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MONETARY EVALUATION OF RADIATION DETRIMENT COST IN COST/BENEFIT ANALYSIS OF PROTECTIVE ACTIONS AFTER NUCLEAR ACCIDENTS

J. QU, D. XUE
Institute of Nuclear Energy Technology,
Tsinghua University,
Beijing, China

Abstract

This paper discusses the monetary evaluation of radiation detriment cost in the cost/benefit analyses of countermeasures after nuclear accidents. The methods used to determine the so-called α factor in cost/benefit analysis are presented. It is pointed out that the approaches found in current literature to the consideration of individual dose in cost-benefit analyses have some limitations. To overcome those deficiencies, we introduced the concept of individual dose evaluation function in this paper. In addition, we developed a modified approach to cost-benefit analyses of protective actions after nuclear accidents.

1. BRIEF INTRODUCTION TO COST/BENEFIT ANALYSIS

The theoretical foundation of cost/benefit analysis is the fundamentals in economics. Mathematically, the concept of cost/benefit analysis can be formulated as follows [1]:

$$X + Y = \min imum \tag{1}$$

where X and Y represents the cost as a result of implementation of protective actions and the cost equivalent of radiation detriment respectively. It is clear from Eq.(1) that the purpose of cost/benefit analyses is to find out an emergency intervention strategy that would make the sum of X and Y minimum.

In the practice of radiation protection it is usually assumed that radiation detriment is proportional to the collective dose in exposed population. Considering this, the radiation detriment cost can be calculated in the following way [1]:

$$Y = \alpha S \tag{2}$$

where S stands for collective dose (man-Sv) whereas α is the monetary amount assigned to a unit of collective dose ($/man-Sv). The value of α in current literature generally varies from about 2000 $/man-Sv to 100 000 $/man-Sv [2].

2. DETERMINATION OF α VALUE

Generally speaking, the magnitude of α reflects the value judgments of decision makers on radiation detriment. We can apply different models to the derivation of α value. For instance, we can use human capital model to estimate α value on the basis of the average GNP (Gross National Production) per capital and the loss of life expectation of population as a result of radiation exposure [3]. The medical cost of the treatment of radiation injuries and other related factors can also be taken into consideration [4].

Besides the models that are based on the fundamentals in economics, e.g. the human capital model, we can also use other models to derive α value. In reference [5], the economic cost people are willing to pay for different risks was studied. The method used in this study is called as willingness to pay. Some of the results are given in Table 1. The calculated value of α correspondent to different risks are calculated and presented in the last column of this table. It is clearly shown that the economic cost people are willing to pay for different risks varies dramatically.

It should be noted that the determination of α value is not only an issue in radiation protection but also an issue that involves economics, politics, public acceptability etc. For this reason, it is unrealistic if only economic factors are taken into account in the estimation of α values.

Table 1 Economic cost people are willing to pay for different risks [5]

Assumed safety actions	Economic cost people are willing to pay for saving a life (US $ in 1990)	α value * (US $/man-Sv)
1.0×10^{-6} reduction in nuclear risk	125000000	7.5×10^{6}
1.0×10^{-3} reduction in risk at coal-fired plants	300000	1.8×10^{4}
governmental health plan for saving 1000 lives	6250000	3.8×10^{5}
automobile safety airbag	1250000	7.5×10^{4}
safer cigarettes	100000	6.0×10^{3}
safer transportation	65000000	3.9×10^{6}

*: The values are calculated on the basis of somatic radiation hazard of stochastic health effects in the general public (6×10^{-2}/man-Sv) [6] and the data in the second column of above table.

3. CONSIDERATION OF INDIVIDUAL DOSE IN COST/BENEFIT ANALYSES

In the practice of radiation protection, it is gradually recognized that different emphases should be given to individuals/population groups according to the magnitude of actual/potential radiation doses they are exposed. So far as Eq.(2) is concerned, it means that proper consideration should be given to the distribution of the collective dose S with individual dose. In the NRPB regulations on radiation protection, individual dose is divided into three ranges, with each being assigned a corresponding α value (Table 2) [7].

Table 2 Values of α for public radiation dose valuations suggested by NRPB

Annual individual dose (AID) range	Value of α (£/man-Sv)
AID < 0.05 mSv	2000
0.5 mSv > AID ≥ 0.05 mSv	10000
5 mSv ≥ AID ≥ 0.5 mSv	50000

To apply the concept above to radiation protection optimization beyond normal operations of nuclear facilities, NRPB proposed a new method of considering the dependence of α value on individual dose [4]. The idea of this model is that a baseline α value is used for the radiation detriment valuations in dose ranges below a level of no concern. This α value can be derived on the basis of economic and other related considerations. Above the dose level of no concern, individual aversion to risk increases with increasing dose. To take this into account, the radiation detriment is evaluated by the product of the baseline α value and a multiplying factor which increases with increasing dose.

Similar model is adopted in the international Chernobyl project technical report by IAEA [8]. The α value in this report is described as follows:

$$\alpha_i = \alpha_{ref}\left(\frac{d_i}{d_0}\right)^a \qquad (3)$$

where:

$\alpha_i = \alpha$ factor for annual individual dose d_i;
$\alpha_{ref} = \alpha$ factor for annual individual dose below d_0;
a = public risk aversion exponent. It varies in the range between 1.2 and 1.5.

Another way of considering individual dose distribution is to express the radiation detriment cost as sum of two items [1,9]. For instance, it is formulated as follows in reference [10]:

$$Y = \alpha S + \sum_i \beta_i S_i \tag{4}$$

where the first item on the right side has the same meaning as Eq.(2). S_i represents the collective dose in the ith population group. β_i stand for the cost equivalent assigned to a unit of collective dose in that group. The determination of the value of β_i is a complicated issue. As the following analysis shows, the two models mentioned above are identical although they are formulated in different ways.

Suppose that the value of α is a function of individual dose x and can be formulated as follows:

$$\alpha = \begin{cases} \alpha_0 & (x \le ID_0) \\ \alpha(x) & (x > ID_0) \end{cases} \tag{5}$$

According to Eq.(2), the radiation detriment cost equivalent can then be calculated as follows:

$$Y = \int_{ID_l}^{ID_r} \alpha(x) \bullet CD(x)\,dx = \alpha_0 S + \Delta Y \tag{6}$$

$$S = \int_{ID_l}^{ID_r} CD(x)\,dx \tag{7}$$

$$\Delta Y = \int_{ID_0}^{ID_r} [\alpha(x) - \alpha_0] \bullet CD(x)\,dx \tag{8}$$

where ID_l and ID_r stands for the left and right end of the whole range of individual dose over which collective dose is to be integrated. It is clearly shown from Eqs (6) and (8) that ΔY represents an additional cost equivalent as a consequence of considering individual dose distribution in dose ranges above ID_0.

4. AN IMPROVED APPROACH TO COST/BENEFIT ANALYSES

There exists a common limitation in the methods mentioned above for radiation detriment valuations. That is, the determination of α, β as well as the risk aversion exponent in practical applications is considerably subjective. Few quantitative criteria are available. Because of this, the evaluation of radiation detriment in cost/benefit analyses is sometimes quite arbitrary.

In order to take individual dose distribution into consideration in cost/benefit analyses reasonably, the concept of individual dose evaluation function is introduced in this paper. An individual dose evaluation function is a function of individual dose. It increases with increasing individual dose. Collective dose contributed from a certain range of individual dose will be evaluated by the value that the individual dose evaluation function applied takes in that individual dose range.

On the basis of the concept of individual dose evaluation function, an improved approach to cost/benefit analysis is proposed in this paper. The idea of this approach is the following. Radiation detriment cost is evaluated by an individual dose evaluation function. The individual dose evaluation function should sufficiently reflect the effect of individual dose distribution on the valuations of radiation detriment. At the same time, it should not unreasonably overestimate the radiation detriment cost so that the evaluated cost of potential collective dose without countermeasures would significantly exceed the economic cost as a consequence of implementing protective measures at a dose level acceptable to the general public. In this model the individual dose evaluation function will not be selected in advance of a cost/benefit analysis. It will be derived based on the economic cost under certain conditions as a result of taking countermeasures after nuclear accidents. In other words, we add an additional constraint to cost/benefit analyses which will be determined by specific accidental characteristics.

In this paper, we suppose that an individual dose evaluation function takes the form of a power function. The mathematical model of the improved approach to cost/benefit analyses can then be formulated as follows:

$$X + Y = \min imum \tag{1}$$

$$Y = \sum_i EF_i \bullet CD_i \tag{9}$$

$$EF_i = k_1 \bullet ID_i^{k_2} \tag{10}$$

where:

EF_i = value of an individual dose evaluation function in the ith dose range;
CD_i = collective dose contributed from the ith individual dose range;
ID_i = the medium point of the ith individual dose range;
k_1, k_2 = constant.

Suppose that X_0 stands for the economic cost as a consequence of taking protective actions at a dose level that is acceptable to the general public (ID_0). We can get k_1 and k_2 by solving the following equations:

$$\begin{cases} k_1 \bullet ID_0^{k_2} = \alpha_0 \\ \sum_i k_1 \bullet ID_i^{k_2} \bullet CD_i = X_0 \end{cases} \tag{11}$$

After having obtained the constant k_1 and k_2, we can derive the optimal dose intervention level initiating a protective measure using Eqs (1), (9) and (10).

As an example, we studied the optimization of dose intervention level for relocation using the improved model described above. The reference nuclear power plant is Biblis, Germany. The source term used is F3b-DE from German risk study phase B [10]. All calculations have been done using the European code package for accident consequence assessment COSYMA [11].

The preliminary results of the calculations show that the constant k_1 and k_2 depend upon shielding factor to external radiological exposures. For shielding factors in the range between 0.1 and 0.2, k_2 varies from about 2.0 to 2.5. When the shielding factor locates in the range between 0.5 and 1.0, it takes value between 1.2 and 1.6. This result is very close to the risk aversion exponent given in reference [8].

5. CONCLUSIONS

It is necessary to explicitly take individual dose distribution into consideration in cost/benefit analyses of countermeasures after nuclear accidents. For this purpose, some methods have been in place. There are, however, apparent deficiencies in those models. As a way of overcoming those deficiencies, we introduced the concept of individual dose evaluation function in this paper. In addition, we developed a modified approach to cost-benefit analysis of protective actions after nuclear accidents.

The improved model proposed in this paper can be used to determine an reasonable individual dose evaluation function and the optimal dose intervention levels of protective measures at the same time.

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