How Safe is "Too" Safe?

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by S.C. Black and F. Niehaus

Any human activity involves some risk to life or health. Although it is possible to reduce the existing risk of a particular activity, it is not possible to reach the "zero risk" or "absolute safety" that is often demanded. Once this general fact is recognized, it then becomes necessary to define an acceptable level of risk.

Three methods are most commonly used for determining an acceptable level of risk: By the first method, *putting risks into perspective,* it can be determined if the risks of a technology compare favourably with the existing risks of presently accepted technologies Refs.[1, 2]. It has been suggested that the risk of a new technology should be at least a factor of 10 lower than well-established technologies Refs.[3, 4] In the second method, a *comparison of risks and benefits* of a set of alternatives may be used to choose among options. Such a procedure requires that risks and benefits be expressed in common units, usually in monetary terms. However, these two methods do not answer the question of whether or not a given technology should be made safer. Therefore, in the third method, decisions on safety are based on the more sophisticated approach of *cost-effectiveness analysis,* which is synonymous with marginal cost-benefit analysis.

COST-EFFECTIVENESS ANALYSIS

Safety expenditures generally follow an economic law of diminishing returns. The general relationship of this law is outlined in Figure 1 Ref. [5] and case studies have been given in Refs.[6, 7]. This figure indicates that it is possible to reduce a relatively high risk to a much lower level (e.g. ΔR_1) at rather low additional costs (e g. ΔC_1). However, it becomes more and more expensive to reduce the risk even further (e.g. from S_5 to S_6). The relation $\Delta R/\Delta C$ (i.e. the first derivative) at each point of the curve is a measure of the cost-effectiveness of further risk reduction from the level of safety represented by that point. These marginal costs of risk reduction are measured in such terms as human health effects avoided per unit cost of risk reduction (e.g. lost man-days avoided per million dollars*). Two main conclusion can be drawn from this figure:

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 any existing risk even further; however, it is not possible to reduce the risk to zero.

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* All monetary costs appearing in this article are in US dollars

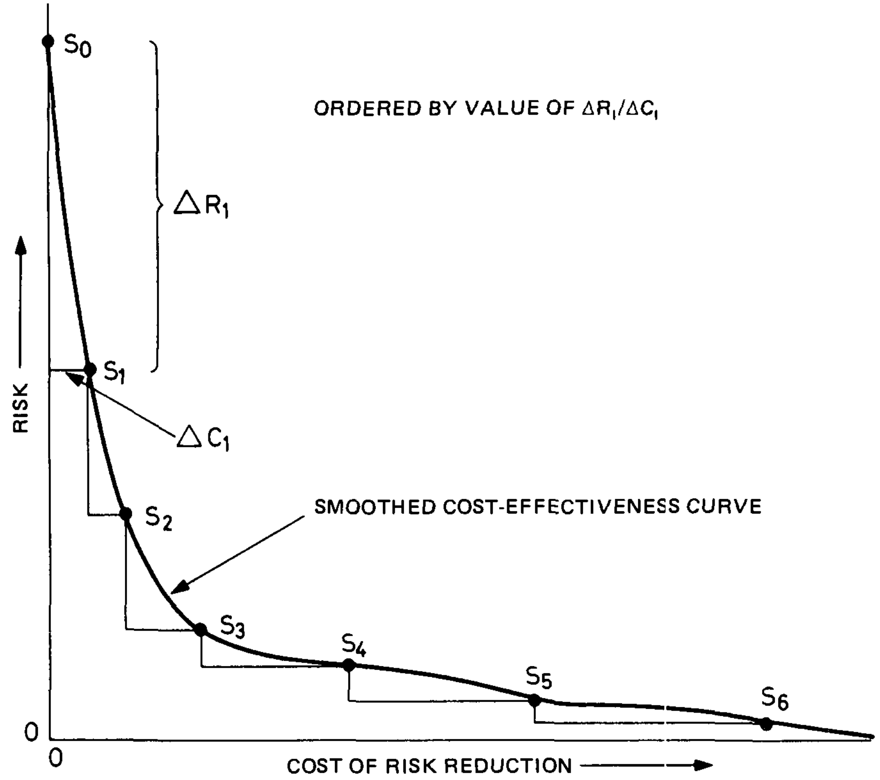

FIGURE 1. ***Cost-effectiveness of risk reduction*** **Ref. [5].**

Two implications of these findings need further discussion. Firstly, should technologies be made *as safe as technically achievable?* Though this would be a very appealing approach at first glance, our daily experience demonstrates that this is not feasible. In the case of automobiles, for example, there exist innumerable opportunities to increase safety. But it is obvious that not all streets can be protected by a set of crash-fences or supplied with streetlights, that not all grade-crossings can be replaced by underpasses, etc Decisions on safety, therefore, have to be made in such a manner as to spend the limited resources of society in a cost-effective way. The two conclusions from Figure 1 imply that "safe" is always determined by a compromise between the two objectives of using limited resources most effectively (minimizing cost) and of achieving the highest level of safety (minimizing risk).

Secondly, can a monetary value be assigned to a human life? Any point on the curve in Figure 1, which might be chosen as a limit where no further risk reduction is considered, is characterized by specific expenditures per unit of risk reduction. In particular, any mortality risk averted implies a monetary value per human life saved. This ratio, in any decision on safety, has often been misinterpreted and has been the cause of much confusion.

Many attempts have been made to derive a "value of human life" Ref. [8] (e.g. human capital approach, willingness-to-pay approach). It is the personal opinion of the authors that such approaches are irrelevant with regard to decisions on safety and in fact dangerous for gaining public acceptance for safety standards. The basic rationale for choosing a standard value for such a ratio should *not* be to try to determine the "value of a human life". Such a ratio is only valid for the purpose of *comparing safety expenditures* in various areas of risk to which man is exposed. At present, such expenditures seem to centre around a value of $ 300 000 per life saved This value merely reflects a wide range of existing practice; it does not arise from any general rule or methodology. Expenditures much larger than this value for marginal cost of risk reduction would indicate that it would be more cost-effective to allocate the limited resources of society to other areas where they could achieve a larger risk reduction. These considerations are especially valid for basic services to society, such as electricity production, where expenditures that go beyond the principle of "as low as reasonably achievable" (ALARA) are directly reflected in the price of a kWh and are thus borne by every member of society. It has been proposed Ref [9] that a value be uniquely applied in industries and that deviations should be reflected in increases or decreases in their tax payments.

The rationale for the above approach is an optimal allocation of the limited resources of society to safety expenditures. However, it does not answer the more general question about total expenditures on safety since, as suggested by Figure 1, any existing risk may be reduced beyond any given limit at very high costs Nevertheless, the following will suggest that a practical limit to risk reduction does exist, because excessive expenditures for risk reduction will actually increase the total risk to society.

Consider the question of reducing further the risks due to the operation of nuclear power reactors. For safety measures at these extremely high marginal costs of risk reduction it becomes important to account for the occupational and public risk involved in the production of safety equipment itself, which has not been considered in Figure 1. This suggests that that curve should be slightly modified As shown in Figure 2 a linear term should be added to include the risk due to the production of safety equipment. This does not modify the relationship in Figure 1 if the marginal costs are relatively low. However, for much higher values, this linear term, when added to the other curve, results in a summed curve for total risk that passes through a minimum. At high costs the total risk curve no longer approaches the zero-level of risk, but approaches the risk of producing safety equipment. The minimum occurs when the marginal costs of risk reduction (that is the first derivative of the operation curve) are equal to the specific risk of production of safety equipment (i.e. the steepness of the linear term).

THE RISK OF PRODUCING SAFETY EQUIPMENT

Calculating this risk is identical to determining the slope of the straight line in Figure 2, representing *health effects per unit cost of safety equipment.* For our calculations, we assumed that installed safety equipment consists of 30% construction work, 10% services, and 60% machine tools plus electrical equipment. To produce machine tools, for example, requires mining of ores and coal, refining the ores, producing coke, making steel, casting, transporting, use of electricity, etc., so that a matrix of activities results. This matrix is called an input/output table and is used in economics to describe the interrelationships among economic sectors in monetary terms. Using these tables and using occupational

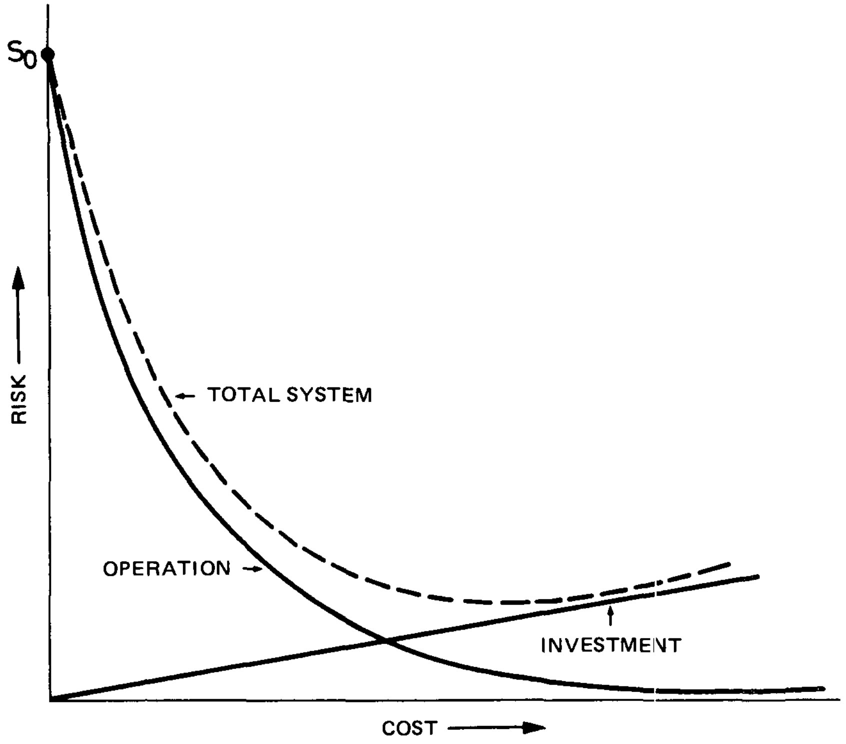

FIGURE 2. Principal relationship of cost-effectiveness of risk reduction *considering the total economic system.*

data on injuries and fatalities, it is possible to construct a matrix illustrating health-effects flows instead of monetary flows. A simple mathematical procedure (the inverse Leontief-Matrix) allows one to sum the risks involved in all steps of preprocessing. The occupational effects used herein are derived from the 1973 data for the Federal Republic of Germany. Table 1 shows sample results for some branches of industry. It can be seen that mining causes the largest health effects per unit value of goods produced though it requires less total working hours than construction. Job-related driving fatalities are largest for construction.

Taking the composition of safety equipment mentioned above, the total occupational risk and the required hours of work are given in Table 2. Noteworthy is the relatively high contribution towards health effects from job-related driving accidents. The data in Table 2 include fatalities and lost working hours due to illnesses. They have been aggregated by assuming that one death is equivalent to 6000 lost man-days.

Table 1. Total working hours and occupational health effects for production of goods and services having a value of one million dollars

Industry	Total working hours	Occupational accidental deaths (10^{-2})	Job-related driving fatalities (10^{-2})	Occupational chronic deaths (10^{-3})	Lost working hours
Machine tools & electrical equipment	82 000	0.470	0.354	0.302	416
Mining	76 600	1.916	0.340	8.740	1040
Stone and earth	63 200	1.182	0.356	0.894	438
Textiles and clothing	119 600	0.270	0.314	0.232	336
Services, provisions & fine goods	75 000	0.566	0.210	0.206	118
Construction	101 000	1.492	0.592	0.344	630

Table 2. Total occupational risk of producing safety equipment worth one million dollars

Total working hours	87 000
Lost working hours	450
Occupational accidental deaths	7.86×10^{-3}
Driving fatalities	4.12×10^{-3}
Occupational chronic deaths	0.306×10^{-3}
Total deaths	12.28×10^{-3}
Σ equivalent death*	$21\ 6 \times 10^{-3}$
or	
Σ equivalent lost working days*	130

* 1 death = 6000 lost man-days

Whereas the quality of the data on occupational accidents is rather good, no such data exist for the risks to the general public To get an order of magnitude estimate the following assumptions were made to estimate risk to the public:

From energy; assume that a total primary energy of about 700 tonnes of coal equivalent (tce) is needed to produce equipment worth \$ 1 million Ref. [10]. If this energy is produced by coal and 10 deaths/GW-yr(e) are assumed, the total risk would be 2.6×10^{-3} deaths/\$ 1 million of equipment.

From industry; 1970 data for the Federal Republic of Germany Ref [11] suggest that the risks from industrial emissions are about equal to those from energy production.

From driving accidents, assume that the public risk from driving accidents is about equal to the respective occupational risk.

In total, this suggests that the public risk adds about 50% to the occupational risk. Thus, the specific risk of producing safety equipment (r_p) is estimated to be about 3×10^{-2} equivalent deaths or 180 equivalent lost man-days per million dollars of equipment. More specific details of the calculations leading to this value of r_p are described in Ref. [12].

APPLICATIONS

The specific risk, r_p, sets the slope of the straight line in Figure 2. It also implies that expenditures of \$ 33 million for safety equipment would cause 1 equivalent death during construction and installation.

This value can now be used to determine the minimum risk of the total system curve. This minimum occurs where the marginal cost of risk reduction (the "Operation" curve) has the same slope, though opposite in sign, as the "Investment" line. At this point the production and installation of safety equipment would result in one equivalent health effect among the workers and the public in an attempt to prevent one estimated equivalent effect among the public at some future time. In other words, one statistically certain death is caused at the present time instead of one hypothesized death at a later time. Naturally, any costs of safety measures which exceed the minimum will cause more health effects than they prevent. Thus, this level of about $ 33 million per equivalent life saved seems to establish an absolute limit in physical terms for reducing risk. (It should be noted that such a principle is also used in medical practice; e.g recommendations for vaccination against smallpox have been withdrawn since the risk of the vaccination itself became higher than the risk of catching that disease).

Certainly, these risks to the workers and the public would also occur if instead of safety equipment other goods were produced However, this does not suggest that only net effects should be considered, since the production of other goods would have a benefit for society, and the risks arising from the various ways of producing these goods should be compared.

It will now be interesting to compare this result with actual expenditures on safety in various branches of industry. For a compilation of data the reader is referred to Ref. [9]. A sample of expenditures from Ref. [6] is given in Table 3 It can be seen that r_p is exceeded in several cases The second column gives the ratio between effects saved and effects caused. A ratio of 1 would indicate that no net savings are achieved, numbers greater than 1 indicate that the risk has actually been increased. However, it is not suggested that the marginal cost of risk reduction actually be increased to this level of $ 33 million per equivalent life saved for the reasons discussed below.

Calculating from Table 2, about 1400 man-years of labour requirements would be associated with shifting one equivalent death (or 6000 equivalent lost man-days) from the time period of operation (or later) to the time period of construction without achieving any net benefit. This point needs further discussion Let us take the example of recombiners and six charcoal beds from Table 3

The cost-effectiveness of risk reduction for the added six charcoal beds was estimated to be $ 22 million per equivalent life saved (based on two fatalities per 10 000 man-rem). The total investment costs of this system per plant are about $ 3 million. Let us assume that these systems are implemented in 10 reactors; thus total investment would be $ 30 million. The cost-effectiveness data infer that this investment would save about 1.36 equivalent lives. This paper suggests, based on the data from the Federal Republic of Germany, which may not be directly applicable to this specific situation, that the production of these 10 systems would lead to about 0.91 equivalent occupational and public deaths. Thus, the risk would actually be decreased only by about 3000 lost man-days. For decreasing the risk by one-half a life, society would have to invest 1300 man-years of labour requirements not counting the energy and raw materials needed. In total, society would expend 1300 man-years of labour and 0.9 fatalities to prevent 1.4 serious health effects.

Table 3: Comparison of marginal costs of risk reduction Ref. [6] with r_p (1 equivalent death/33 million dollars)

Safety Measure	Millions of dollars per life saved	(Millions of dollars per life saved) · r_p *
Automobile seat belts	0.3	0.01
Fire control in high-rise flats	40	1.21
50% flue-gas desulfurization for power plant with:		
30 metre stack	0.2	0.006
120 metre stack	2.5	0.08
Nuclear power plants with:**		
Recombiners	9	0.27
6 charcoal beds added	22	0.66
12 charcoal beds added+	150	4.5
Iodine treatment+	500	15.0

* A value greater than 1.0 indicates that the risk of providing safety is greater than the reduction in risk sought

** Based on 2 effects per 10^4 man-rem (fatal cancer plus serious genetic effects, all generations).

\+ Proposed, not implemented

Therefore, the question remains how many man-days of labour requirements should be used to prevent one man-day of health effects. It is clear that this problem needs considerable study; a solution cannot be provided here. As a rough estimate, let us assume that society should expend one man-year of work to gain one man-year of life. In this case the loss of one equivalent life can be aggregated with 59 work-lives (1400 man-years) per $ 33 million resulting in a total investment of 60 man-lives or an effective r_p of 1 equivalent life per $ 0.5 million. This value is clearly dominated by labour requirements. With regard to radiation protection it should be noted that this value would be equivalent to $ 100 man-rem.

To return to the question of safety in nuclear power plants, consider the recent EPA study Ref. [7] which presents cost-effectiveness calculations for risk reduction systems in the total fuel cycles for pressurized-water (PWR) and boiling-water (BWR) reactors. The inverted marginal costs of risk reduction are plotted on a log scale in Figure 3. If a specific risk r_p of 1 death/$ 33 million is applied, it can be seen that several risk 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 million

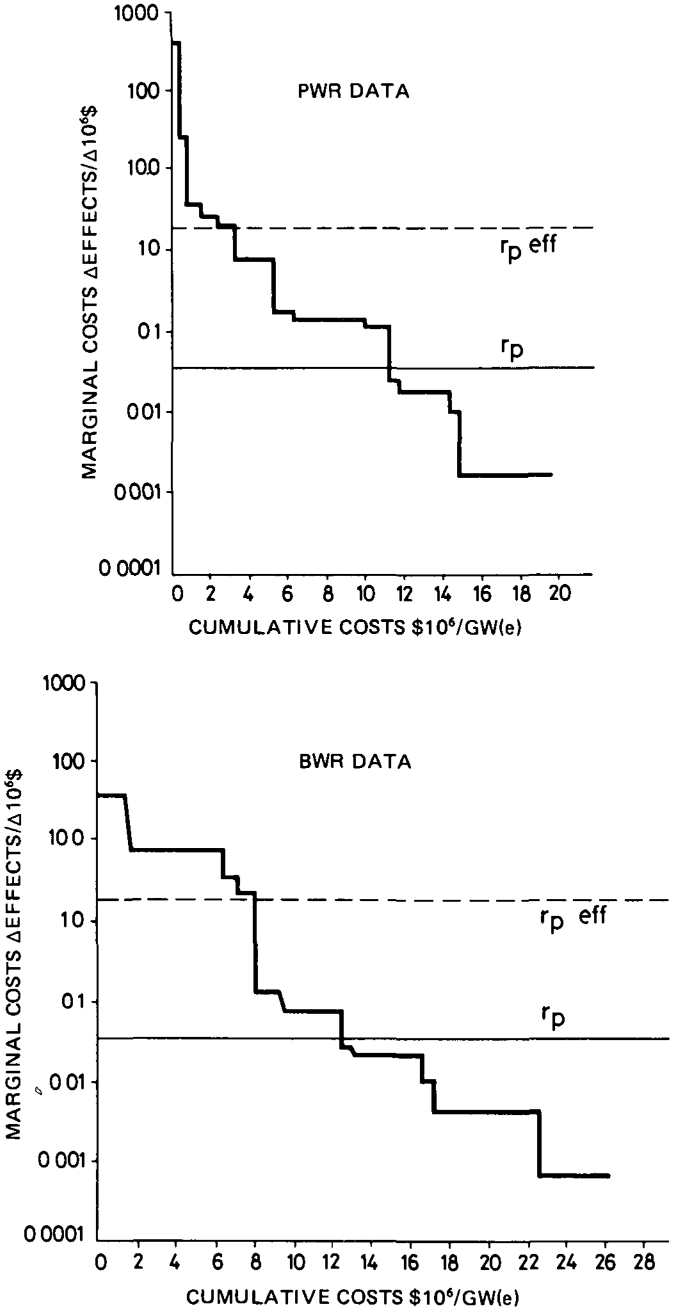

FIGURE 3. Cost-effectiveness of risk reduction Ref. [7].

for PWR and BWR, the marginal cost of risk reduction – considering the total economic system – would reach the minimum described by Figure 2 above. The effective r_p based on health effects plus labour requirements is also plotted in the diagram.

It has to be noted that equating one effect in the future with one effect during construction contains a value judgement. We agree with the suggestions in Ref. [13] that no discounting factor should be applied for future effects: 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.

The calculations herein are based on expected values and use specific assumptions for aggregating various societal risks. 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

SUMMARY

This paper suggests that total risk cannot be reduced beyond any given limit At a certain point the occupational and public risk of producing safety equipment becomes higher than the reduction achieved in an existing risk. Based on data from the Federal Republic of Germany it has been estimated that 1 equivalent death or 6000 equivalent lost man-days are caused during the construction and installation of safety equipment costing about $ 33 million. Thus, expenditures on safety at marginal costs of risk reduction higher than $ 33 million per equivalent life saved would actually lead to an increase in risk One might conclude that it had been made "too" safe. Furthermore, this expenditure implies that 1400 man-years of effort per equivalent life have been used for no net gain in safety.

The advantage of the method explained herein is that it describes the effectiveness of risk reduction in physical terms, i.e., occupational and public risks and labour requirements of production of safety equipment, thereby avoiding a trade-off between money and human life.

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