1,000 man-rem is one fatal effect.

Calculational Results

Calculations, based upon the occurrence of the reference accident in WASH-1400 and the population distribution model previously discussed, were performed for various distances between the NPP and DPA. Fig. 7 gives the results for $r = \infty$ which constitutes the "base case" where there is no DPA, and the NPP is assumed to exist on an infinite plane with a uniform population density of $248/\text{km}^2$. Fig. 7 shows the incremental acute deaths and incremental man-rem as a function of distance from the NPP. Incremental man-rem are expressed in man-rem/m and may be considered as the quantity of man-rem in the one meter annular ring at the indicated distance as calculated by equation (3). The integral under the curves, therefore, gives the total man-rem and acute deaths which would occur under the assessment conditions.

These integrations indicate 5936 acute deaths plus 21.3×10^6 man-rem would result under "base case" conditions. These figures can then be multiplied by probability for occurrence for the reference accident ($5 \times 10^{-6} \text{yr}^{-1}$) which yield the expected value in terms of man-rem and acute deaths per year. Since the reference accident accounts for about 61% of the total accident risk, one can determine the overall risk for light water reactors (average of PWR and BWR) for base case conditions to be 0.049 acute deaths and 175 man-rem per year.

Similar calculations were performed including the DPA at various distances from the NPP. Fig. 8 gives the results of calculations for the distance of 10 km between the NPP and DPA. Fig. 9 gives the results for a distance of 20 km. In both figures the base case curves are also given so that the net effect of siting the NPP at the indicated distance from the DPA may be discerned as the difference in area under the two curves.

Table I gives a summary of results of reference accident calculations for various distances. Included for comparison is the total population dose in man-rem calculated without separation of exposures resulting in acute death.

Aggregated Dose

The result of aggregating the effects of acute death plus population dose into "equivalent man-rem ($\hat{=}$ Man-Rem)" are given in Table II. Results are presented for assumed equivalency factors of 10^3 and 10^4 Man-Rem/acute deaths. It can readily be seen that the results are quite sensitive to this factor. Perhaps future work will bring new insights as to what a proper or acceptable factor should be. For the present, however, discussions will be limited to results calculated at the assumed extremes of its range.

Routine Releases

The effects of low-level routine releases as a function of population distribution may be estimated by scaling from the accident dose model. To estimate these effects the following assumption are used:

1. Population Distribution: Same as for accident calculations;
2. Average Fenceline Dose: 10.0 mrem/yr.;
3. Meteorology: Stability classification - "C"
   Wind velocity - 2.5 m/sec.
   Sector angle - 20^o.

The results are given in Table II. It should be noted that total population doses resulting from continuous routine releases are a small fraction of expected value doses resulting from potential accidents.

Power Transmission Costs

As a basis for estimating power transmission costs, data from KFA Jülich (1974) will be utilized. Fig.10 summarizes data from this report for energy transport costs in the FRG. For purposes of this report it will be assumed that electrical energy will be transmitted from the NPP to the center of the DPA by a 380 KV two-system transmission line. Costs for sub-system transmission (distribution within and around the DPA) will not be considered. From the data in Fig. 10 a value of 1.8 DM[*]/G Cal·100 km will be assumed. It will be further assumed that this cost will scale linearly with distance. This latter assumption is somewhat crude but conservative since, in fact, as one approaches the DPA, transmission cost per unit distance increases somewhat due to incrased land values and other considerations. Under the above assumptions we estimate the cost for this long distance power transmission to be 10^5DM/km-yr (4 x 10^4 \$/km-yr). This estimate includes capital costs as well as maintenance and operational costs.

Effects of Remote Siting

Total aggregated population dose effects in terms of expected value equivalent man-rem are plotted as a function of NPP-DPA distance in Fig. 11. The upper curve assumes an equivalency factor of 10^4 man-rem per acute death and the lower curve assumes 10^3. The dashed line at the 20 km distance indicates the limit of the DPA.

---

[*] 1 Deutsch Mark = about 0.40 US dollar.

It can be noted that the effects decrease with distance as might be expected. However, at distances beyond approx. 30 km the net reduction in consequences per unit distance is essentially negligible. Also, both the relative and absolute effects are greatly influenced by the assumed equivalency factor between acute deaths and man-rem.

To evaluate the marginal costs of remote siting, the net effects are shown in Fig. 12. These curves give only the effects due to the presence of the DPA at the indicated distance since base-case effects have been subtracted. On the same graph, power transmission costs are plotted. These, in turn, allow a comparison of incremental costs per unit distance against population dose effects. The marginal costs in terms of cost per unit population dose reduction as a function of distance between the NPP and DPA is given in Fig. 13. As can be seen from these curves, the marginal costs outside of the limits of the DPA increase greatly with siting distance. At distances in excess of 50 km, the equivalency factor is not important since no additional acute deaths occur at these distances. At closer distances, the equivalency factor has a significant effect upon the results. However, even using the 10^4 man-rem/acute death factor, we find the marginal cost of remote siting to be higher than the 1,000$/man-rem guideline value at almost all distances.

Discussion

The rationale for the siting of nuclear reactors is quite complex, involving the consideration of several factors. It is recognized that the minimization of potential public exposure to radioactivity is but one factor; however, it is probably the most important single factor considered which is not directly related to power production. Indeed, in many cases it is the overriding consideration in site selection.

This report has attempted to gain an insight into the cost-effectiveness of remote siting as a means of minimizing potential radiation exposure. A simplified approach was used in which the reduction in population dose as a function of increasing distance between the nuclear power plant and the densely populated area it serves is evaluated against the resulting increase in power transmission cost. Population distribution may vary greatly from site to site; in practice, each case should be considered separately. The model also considered only power transmission costs as an economic variable; other advantages, such as the use of secondary heat, were not included.

A difficult problem is the consideration of high-level radiation exposures which result in acute deaths; incorporation of such consequences into the quantitative analysis cannot be done rigorously. The method used was the assumption of an equivalence value between population dose in man-rem and acute deaths. If the values assumed in this report are not acceptable, the methodology can still be used with other values.

Concluding Remarks

These calculations indicate that, based upon the guideline value of $1,000/man-rem suggested by the USNRC (1975), remote siting of nuclear power facilities would not seem to be a cost-effective way to control potential radiation exposures. This statement must be interpreted cautiously, however, because it is based upon the results of an idealized model.

The important point is that only the biological effects of potential radiation exposure were considered. Although remote siting would not seem to be cost-effective using this criterion, there are certainly other factors involved. Some of these factors may include the availability of cooling water, acceptable geological conditions, etc. In addition, we should not overlook the importance of the psychological and sociological levels of risk referred to in the introduction (Otway and Pahner, 1976). If these factors were to be considered remote siting might be justified.

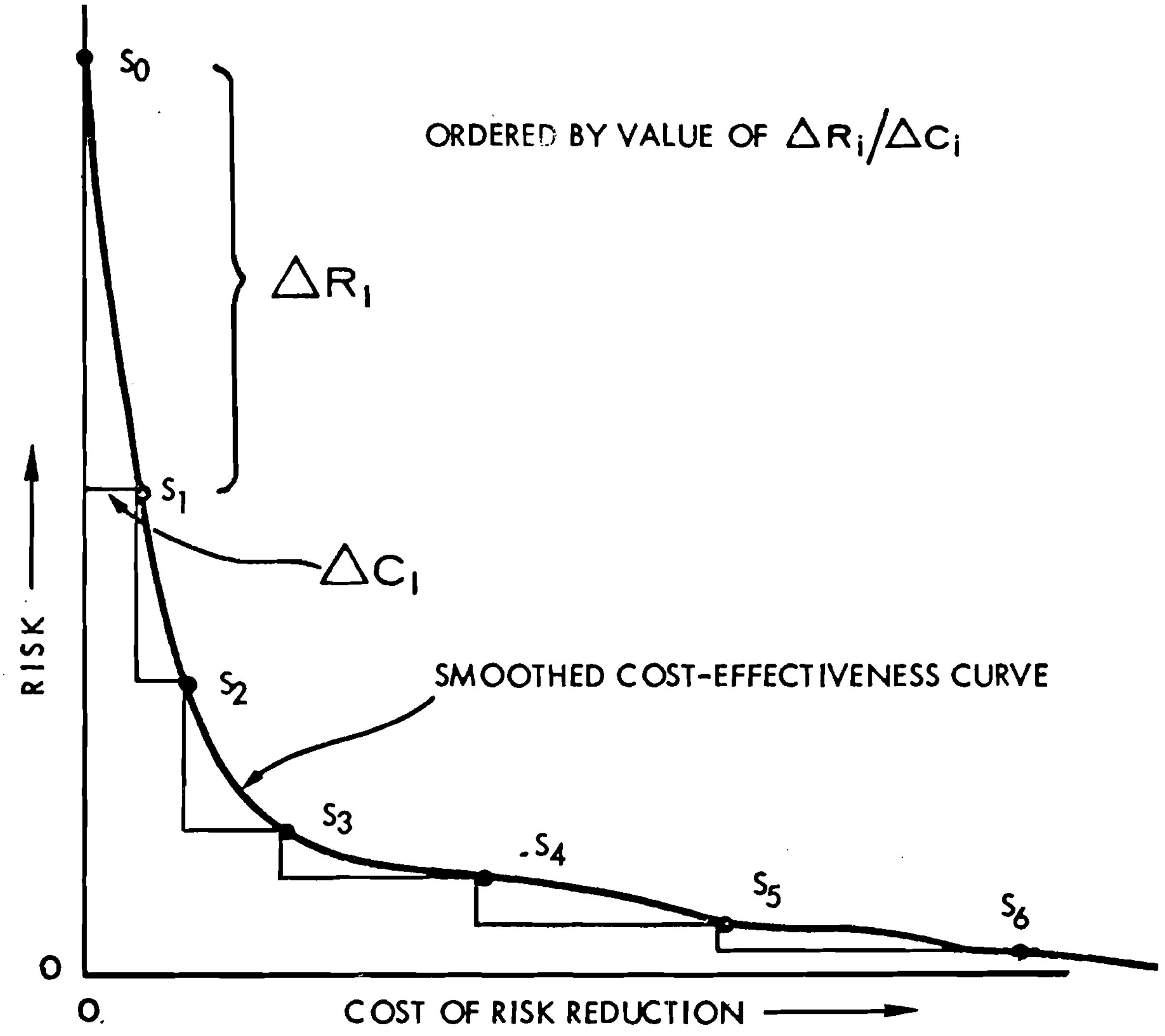

Figure 1. Cost-effectiveness of risk reduction.

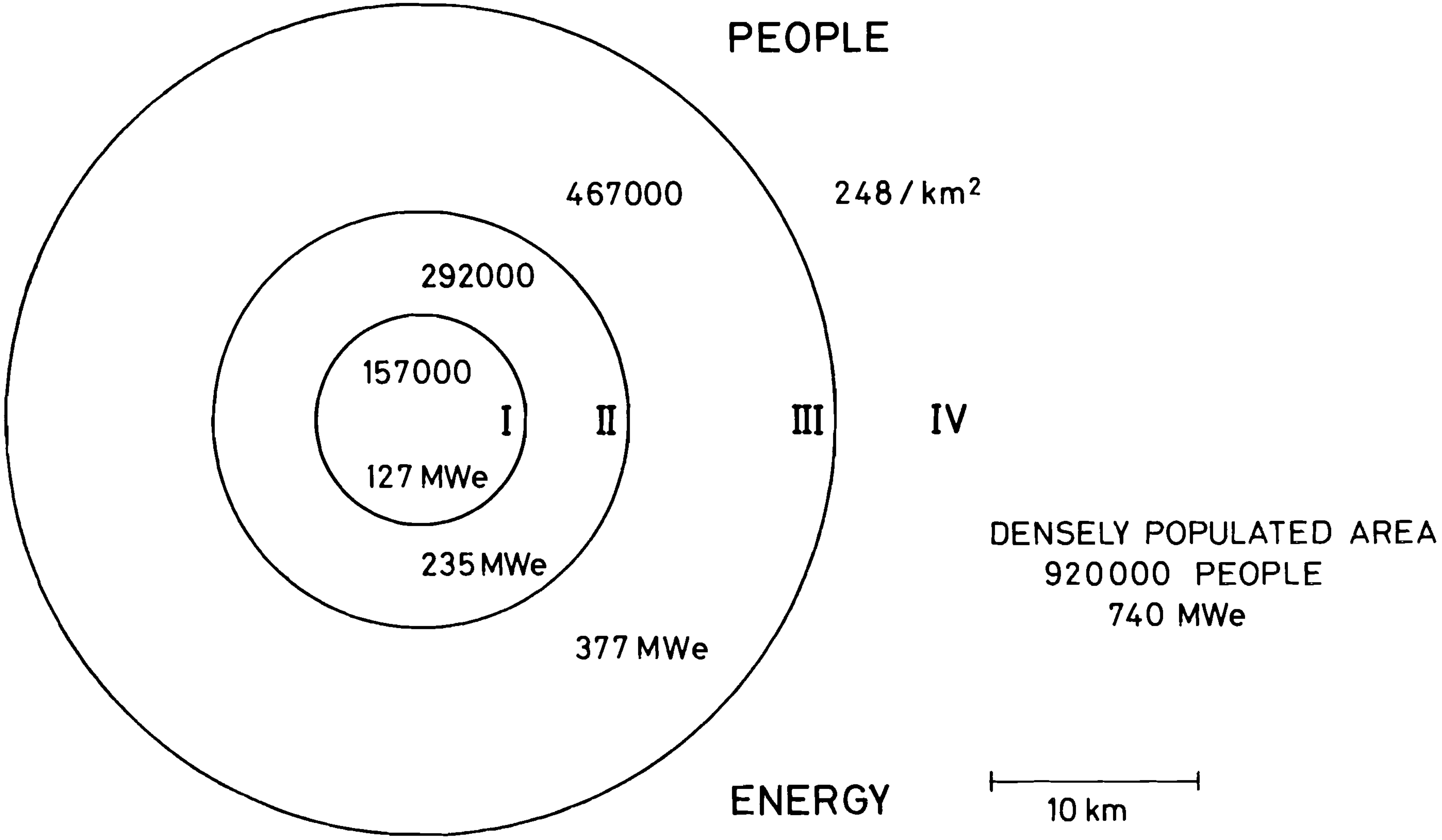

Figure 2. Model population distribution.

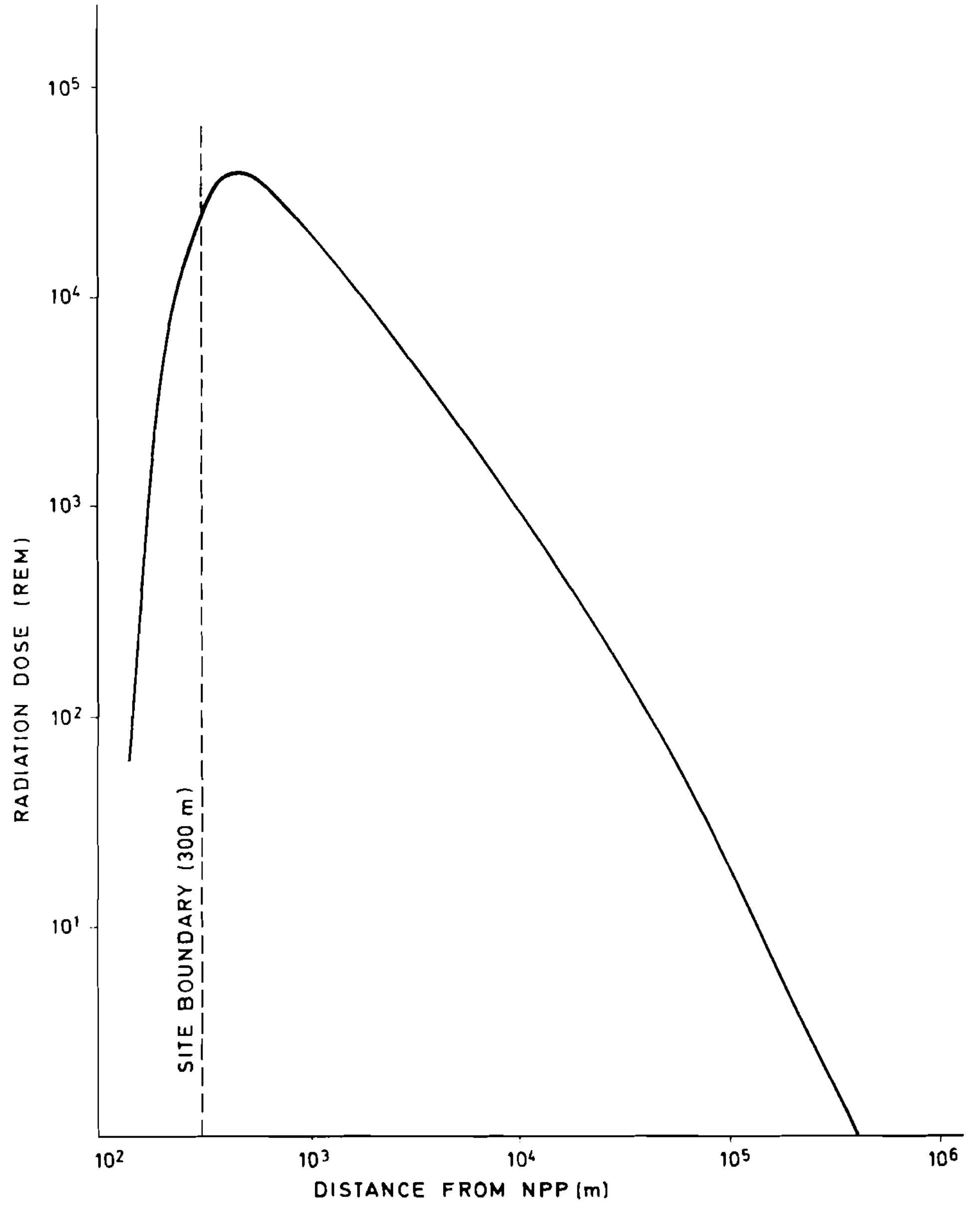

Figure 3. Radiation dose vs. distance for reference accident.

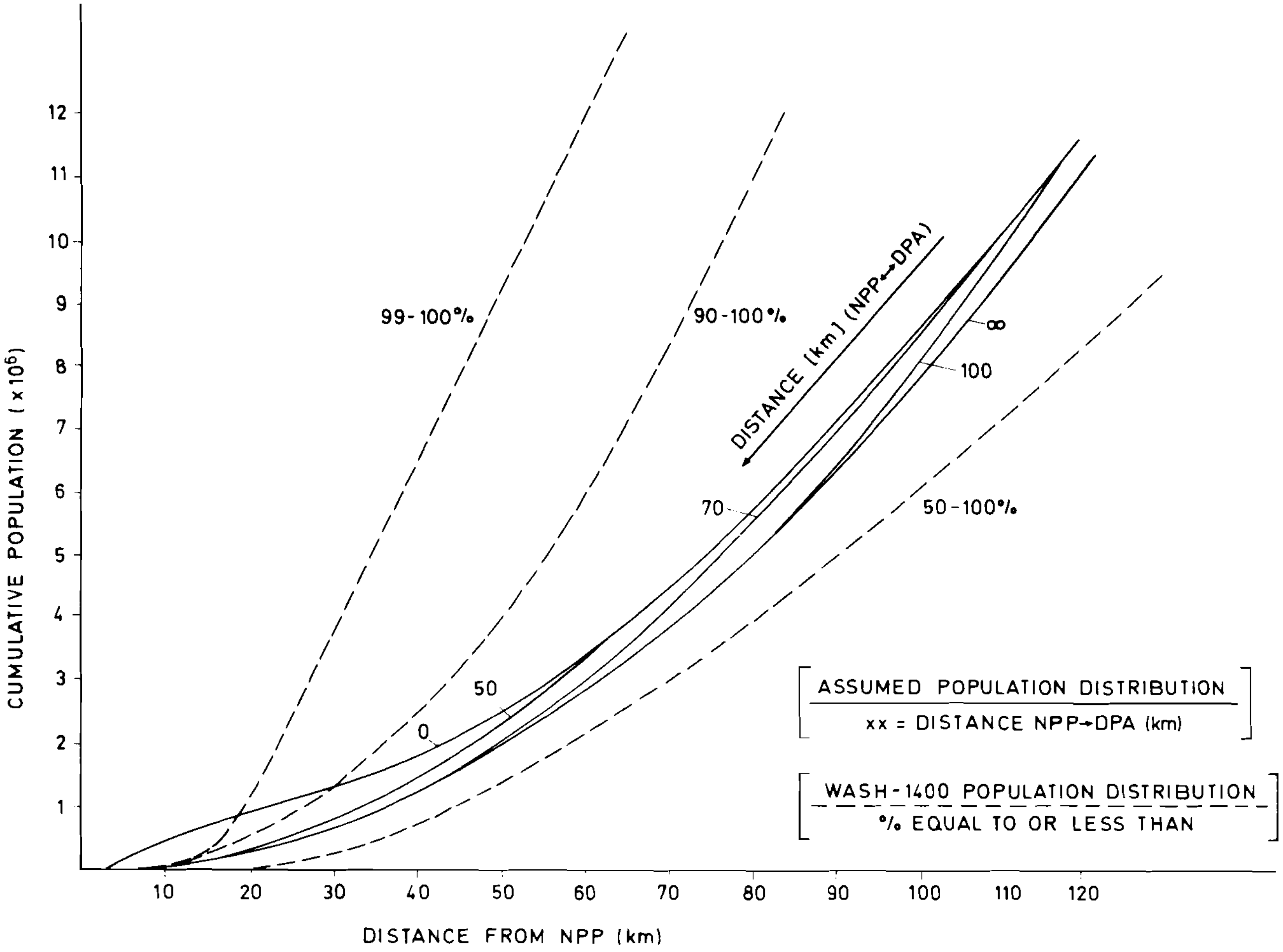

Figure 4. Cumulative population distribution for various sites (model area and WASH–1400)

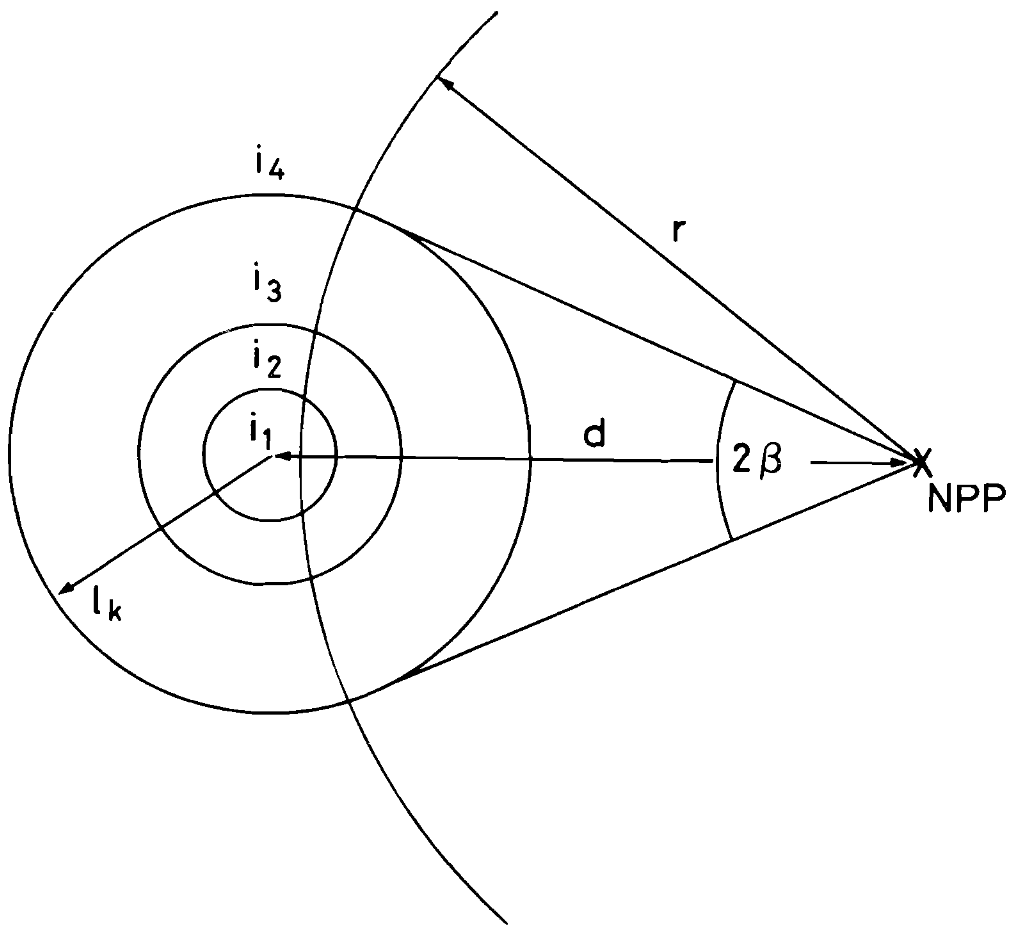

Figure 5. Notation of calculational model.

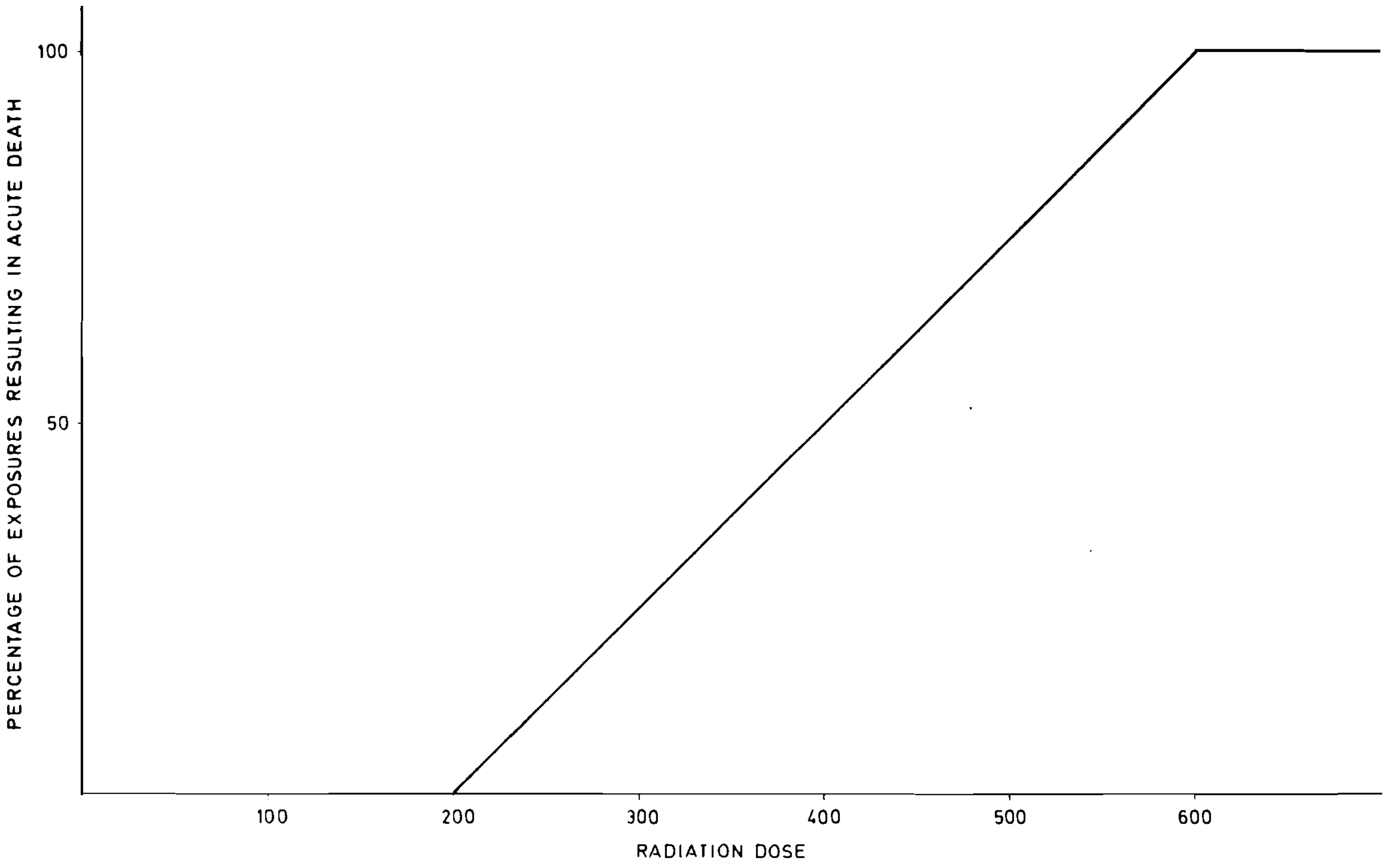

Figure 6. Effects of radiation exposure.

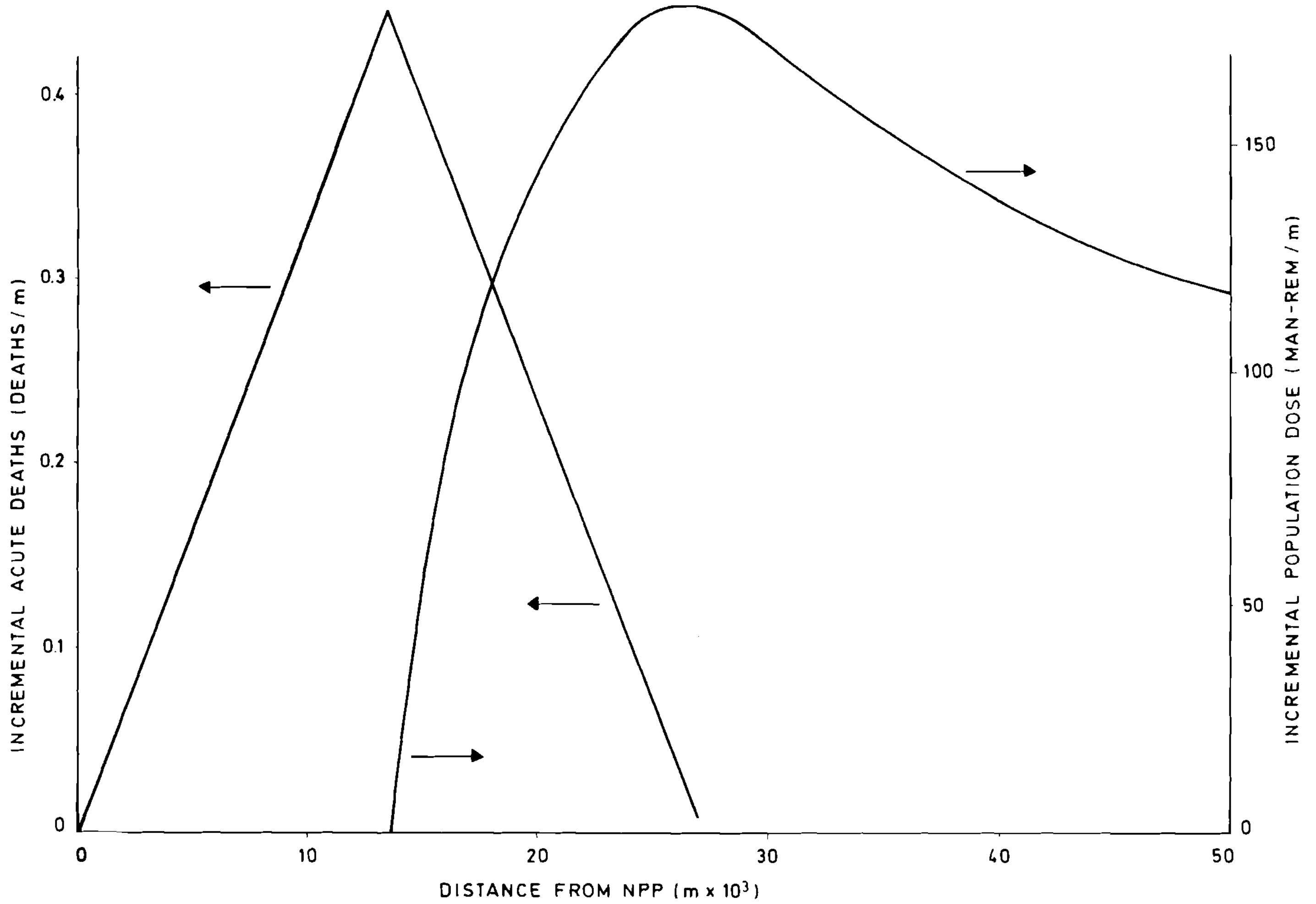

Figure 7. Incremental effects of the reference accident (average population distribution).

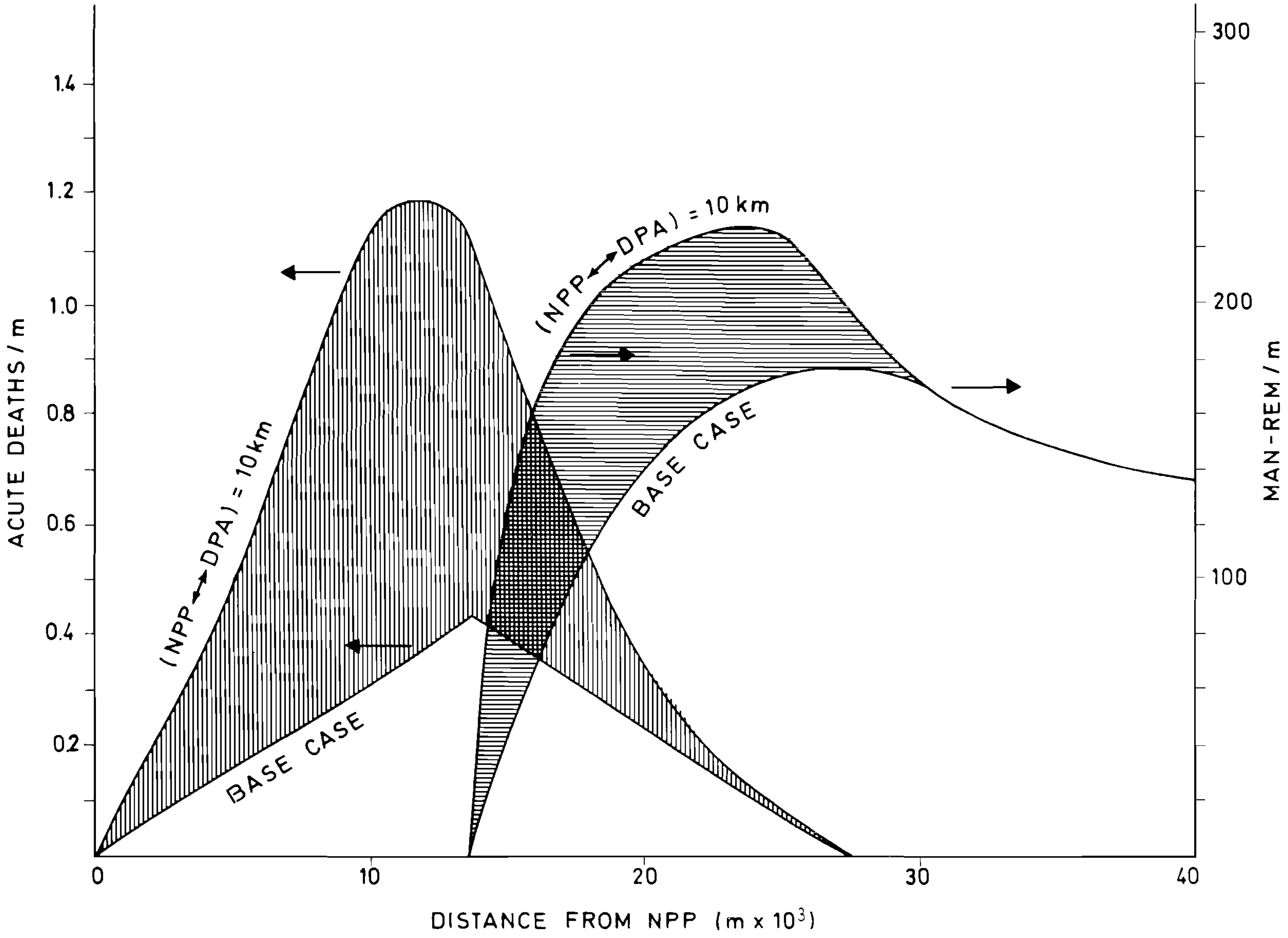

Figure 8. Radiation effects for a siting distance (NPP ⟷ DPA) of 10 km.

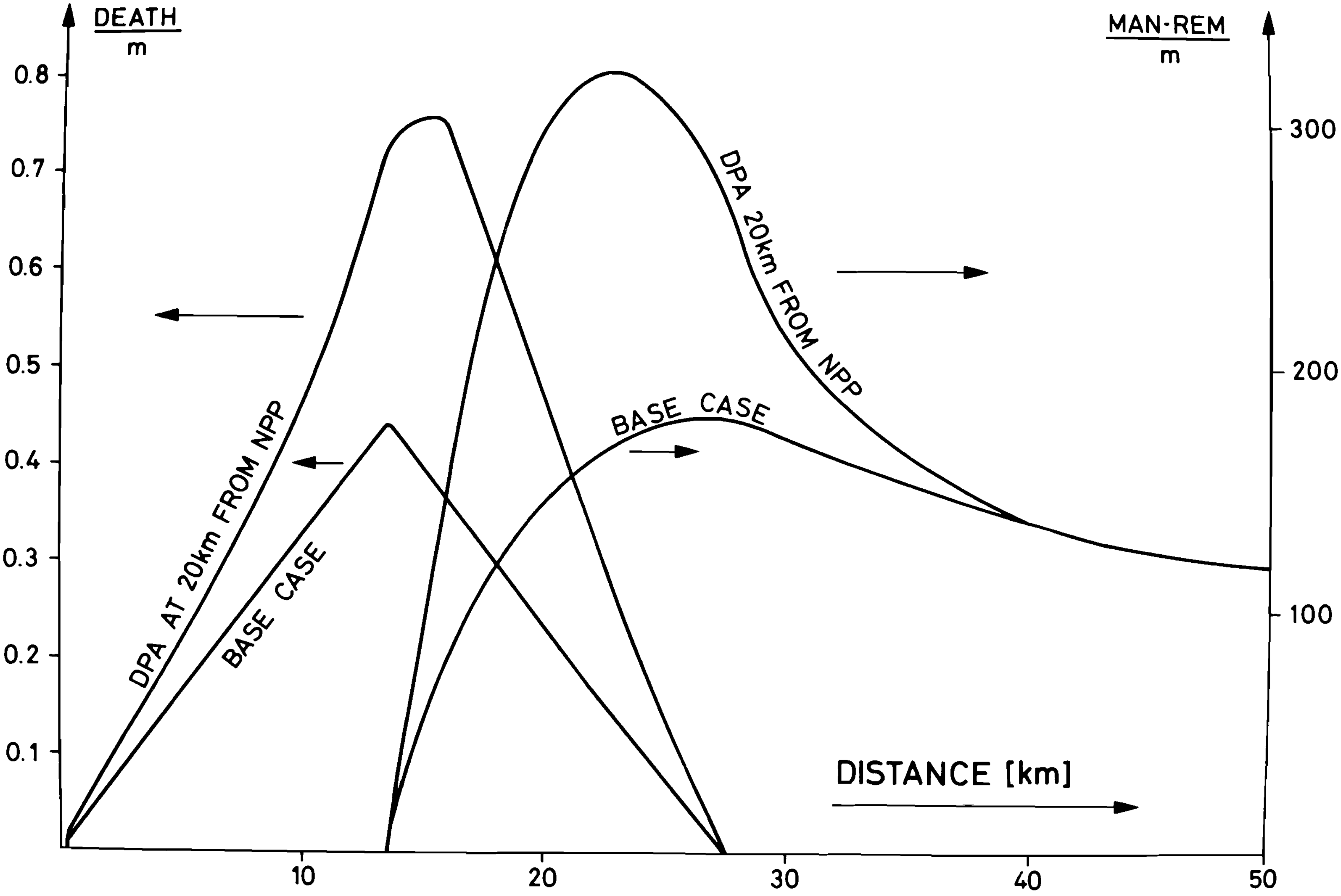

Figure 9. Radiation effects for a siting distance (NPP ⟷ DPA) of 20 km.

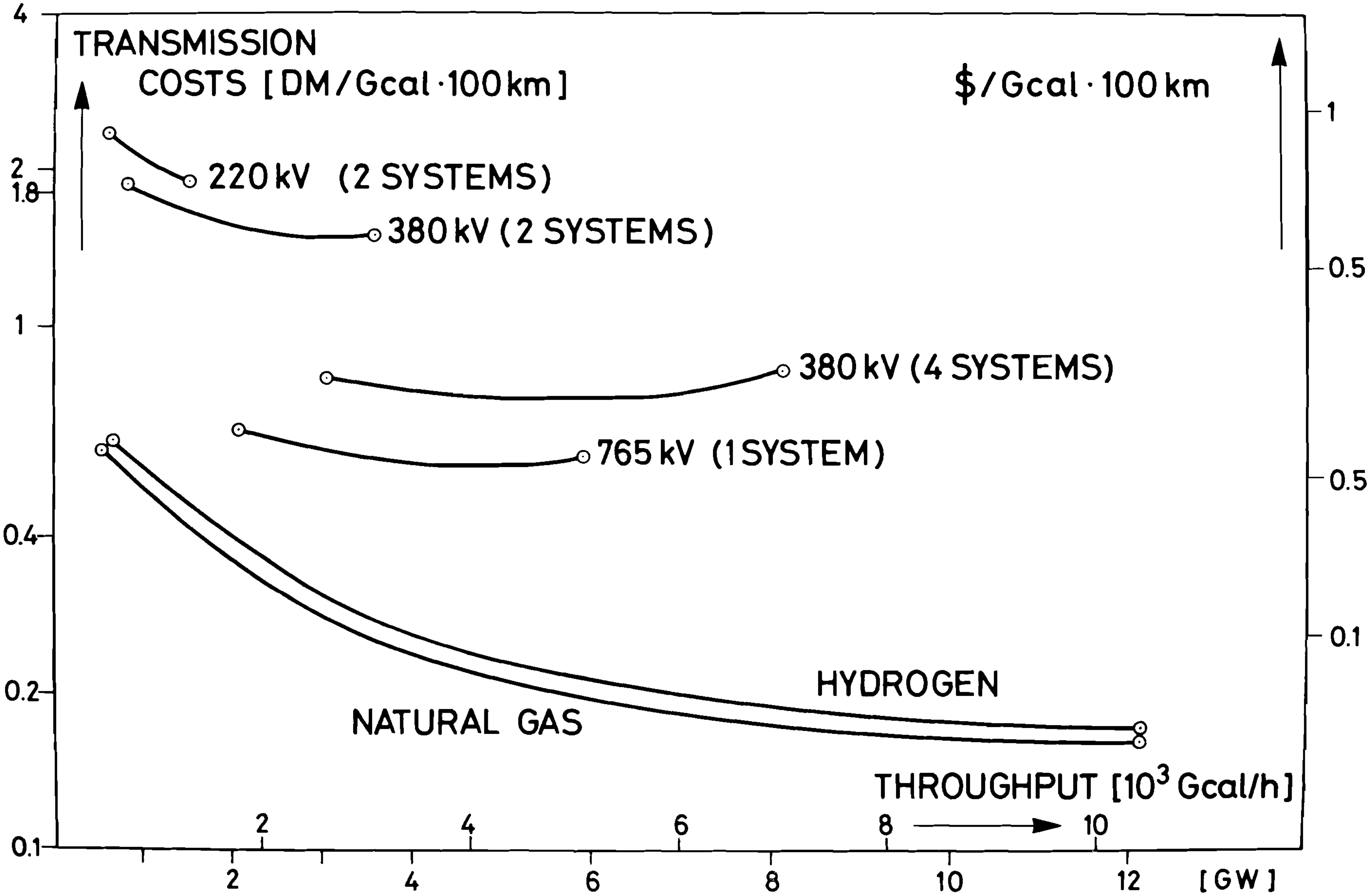

Figure 10. Energy transportation costs (KFA–Juelich, 1975).

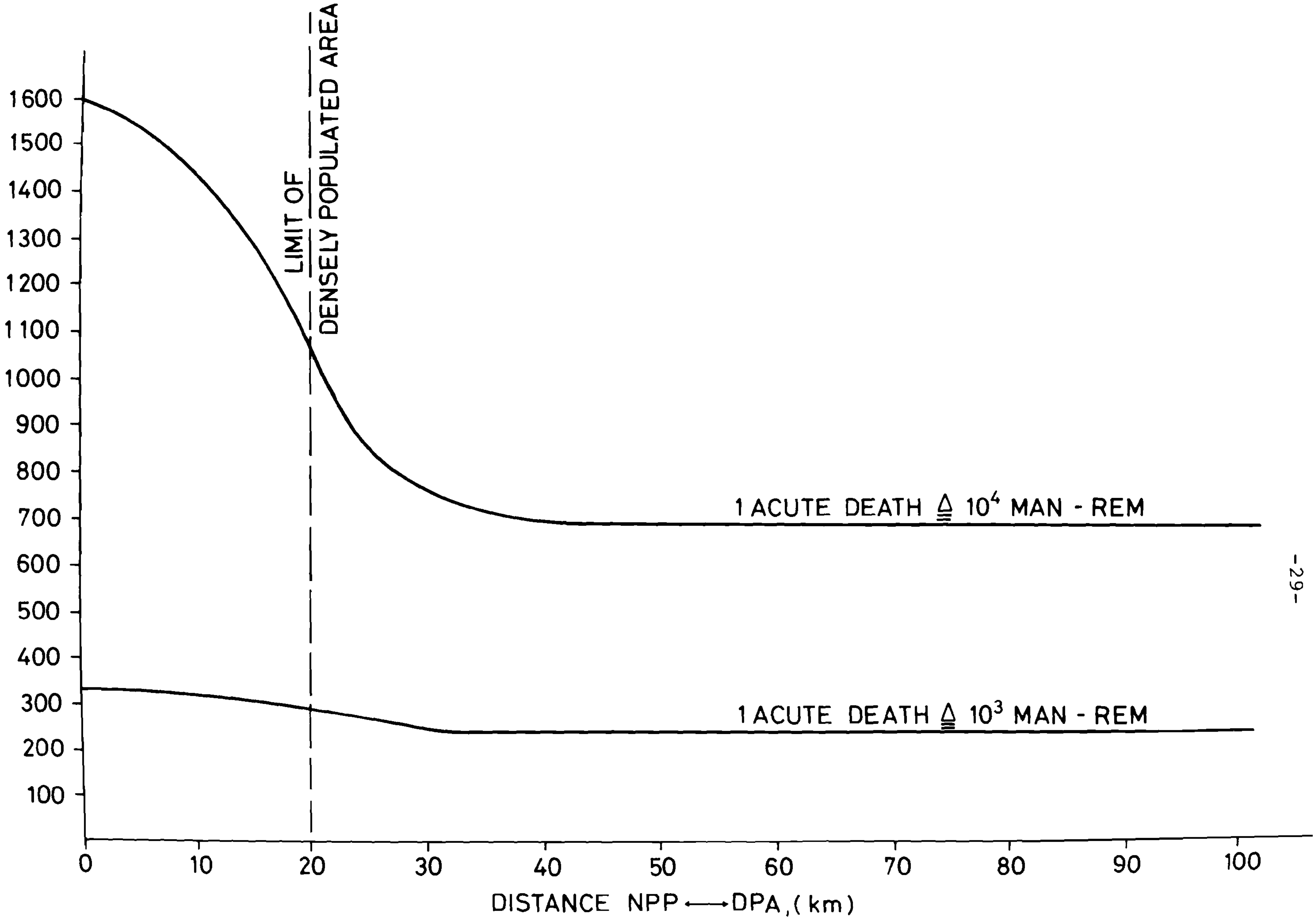

Figure 11. Expected value of population dose vs. siting distance (aggregated effects)

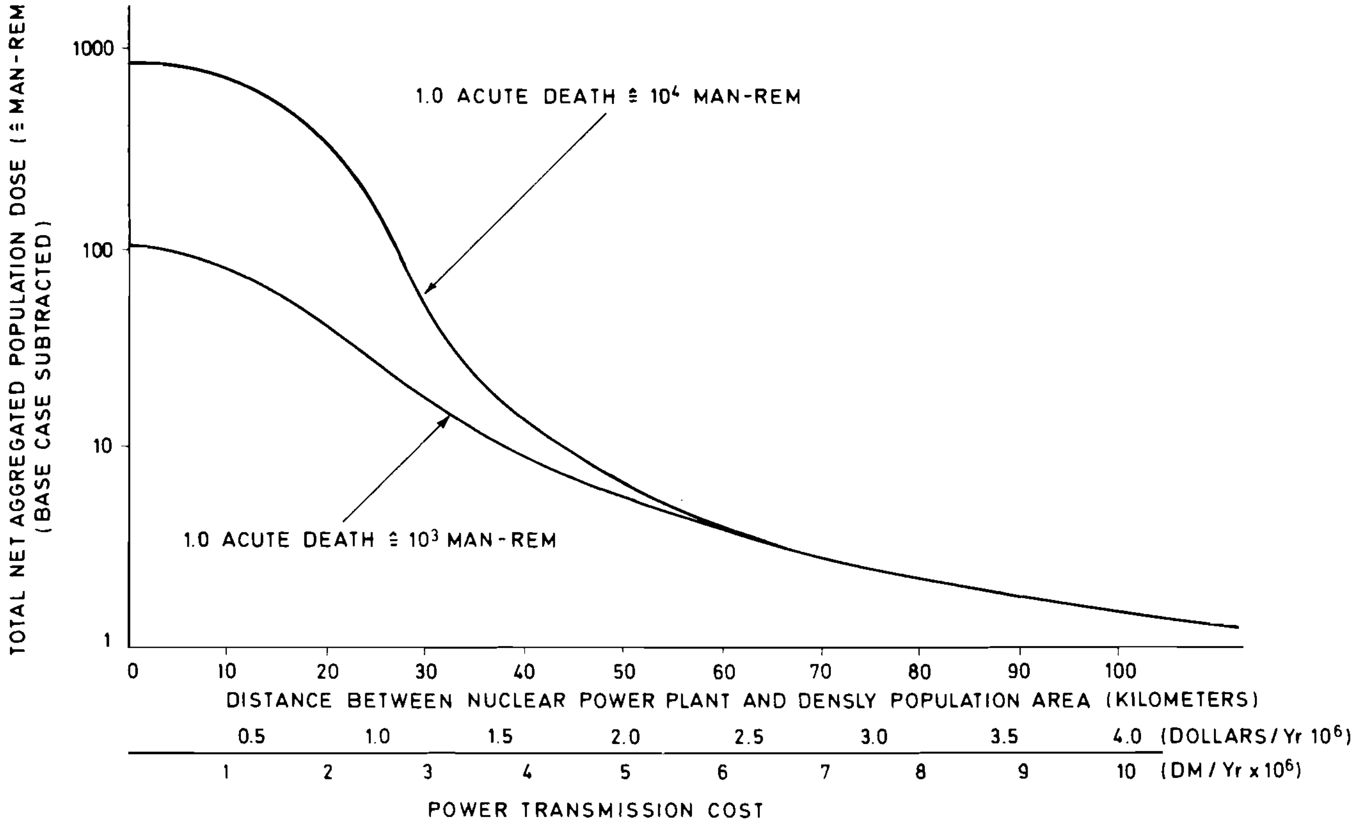

Figure 12. Net effects of remote reactor siting.

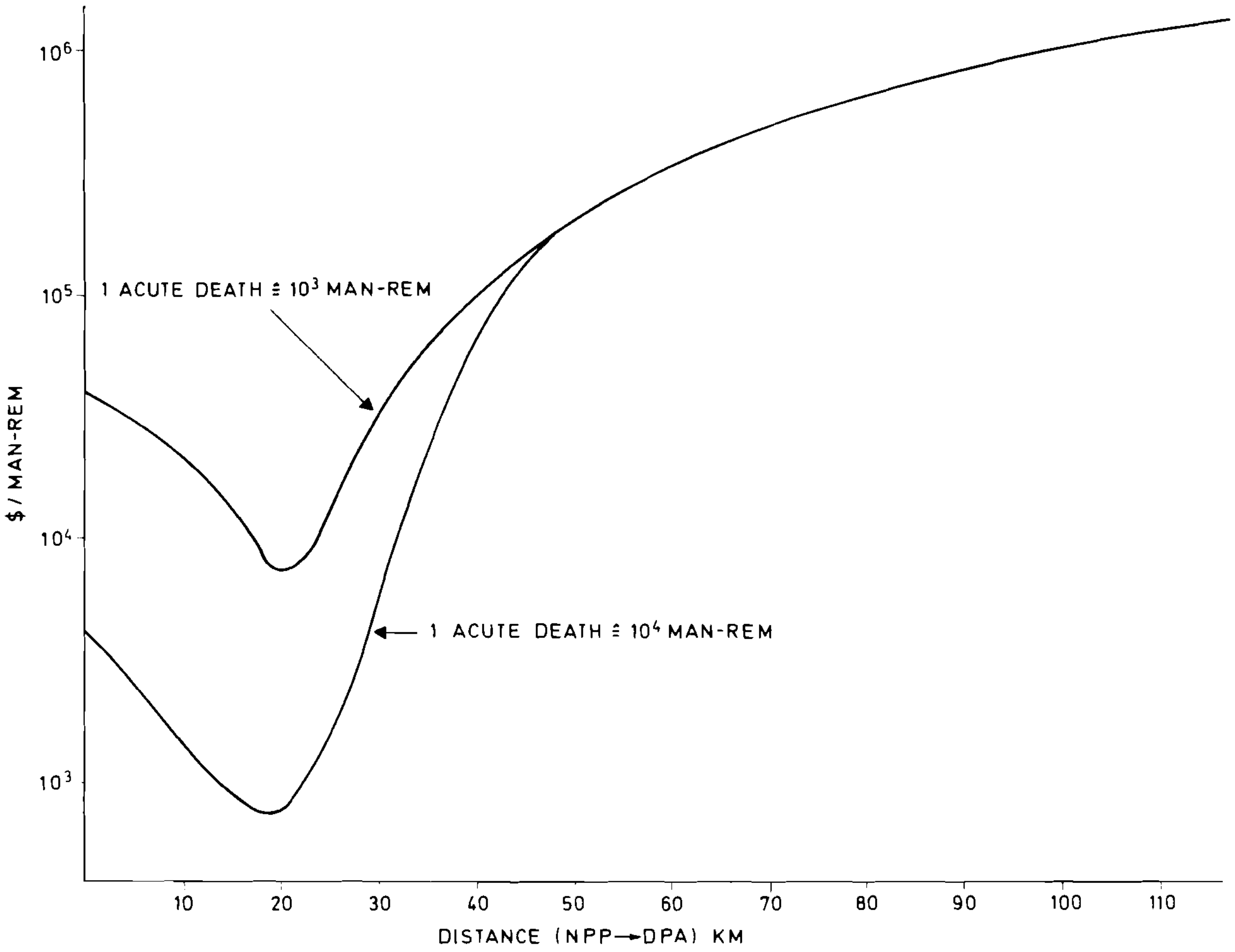

Figure 13. Marginal costs of risk reduction for remote reactor siting.

TABLE I

Summary of Effects of Reference Accident[1] at 1000 MW(e) Light Water Reactor

DISTANCE[2] (km)	EFFECTS PER ACCIDENT			EXPECTED VALUE[5]	
	TOTAL POPULATION DOSE[4] (Man-rem x 10^6)	ACUTE DEATHS	RESIDUAL POPULATION DOSE (Man-rem x 10^6)	ACUTE DEATHS / Yr.	MAN-REM / Yr.
	29.6	5936	21.3	0.0487	175
100	29.9	5936	21.5	0.0487	176
70	30.2	5936	21.8	0.0487	179
50	30.4	5936	22.1	0.0487	181
30	31.7	6526	23.0	0.0535	189
20	35.6	10238	23.2	0.0839	190
10	44.1	15274	22.1	0.1252	181
0[3]	58.6	17231	21.9	0.1412	180

Notes:

[1] Parameters of Reference Accident as discussed in WASH-1400 (1974).

[2] Distance between Nuclear Power Plant and Center of DPA (Densely Populated Area).

[3] Assumes NPP located at Center of DPA.

[4] Population Dose as calculated without regard as to whether exposure results in acute death.

[5] Reflects accident probability of 5 x 10^{-6} accidents/yr. plus assumption that reference accident risk constitutes 61% of overall average risk of LWR accidents.

TABLE II

Aggregated Effects of Radiation Releases at Remotely Sited 1000 MW(e) Nuclear Power Plant

Distance	Total Accident Effects[2] (≙ Man-Rem/Yr.)		Routine Releases (Man-Rem/Yr.)	Net Effects[3] (≙ Man-Rem/Yr.)	
	$\frac{10^3 \text{ Man-Rem}}{\text{Acute Death}}$	$\frac{10^4 \text{ Man-Rem}}{\text{Acute Death}}$		$\frac{10^3 \text{ Man-Rem}}{\text{Acute Death}}$	$\frac{10^4 \text{ Man-Rem}}{\text{Acute Death}}$
∞	224	662	5.8	-	-
100	225	663	5.9	1.1	1.1
70	228	666	5.95	4.2	4.2
50	230	668	6.0	6.2	6.2
30	243	724	6.3	19.5	62.5
20	274	1029	7.0	51.2	368.2
10	306	1433	8.7	84.9	773.9
0	321	1592	12.0	103.2	936.2

Notes:

[1] Distance between Nuclear Power Plant (NPP) and Center of Densely Populated Area (DPA).

[2] Total aggregated effects of acute deaths plus residual man-rem expressed in equivalent man-rem/yr. Equivalence factor as indicated.

[3] Net Effects = Accident Man-Rem + Routine Release Man-Rem - Base Case (∞). These are net effects due only to the presence of DPA at the indicated distance. Equivalence factor as indicated.

REFERENCES

Cohen, J.J. Cost-Effectiveness of Release Prevention Controls for Tritium and Krypton-85. Proceedings of the IAEA/NEA Symposium on the Combined Effects on the Environment of Radioactive, Chemical and Thermal Releases from the Nuclear Industry. IAEA-SM-197/17; STI/PUB 404, Stockholm, June 2-6, 1975.

Gros. J.G. A Paretian Approach to Power Plant Siting in New England. Ph.D. Dissertation, Harvard University, 1974.

Hull, A.P. Reactor Effluents: As Low as Practicable or as Low as Reasonable. Nuclear News 15 (11), 1972.

KFA Juelich. Programmstudie Sekundaerenergiesysteme. Juel-1148-SE, December, 1974.

Linnerooth, J. The Evaluation of Life-Saving: A Survey. IIASA RR-75-21, Laxenburg, Austria, International Institute for Applied Systems Analysis, July, 1975.

Linnerooth, J., and Otway, H.J. Methodologies for the Evaluation of Mortality Risk (in press).

NAS·NCR. The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. National Academy of Sciences, Nat. Research Council, Washington, D.C., November, 1972.

Otway, H.J. and Pahner, P.D. Risk Assessment. To be published in the April 1976 issue of Futures, 1976.

Pahner, P.D. The Psychological Displacement of Anxiety: An Application to Nuclear Energy. Laxenburg, Austria, International Institute for Applied Systems Analysis, 1976 (in press).

Slade, D.H., ed. Meteorology and Atomic Energy. TID-124190, July, 1968.

USAEC. Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low as Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents. January, 1973.

USAEC. Comparative Risk-Cost-Benefit study of Alternative Sources of Electrical Energy. WASH-1224, December, 1974.

USAEC. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400, August, 1974.

USEPA. Environmental Analysis of the Uranium Fuel Cycle. Parts I, II, and III, EPA-520/9-73, Washington, D.C., October, 1973.

USEPA, Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry. EPA-520/4-002, Washington, D.C., February, 1974.

USNRC. Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents. Proposed Regulations to Title 10, Part 50, Federal Register Vol. 40, No. 87, May, 1975.

Wilson, R. The Costs of Safety. New Scientist (274), October 30, 1975.