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HOW SAFE IS "TOO" SAFE?

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PREFACE

Decisions on future energy strategies have to be based on a comparison of their risks and benefits. The risk of a given technology is variable and may be further reduced by additional safety measures which, however, usually incur additional expenditures.

Cost-effectiveness analysis is one methodology which can be used to address the question of "how safe is safe enough" and which level of risk is "as low as reasonably achievable"(known as the "ALARA" approach). This paper introduces a method which does not limit the analysis of cost-effectiveness of additional safety equipment to a specific facility, but provides a systems approach which allows consideration of the total economic system of a country.

ABSTRACT

Safety expenditures usually follow the law of diminishing returns, i.e. marginal cost of risk reduction increases progressively with the level of safety achieved. Though the risk of a facility can in principle be reduced below any given value it is not possible to reduce the risk to zero, to reach "absolute safety". This poses the question about the level at which further risk reduction is no longer cost-effective.

This paper demonstrates that these considerations are only valid if a system element (e.g. a plant) is analysed. When the total economic system is considered another source of risk has to be added: the occupational and public health effects associated with the production of safety equipment.

Using some simplifying assumptions and data from national economic input-output tables and occupational accident statistics it is possible to derive a linear relationship between the cost of the safety equipment and the health effects caused by its production. When this relation is combined with the exponential risk-cost relationship of the facility under consideration, the combined curve exhibits a minimum value where the health effects of producing the safety feature equals the health effects avoided when it is installed. It is shown that if one probable health effect at some unknown future time is avoided by use of $ 30 million of safety equipments, one equivalent health effect will certainly occur at the present time. The problem of balancing these two effects is a societal decision which is not addressed herein.

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INTRODUCTION

Any activity of man involves some risk to his life or health. Though it is possible to reduce these risks, it is not possible to reach the "zero risk" or "absolute safety" that is often demanded. Once this general fact is recognized, it becomes necessary to decide which risks are acceptable and to what extent risks have to be reduced.

In the past, exposures to industrial risks were gradually reduced until an acceptable level was reached. Modern technological systems are capable of hypothetical hazards so large that determination of the appropriate level on the basis of experience is not acceptable. It is necessary to use predictive methods to estimate these risks. Risk assessment (Otway et al. 1977) methodology implies the need for the formal (systematic) evaluation of estimated risks using some defined acceptability criteria.

There are three primary methods for this evaluation:

Putting Risks into Perspective

This approach has been most widely used and is based on the assumption that a new risk is acceptable if it does not exceed present levels of already accepted risks (Reactor Safety Study 1975) and it has been suggested that a new technology should present a risk which is at least a factor of 10 lower than well-established technologies (Higson 1978, Tattersall et al. 1972). This approach poses the problem of the comparability of risks from very different sources (e.g. airplanes with chemical plants) and does not consider the value of a technology to society.

Comparisons of Risks and Benefits

Once it has been established that a risk is not out of proportion with other similar risks, a common basis for a comparison of technologies can be achieved by normalizing their risks to a common measure of benefits which they can provide to society. This approach implicitly assumes that for a higher benefit a higher level of risk should be acceptable (Inhaber 1978, Black et al. 1978)

Cost-Effectiveness of Risk Reduction

The above-mentioned methods allow for a comparison of options, however, they do not indicate whether these levels of safety are adequate, or whether the risk should be reduced even further. Safety philosophy requires risks to be reduced to levels "as low as reasonably achievable" (known as the "ALARA" approach). Cost-effectiveness procedures may be used for this problem and some relevant aspects are discussed below.

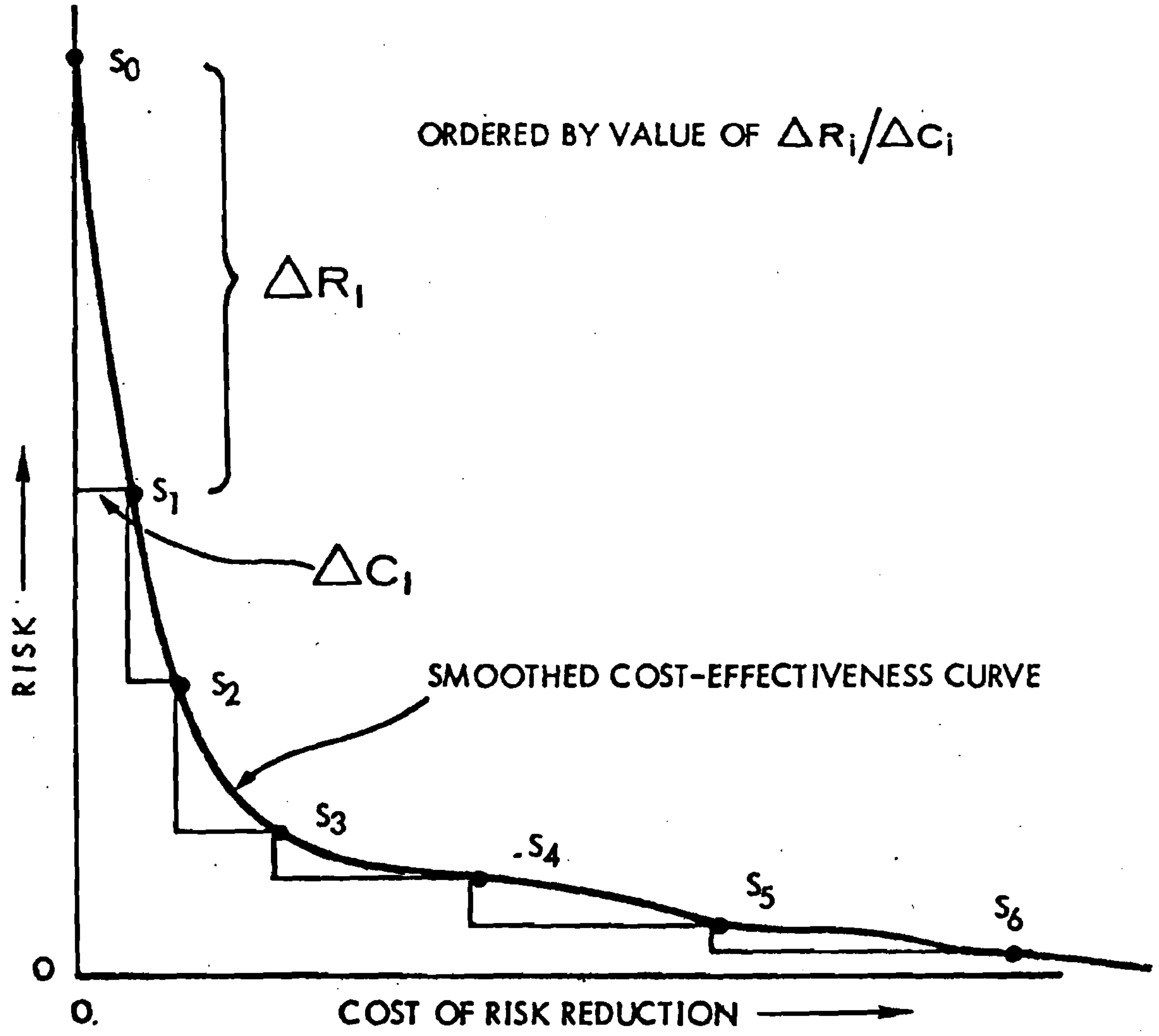
COST-EFFECTIVENESS OF RISK REDUCTION

It has been assumed that safety expenditures generally follow the law of diminishing returns (Rowe 1977). The general relationship of this law is outlined in Figure 1 and has been recognized in several case studies (Roy and Ciceri 1978, U.S. Environmental Protection Agency 1976). Two main conclusions can be drawn from this diagram:

1. the marginal cost of risk reduction increases with the level of safety achieved; and

2. for any given safety level it is possible to reduce the risk even further, however, it is not possible to reduce the risk to zero.

Society is, however, constrained by the limited resources at its disposal and this poses the question about "how safe is safe enough?" (Fischhoff et al. 1978) The two observations from Figure 1 imply that "safe enough" is always determined by an arbitrary compromise between the two objectives of the efficient use of limited resources (minimizing costs) and achieving the highest safety (minimizing risk). Since the units of these objectives are money and health effects respectively, any such solution implies a specified expenditure per unit of risk reduction. In particular, the use of mortality risk leads to a monetary value being assigned to a human life (Strictly, determination of the value of a human life would be only one method of deriving an appropriate expenditure for risk reduction. In general, the expenditure will be defined by the societal consensus over the resource allocation for safety. Although this value will be quoted in dollars per life saved, it will not in fact be the "value of human life".) Such values can be compared for safety expenditures in various risk areas. It has been suggested (Linnerooth 1977) that a value of $ 300,000 per life should be



Source: Rowe (1977).

Figure 1. Cost-effectiveness of risk reduction.

chosen which could be weighted by some factors describing specific attributes of the actual situation. Such a procedure implies the objective that safety expenditures should be spent most cost-effectively on various technologies but does not answer the more general question of "how safe is safe enough?"

In contrast to the above approach, this paper will suggest that a practical limit to risk reduction does exist. The typical curve shown in Figure 1 relates to one particular technological facility and the fact that such a plant or technology is only one element in the total economic system is overlooked. Therefore, the fact that the safety measures themselves cannot be produced without risk is also neglected. Thus it follows that Figure 1 applies only to the system element (e.g. a plant). If the total system is considered, however, the curve from Figure 1 will actually have a minimum risk and this will be described in more detail below.

RISK IDENTIFICATION AND QUANTIFICATION

The term "risk" is used in a variety of contexts, generally to describe the possibility of negative outcomes. But its precise meaning is usually not defined (Schaefer 1978). "Risk" is used here to mean some measure of the detrimental effects that may be associated with a technology. The technical data that describe these risks may be classified into:

- events and their probability of occurrence (e.g. emissions, accident sequences, wind direction, etc.)
- consequences of these events (e.g. health effects, property damage, etc.)
- distribution of consequences within the population affected
- uncertainties in these estimates

The measurement of the technological risk in terms of these categories may be termed the "objective" part of the risk, although they will often have a certain degree of subjectivity, introduced by the judgments of the technical experts. However, the combination rule for aggregation of these data is not specified by any natural law. Therefore, there is no such thing as an objective unified measure of risk. Any mathematical procedure to combine these data is part of an evaluative process and thereby subjective.

Since methods for integrating the above mentioned categories of technical data which describe risks have not yet been sufficiently developed, the measure to be used here is the expected value, where risk is defined as the multiplicative combination of probability and the consequences of an event. It should be noted that this procedure has the effect of treating one death per year as equivalent to 100 deaths occurring once in 100 years.

Further, these calculations will be limited to impacts on human health. This poses the difficult problem of aggregating risks due to deaths and illnesses. As sooner or later everybody has to die, death will be quantified in terms of loss of years of life. It is common to equate each fatality with a loss of 6,000 man-days (U.S. Atomic Energy Commission 1974, American National Standards Institute 1968), and this procedure is used in this paper. However, it is possible to apply the following methodology to any otherwise defined measure of risk.

THE RISK OF PRODUCING GOODS AND SERVICES

The Methodology

The risk of illness and death is inherent in any production of goods and services in an economy. Usually, these risks are expressed in terms of hazards per year and million people involved. Table 1 gives an overview of these risks for the Federal Republic of Germany in 1973. It should be noted that these risks vary within two orders of magnitude for different branches of industry.

In combination with data from economic input-output tables, these data can be used to calculate the total risk involved in the production of goods and services. The procedure applied is similar to the calculations performed for energy analysis which have been described in detail elsewhere (Kolb et al. 1975, Niehaus 1975, Chapman 1974, Herendeen 1974).

Table 1. Selected occupational fatality risks in the Federal Republic of Germany, 1973.

Industry	Individual risk per year
Inland shipping	1.6×10^{-3}
Mining	1.1×10^{-3}
Underground construction	6×10^{-4}
Iron and steel	2.5×10^{-4}
Textiles, clothing	8×10^{-5}

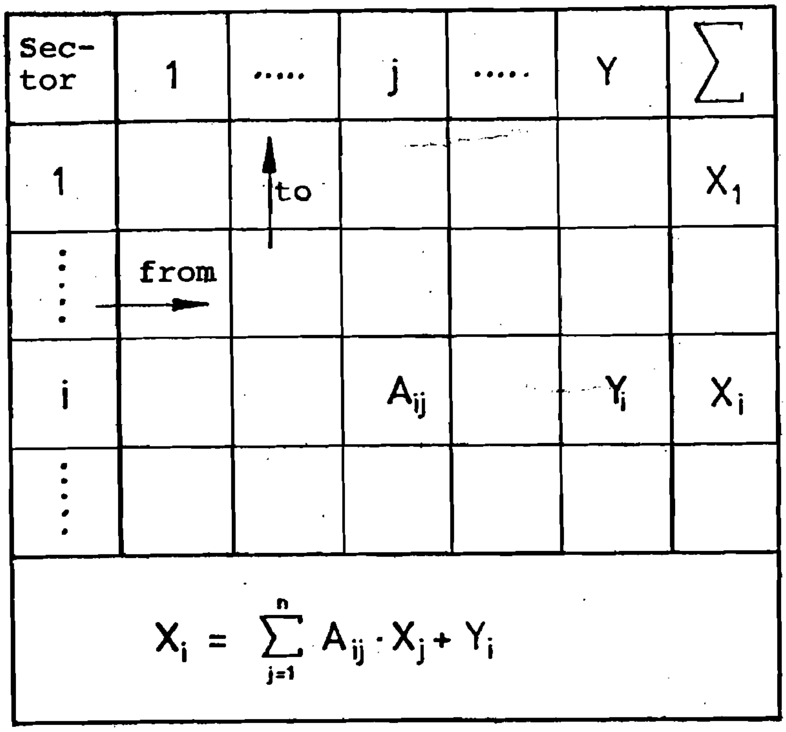


Figure 2. Structure of input-output coefficient matrix.

An input-output table describes the economic interrelations of an economy in monetary values. In order to allow for easier handling it can be reduced to an input-output coefficient matrix. Its principal design is outlined in Figure 2. An element A_{ij} gives the percentage of the total output of sector j which has been obtained in form of preprocessed goods from sector i (derived from monetary values). Y_i denotes total final consumption of goods from sector i and X_i denotes total production of sector i. Thus, assuming linearity and time invariance, total production of sectors can be written as:

$$X_i = \sum_{j=1}^{n} A_{ij} X_j + Y_i \quad , \qquad n = \text{number of sectors.} \qquad (1)$$

Total production of sector i is the sum of final consumer products and preprocessed goods for other sectors of the economy.

This can be written more easily in the form of vectors (e.g. $\underline{X}$) and matrices (e.g. $\underline{\underline{A}}$) as

$$\underline{X} = \underline{\underline{A}}\,\underline{X} + \underline{Y} \quad . \tag{2}$$

It follows that

$$\underline{X} = \underline{\underline{(I - A)}}^{-1}\,\underline{Y} \quad , \qquad \underline{\underline{I}} = \text{unit matrix.} \tag{3}$$

$\underline{\underline{(I - A)}}^{-1}$ is known as the inverse Leontief matrix.

The elements of this matrix $(I - A)^{-1}_{ij}$ denote the percentage of a value unit which has to be produced by sector i in terms of preprocessed goods for all other sectors in order to allow for the production of one value unit of goods of sector j.

Its meaning is better understood if the matrix is developed into a series

$$\underline{\underline{(I - A)}}^{-1} = \underline{\underline{I}} + \underline{\underline{A}} + \underline{\underline{A}}^{2} \ldots \tag{4}$$

If one considers the vector of final consumption $\underline{Y}$ then the vector for final production $\underline{Z}_0$ and the nth step of preprocessing are given (for n = 1,2...) by

$$\underline{Z}_0 = \underline{\underline{I}}\,\underline{Y}$$

$$\underline{Z}_1 = \underline{\underline{A}}\,\underline{Y}$$

$$\underline{Z}_2 = \underline{\underline{A}}\,\underline{Z}_1 = \underline{\underline{A}}^{2}\underline{Y}$$

$$\vdots$$

$$\underline{Z}_n = \underline{\underline{A}}^{n}\underline{Y}$$

Total production therefore is

$$\underline{X} = \sum_{n=0}^{\infty} \underline{Z}_n = (\underline{\underline{I}} + \underline{\underline{A}} + \underline{\underline{A}}^2 \ldots)\underline{Y} \quad , \tag{5}$$

which is equivalent to Equation (3).

This approach can be extended to calculate the total risk of the production of goods by superimposing "risk flows" on monetary flows.

A "Specific Risk Matrix" $\underline{\underline{S}}$ is constructed where the elements

$$S_{ij} = \frac{R_{ij}}{X_j} \tag{6}$$

denote the value specific risk of the type i in sector j and R_{ij} denote the total health effects of type i in a one year's production of goods from sector j.

Thus matrix $\underline{\underline{S}}$ has the dimension of health effects per monetary values (e.g. death per million \$). It is not a square matrix and consists of as many lines as health effects are considered.

The product

$$\alpha_{ik\ell} = S_{ik}(I - A)^{-1}_{k\ell} \tag{7}$$

denotes the health effect of type i which occurs in sector k through production of preprocessed goods for all other sectors to enable production of one value unit of final products from sector ℓ. The summation

$$H_{i\ell} = \sum_k S_{ik}(I - A)^{-1}_{k\ell} \quad , \tag{8}$$

therefore, gives the total risk (including all steps of preprocessing) of type i for the production of one unit of final products. In form of matrices this can be written as

$$\underline{\underline{H}} = \underline{\underline{S(I - A)}}^{-1} \tag{9}$$

Results

Using data from the Federal Republic of Germany (Bundesregierung 1974; Deutsches Institut für Wirtschaftsforschung 1972), the matrices described above have been constructed. Because of the overlap of several sectors in the various statistics it became necessary to aggregate the original 60 sectors of the input-output table and the 38 sectors of accident statistics to 19 sectors (e.g. machine tool industry and electrical equipment sector had to be aggregated). Table 2 gives the results of such a calculation for a sample of sectors. It should be borne in mind that, for example, the data on construction already include the data of production of preprocessed goods which this sector receives from other sectors such as "mining" or "stone and earth" industry. The first column gives the total working hours which have to be used to produce goods of the value of DM 1 million of that sector. The large differences reflect the various proportions of labour, know-how and capital (machinery) involved.

The other columns give the respective health effects. It can be seen that occupational accidents and job-related driving fatalities are of the same order of magnitude. Column 4 gives occupational chronic deaths. They occurred during the year under consideration. However, they have been caused by exposure to pollutants during previous work.

THE RISK OF PRODUCTION OF SAFETY EQUIPMENT

These data can be used to calculate the risk of producing safety equipment. Throughout the paper it will be assumed that, for these general considerations, safety equipment requires

-- 30% construction
-- 10% services, and
-- 60% machine tool and electrical equipment.

The data are summarized in Table 3. For the aggregation of lost working days due to illnesses and fatalities one death has been equated to 6,000 man-days. To the total of about $11 \cdot 10^{-3}$ fatalities, equivalent to about 65 lost man-days, illnesses add about 45%.

These data only refer to occupational effects. In addition health effects to the general public have to be considered. They occur mainly due to emissions from plants, including emissions from energy production which has been used to produce these goods. Unfortunately, neither data on emissions nor on health effects exist which could be used for calculations like the one above.

Therefore, the following calculation is suggested which can establish an order of magnitude estimate. Table 4 gives a comparison of total emissions from energy production and other industries in the Federal Republic of Germany in 1970 (Niehaus 1977). From this table one might conclude that about 30% of public health effects are caused by emissions from industry and about 70% from energy production. As about 50% of energy production is used in industry for production of goods, including transport (Kernforschungsanlage Jülich GmbH 1977), it is reasonable to assume that 50% of the health effects from emissions from energy production can be assigned to industry and that they are roughly equal to those from the industrial emissions.

Table 2. Total working hours and occupational health effects for production of goods and services of a value of DM 10^6

Industry	Total working hours	Occupational accidental deaths $[10^{-2}]$	Job-related driving fatilities $[10^{-2}]$	Occupational chronic deaths $[10^{-3}]$	Lost working hours
Machine tools & electrical equipm.	7,790	0.235	0.177	0.151	208
Mining	30,600	0.958	0.170	4.37	520
Stone and Earth	23,500	0.591	0.178	0.447	219
Textiles and clothing	7,410	0.135	0.157	0.116	168
Services, provisions & fine foods	5,780	0.283	0.105	0.103	59
Construction	41,600	0.746	0.296	0.172	315

Table 3. Total occupational risk of producing DM 1 million safety equipment.

Total working hours	17,700
Lost working hours	225
Occupational accidental deaths Driving fatalities Occupational chronic deaths	$3.93 \cdot 10^{-3}$ $2.06 \cdot 10^{-3}$ $0.153 \cdot 10^{-3}$
Total deaths	$6.14 \cdot 10^{-3}$
$\sum$ equivalent death* or $\sum$ equivalent lost working days*	$10.8 \cdot 10^{-3}$ 65

*1 death = 6,000 man-days

Table 4. Emissions in the Federal Republic of Germany, 1970.

Pollutant	Emission [10^6t/a]	Percentage [%]	
		Energy	Industry
CO	11.2	83	17
SO_2	5.3	72	28
C_nH_m	3.3	76	24
NO_x	2.6	98	2
Particulates	2.2	55	45

Using the method described, it is possible to calculate the total energy necessary to produce industrial goods. A detailed calculation has been made (Niehaus 1975), which gives a value of about 35 kg coal equivalent per DM 100 production of machinery and electric equipment goods. If it is further assumed that energy is produced by coal, then data (Tattersall et al. 1972) on public health effects from energy production (3 - 22 deaths/GWa(e)) can be combined with the specific energy requirements. Assuming an efficiency of 40% from coal-fired plants, public risks from emissions of the required energy production would be about $1.3 \cdot 10^{-3}$ deaths per DM 10^6 for an average value of 10 deaths/GWa(e). This value might be too high by a factor of three or too low by a factor of two. Adding the effects of industrial emissions a value of $3 \cdot 10^{-3}$ deaths per DM 10^6 is assumed. A comparison with data from Table 3 shows that public effects from emissions are less than one third of the total occupational risks.

Public effects from job-related driving accidents are assumed to be equivalent to occupational driving accidents. Therefore, the total occupational and public risk of the production of safety equipment is estimated to be

$$15 \cdot 10^{-3} \text{ equivalent deaths/DM } 10^{6}$$

or

90 lost man-days

These data are summarized in Table 5. Therefore, the production of DM 65 • 10^{6} safety equipment has a risk of 1 equivalent death.

Table 5. Occupational and public effects of production of DM 1 million safety equipment.

Occupational	
lost working hours	225
total death	$6.14 \cdot 10^{-3}$
$\sum$ equivalent death	$10.8 \cdot 10^{-3}$
Public (equivalent death)	
energy production	$1.3 \cdot 10^{-3}$
industrial production	$1.3 \cdot 10^{-3}$
driving accidents	$2.06 \cdot 10^{-3}$
$\sum$ equivalent death	$4.66 \cdot 10^{-3}$
Total	
$\sum$ equivalent death	$15 \cdot 10^{-3}$
or	
$\sum$ equivalent lost man-days	90

APPLICATION OF RESULTS

General Implications to Standard Setting

It was shown above that health effects of approximately 1 equivalent death are caused by the production of \$ 30 · 10^6 worth of safety equipment as specified in this paper. This suggests that the general relationship of cost-effectiveness of risk reduction, as outlined in Figure 1, should be modified, as indicated in Figure 3, in order to represent health effects in the total economic system. Any achievement in technological safety through additional equipment has to be paid for not only by additional costs but also by the occupational and public health effects caused by the production of this safety equipment. This risk may be considered to be proportional to these safety investments. Therefore, if the total system of an economy is considered, the risk cannot be reduced to any given value; beyond a certain limit the risk increases again with increasing expenditures for safety equipment. The minimum of the risk-cost relationship is given when the marginal cost of risk reduction, i.e. the first derivative of the curve labelled "operation" is equal to the slope of the linear relationship for investments. (1 death/ \$ 30 · 10^6). The initial design, without additions of safety

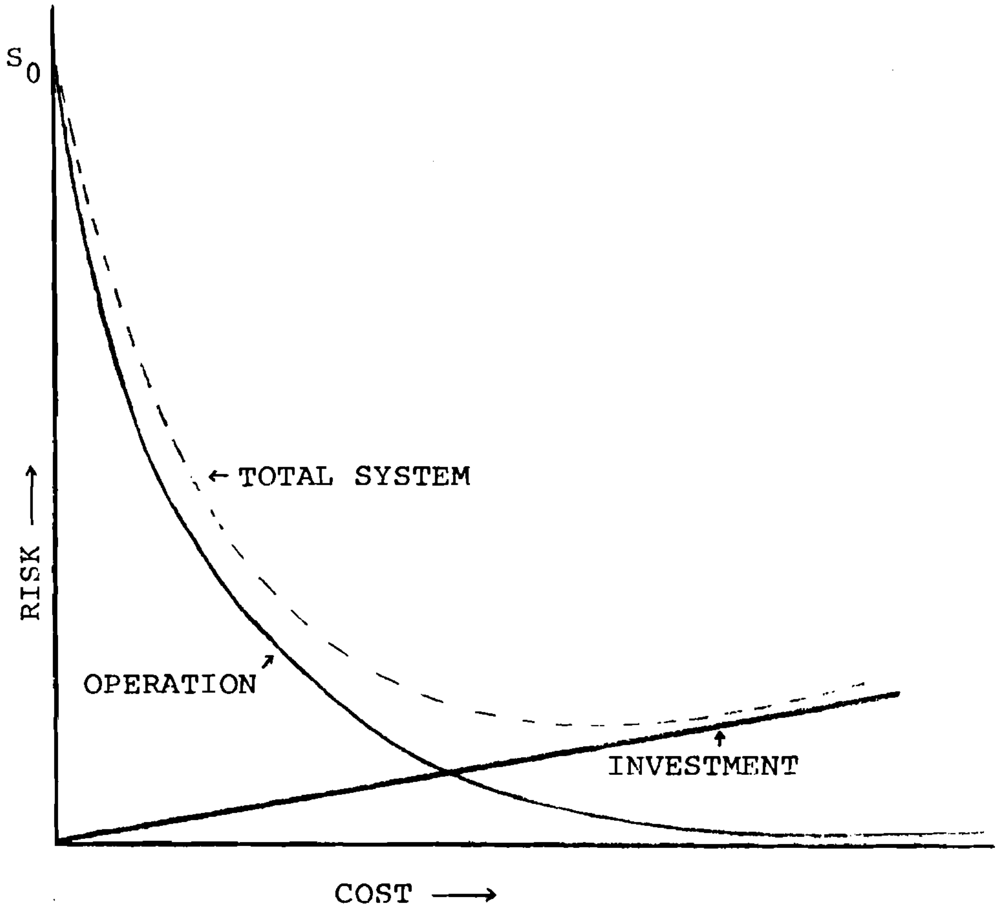


Figure 3. Principal relationship of cost-effectiveness of risk reduction considering the total economic system.

measures, poses a risk (S_0) that is determined by factors intrinsic to the technological process. As a consequence, no fixed number can be attached to the absolute values of the risks or the costs defining the minimum.

Thus any expenditure on safety equipment has the effect of reducing the expected number of health effects predicted to occur during the lifetime operation of the plant at the expense of causing some effects during the construction phase. Moreover, if the safety investments are greater than the amount indicated by the minimum of the curve, then the current health impact will actually be larger than the reduction in future expected effects. For example, Table 6 gives a listing of safety expenditures (Sagan 1976) that have been applied or proposed in various areas. It is apparent that the minimum value, at a marginal cost of $\$ 30 \cdot 10^6$ per expected equivalent death reduced, has actually been exceeded.

However, even expenditure at the minimum of the curve where the same number of health effects are merely antedated still represents a drain on societal resources. In terms of expected effects there is no net benefit, but Table 3 shows that the avoidance of one future expected equivalent death (thereby causing it today) requires about 20 people to work for 30 years (600 man-years) in the production of safety equipment. In addition, it ignores the possibility that medical and technical advances will be able to reduce the risk in an alternative manner in the future.

Safety expenditures at lower cost than indicated by the minimum would result in a net reduction of health effects and a standard value would have to be determined by a trade-off between required costs and man-power, and reduction of health effects. These relationships will be studied in more detail below.

As has been described above practical case studies generally show that costs of risk reduction follow an exponential law and in some cases even exponential power functions. As a conservative estimate an exponential function is assumed here.

Therefore, the total system risk-cost relationship of Figure 3 can be described as

$$R = f(C) = R_0 e^{-\frac{c}{c_0}} + r_p c \tag{10}$$

where R = risk level, c = cost of safety equipment.

Table 6. Marginal costs of risk reduction.

	$\$ 10^6$ per life saved	Lives saved per $\$ 10^6$
Food poisoning control	0.03	33
Automobile seat belts	0.3	3
High-rise flats fire control	40	0.025
50% flue gas desulphurization applied to plant with		
30 m stack	0.2	5
120 m stack	2.5	0.4
Nuclear plants		
recombiners	17*	0.06
6 charcoal beds	43*	0.024
12 charcoal beds**	300*	0.003
iodine treatment**	1,000*	0.001
remote siting	10,000*	0.0001

*based on 1 fatal effect per 10^4 man-rem.
**proposed, not implemented.

Source: Sagan (1976), U.S. Environmental Protection Agency (1976).

with:

R_0 = risk of initial design

c_0 = constant for a particular technology

r_p = specific risk of producing safety equipment (1 death/\$ 30 · 10^6)

The minimum is derived by

$$\frac{dR}{dc} = R' = \left(-\frac{R_0}{c_0}\right) e^{-\frac{c}{c_0}} + r_p = 0 \quad . \tag{11}$$

Therefore, when the costs are:

$$c_M = c_0 \ln \frac{R_0}{r_p c_0} \tag{12}$$

the minimum risk level R_M is given by

$$R_M = r_p c_0 (1 + \ln \frac{R_0}{r_p c_0}) \quad . \tag{13}$$

As outlined above the initial design described by R_0 and $c = 0$ has been arbitrarily defined. Therefore, no meaning is attached to the absolute values of R_M and c_M. It has to be emphasized that these values should not be used to compare different technologies. They only indicate the minimum expected risk achievable given a specific design.

However, the shape of the minimum is the same no matter which design R_0 has been chosen as initial value. Sensitivity studies therefore should not be made with regard to relative changes in risk or cost but with regard to their absolute values.

Figure 4 indicates graphically the impact of r_p on the first derivative $R' = \frac{dR}{dc}$ (see Equation 11). Taking r_p into account shifts the asymptote for the operation curve into positive values. Because of the exponential shape of the curve, c_M is sensitive to the value of r_p.

The negative inverted function of R' gives the marginal costs of risk reduction

$$-\frac{dc}{dR} = f(c) = \frac{1}{\left(\frac{R_0}{c_0}\right) e^{-\frac{c}{c_0}} - r_p} \quad . \tag{14}$$

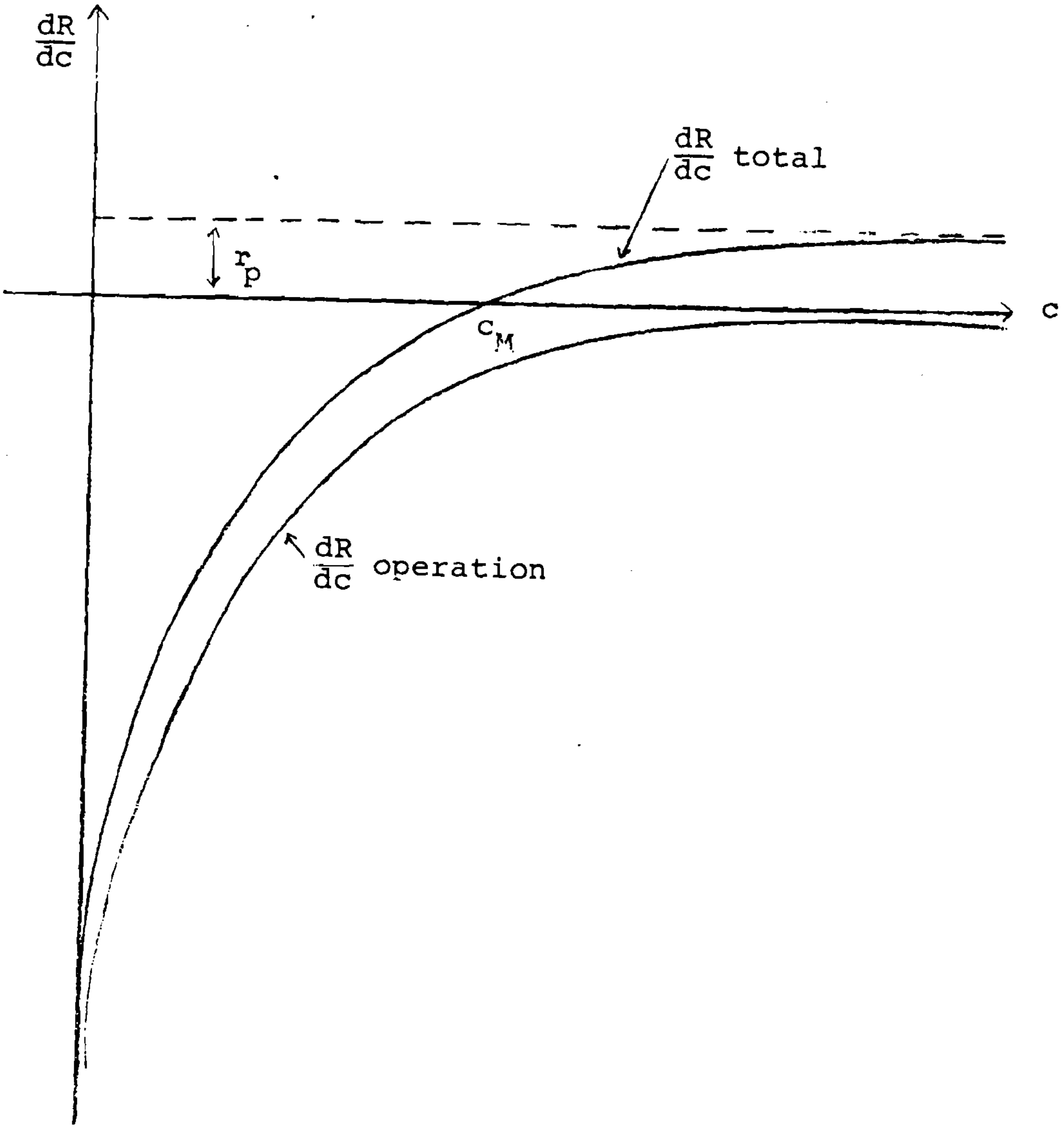


Figure 4. Principal relationship of $R' = \frac{dR}{dc}$ (arbitrary scale).

This function is displayed in Figure 5. In contrast to the operation curve for the facility, for which marginal improvements in risk can always be made at some expenditure, the curve for the total system shows that the marginal costs of risk reduction become infinite at c_M. Expenditures above this result in negative marginal costs; the risk is increasing.

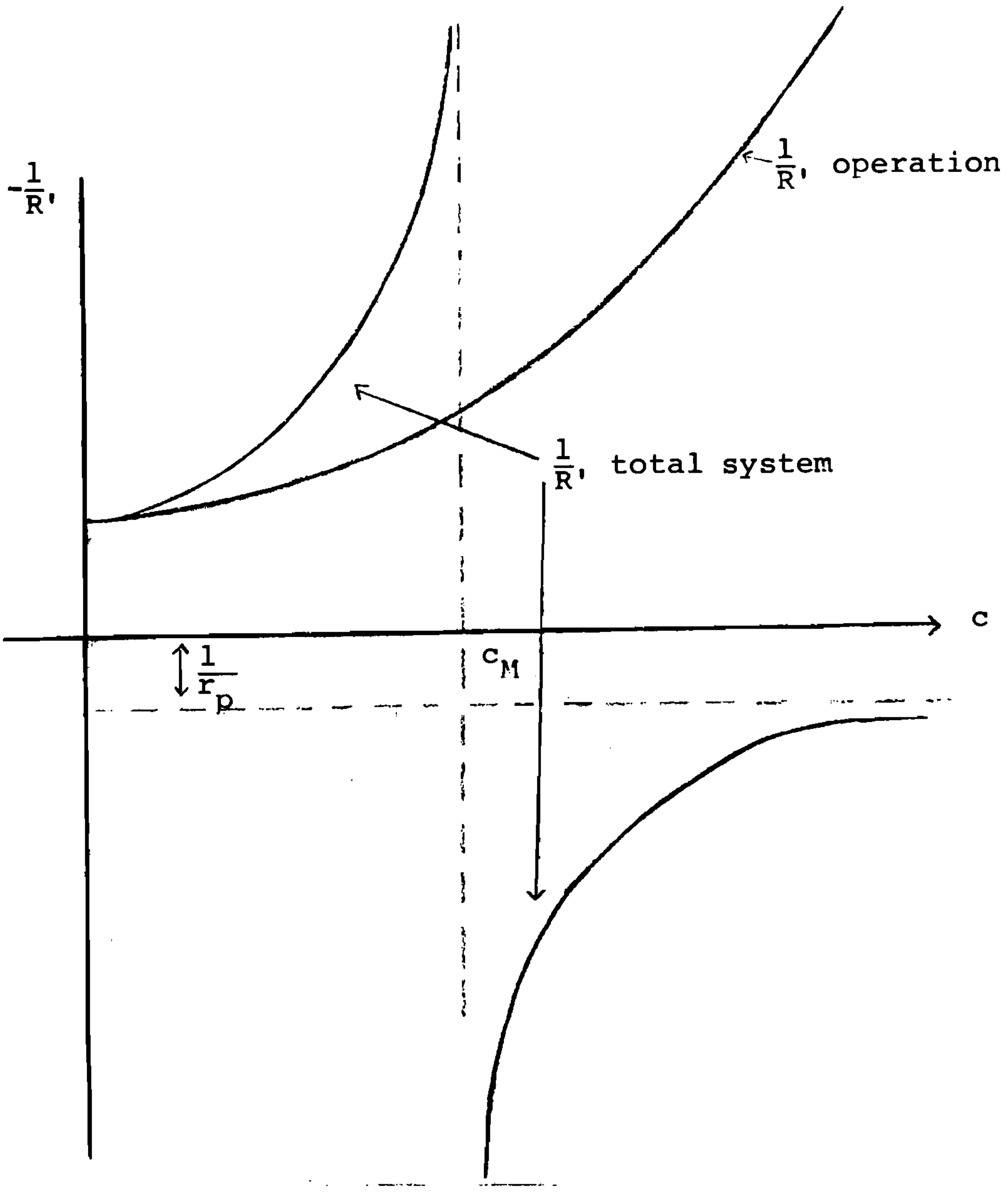


Figure 5. Principal relationship of marginal costs of risk reduction (arbitrary scale).

Application to
U.S. Environmental Protection Agency Results

Consideration of specific risk r_p

The EPA (U.S. Environmental Protection Agency 1976) presents cost-effectiveness calculations for risk reduction systems in the total fuel cycles for pressurised water (PWR) and boiling water (BWR) nuclear power reactors. The inverted marginal costs of risk reduction are plotted on a log scale in Figure 6. It can be seen that they fit the dashed linear line quite well, indicating an exponential relationship. If a specific risk r_p of

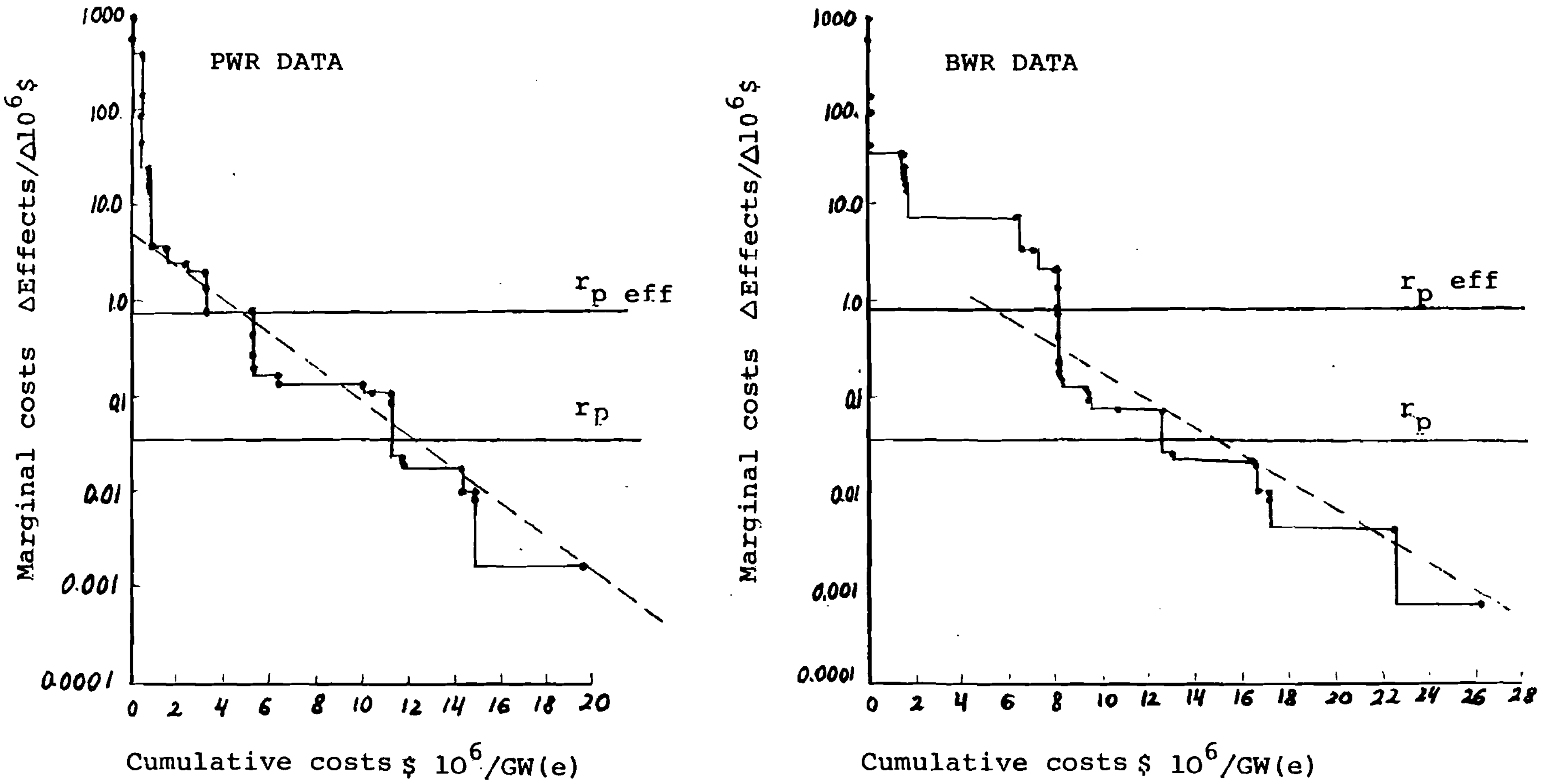


Figure 6. Cost-effectiveness of risk reduction.

1 death/$ 30 · 10^6 is applied, it can be seen that several safety reduction systems have been considered that would in fact prevent less expected health effects than would be caused during their production.

At total cumulative costs of about $ 12 · 10^6 for PWR and BWR, the marginal cost of risk reduction--considering the total economic system--would become infinite (See Figures 4 and 5).

It has to be noted that equating one effect in the future with one effect during construction already contains a value judgment. We agree with the suggestions (Cohen and Tewes 1979) that no discounting factor should be applied for future effects; that therefore one effect in the future should be considered as serious as one effect today. However, this does introduce a factor of conservatism into the calculations as no credit is given to the development of improved methods for medical treatment in the future.

Consideration of r_p and labour requirements

As discussed above, it is not suggested that this absolute limit where marginal costs of risk reduction become infinite, should be the barrier to risk reduction. It has been explained that, at this minimum achievable risk, 615 man-years of labour requirements would be associated with shifting each health effect from the time period of operation (or later) to the time period of construction.

The labour requirements may be included in the specific production risk r_p in order to present a more realistic suggested limit for safety expenditure. However, this poses the value question concerning the aggregation of health effects and labour needs. One way to look at this problem is to consider the extent to which society is prepared to utilize the available labour resources in the reduction of technological hazards. It is clear that this problem needs considerable study and a solution cannot be provided here. However, if it is assumed that society should expend 1 man-year of work to gain one man-year of life, one may equate expected effects and the equivalent man-years of labour. This would allow for an aggregation in terms of man-lives. If one health effect is estimated to lead to a loss of one life, or 6,000 man-days, then 17,800 working hours per DM 10^6 would be equivalent to about 22 man-lives per $ 30 · 10^6.

Thus the value of the effective specific production risk $r_{p\,eff}$ becomes

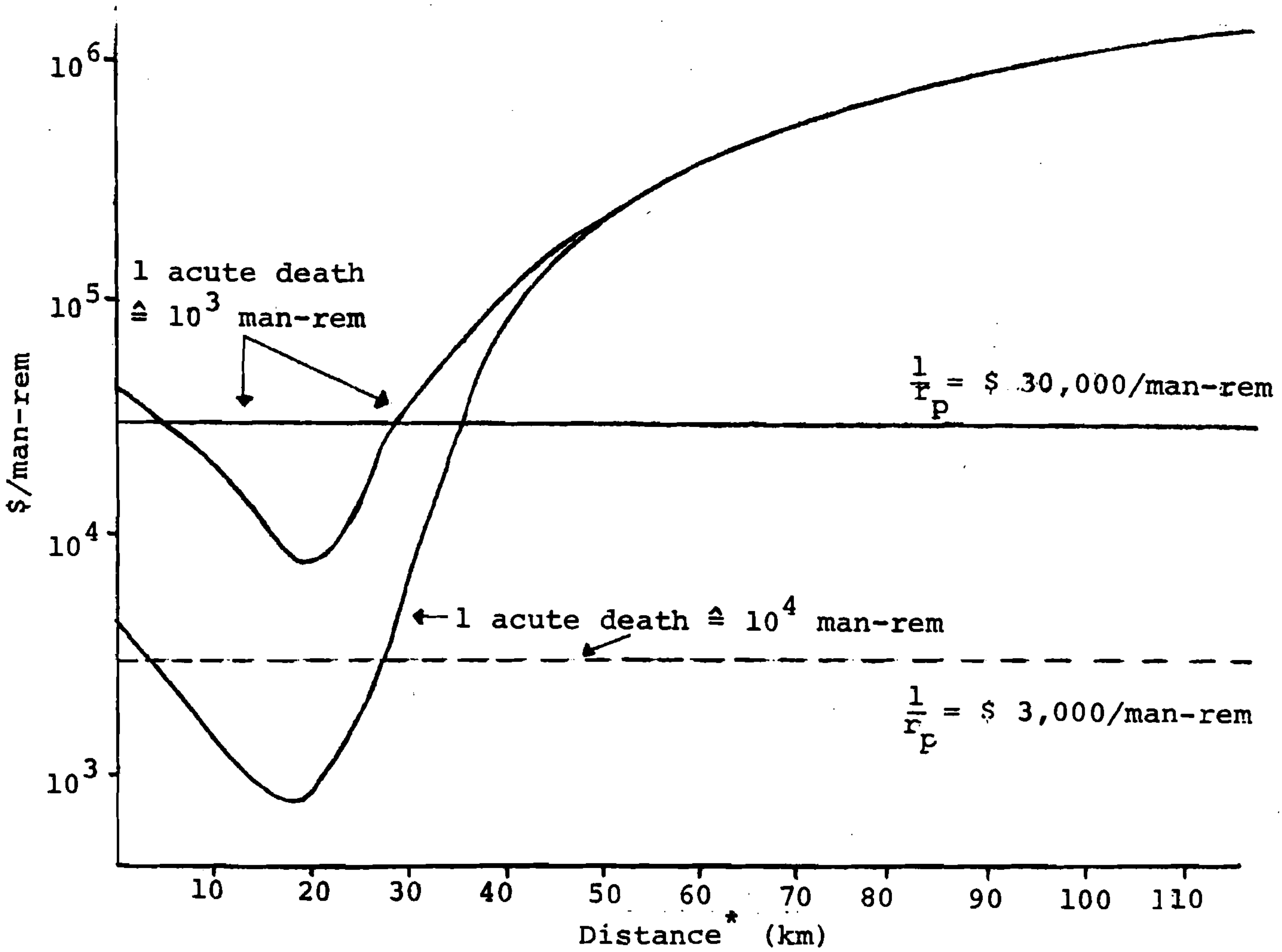
$$r_{p\,eff} = r_p + \frac{22 \text{ man-lives}}{\$\ 30 \cdot 10^6} = \frac{23 \text{ man-lives}}{\$\ 30 \cdot 10^6} \quad . \tag{15}$$

This value is also indicated in Figure 6 and is clearly dominated by the labour requirements.

The condition for minimum risk using this revised value, $r_{p\ eff}$, is that the marginal cost of risk reduction has to be equal to \$ 1.3 · 10^6.

Application to Remote Reactor Siting

Based on data from the draft document of WASH 1400 the marginal costs of risk reduction for remote reactor siting were calculated (Niehaus et al. 1977). Figure 7 plots those marginal costs of risk reduction in \$/equivalent man-rem versus distance between a nuclear plant and a densely populated area. Using the equivalence between 1 death and 10^4 man-rem, $1/r_p$ can be converted into \$ 3,000/man-rem or \$ 30,000/man-rem, respectively. These values are also indicated in Figure 7. However, they are not conservative estimates because the construction of high-voltage transmission lines will involve a higher risk than will the production of safety equipment. These results show that, beyond



*Distance between nuclear power plant and densely populated area.

Figure 7. Marginal costs of risk reduction for remote reactor siting.

a distance of about 30 km, more health effects are expected to occur during construction of the transmission line than are expected to be saved through remote reactor siting. If a $r_{p\,eff}$ of 23 man-lives per \$ 30 · 10^6 is used, the equivalent conversions for $1/r_{p\,eff}$ become \$ 130 and \$ 1,300 per man-rem and these are far below the marginal costs of risk reduction implied by remote reactor siting as plotted in Figure 7. This means that the extra labour man-hours for construction of the transmission line will be greater than the expected loss in population lifetime for all conceivable accidents to the reactor system.

Reduction of Radiation Doses to Nuclear Plant Operators

A value of \$ 1,000/man-rem has been advocated by the U.S. Nuclear Regulatory Commission and others (Niehaus and Otway 1977, U.S. Nuclear Regulatory Commission 1975) as an appropriate index for use in determining the cost-effectiveness of nuclear radiation risk reduction measures. From the figures given above it is evident that if the risk is to be reduced by construction of added safety features, then this value is an upper limit from a risk and labour time aspect. Conversely, it has been argued (Atomic Industrial Forum 1978) that if radiation exposures can be reduced by planning and administrative procedures, then costs can be minimised by reduced down-time and use of fewer men. In this case, the risk reduction would not be associated with added risks elsewhere in the system and the minimum risk would not be applicable.

CONCLUSIONS

It has usually been assumed that it is always possible to reduce a risk below any given value and that the only limitation is the associated increased costs. As a result of this assumption the question of "how safe is safe enough" is posed. However, such a relationship only holds true for a single system element (e.g. a specific facility). If the total economic system is considered one has to take account of the fact that safety equipment has to be produced. This production leads to an occupational risk and also a risk to the public in the same way as the manufacture of any industrial goods. This risk is estimated to be one equivalent death per \$ 30 · 10^6 worth of safety equipment produced. In addition, about 615 man-years of labour are involved.

Thus this paper concludes that the risk-cost relationship actually shows a minimum beyond which additional expenditures intended to reduce a risk will actually increase it. It has been demonstrated that several applied or proposed risk reduction measures already exceed such a minimum level.

The levels quoted here have been derived in a general manner and may not be applicable to any particular situation, nevertheless they do reflect the order of magnitude that would be obtained with a more specific analysis. However, before this methodology is applied to any particular cost-effectiveness problem the following aspects have to be considered in greater detail:

- how to define risks (expected health effects have been used here);
- how to compare health effects and labour requirements (and costs);
- how to compare health effects today versus health effects which would occur in the future; and
- how to compare occupational and public health effects.

One may deduce from the results shown above and using the assumptions given that there is a tendency for present day expenditures on certain safety items to be excessive. In other words the risk is not minimised. However, the basic assumption, namely that risk ought to be minimised, has not been questioned. Although cost-effectiveness techniques can be used to identify the minimum risk, no evaluation is given as to whether this minimum is itself low enough. The solution to this problem which is closely allied to the four aspects mentioned above, demands further investigation into individual and group attitudes towards risk and risk reduction.

The conclusions drawn in this paper do depend on the various assumptions made. Alternative assumptions could give different results; however, the general methodology is valid and could still be applied.

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