COST BENEFIT ANALYSIS
COST EFFECTIVENESS ANALYSIS

J. LOMBARD

cepn **centre d'étude sur l'évaluation de la protection dans le domaine nucléaire**

Boite Postale N° 48
92260 FONTENAY-AUX-ROSES
Tél. : 654.74.67

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J. LOMBARD

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J. Lombard

D/23/05

I - INTRODUCTION

The purpose of the ALARA (As Low As Reasonably Achievable) procedure is to compare various protection options in order to determine which is the best compromise between cost of protection and residual risk (see/1/). When there are several protection options or their introduction affects several dimensions, finding the compromise is not always easy and it is no longer possible merely to use "engineering judgement". In addition, one should be able to justify the choices made when they concern health, whatever the problems posed. In such cases, the use of quantitative decision-aiding techniques is valuable and it is hardly surprising that their use is recommended by the ICRP (see /2/), and has been adopted in various countries such as the United Kingdom (see/3/).

The use of decision-aiding techniques as an aid to selection procedures is not new. Well before the development of operational research during the 1950s, methods such as cost benefit analysis were used with varying degrees of success. The main lesson drawn from these various experiments is that there is no ideal method suited all possible situations. It is clear that the choice of a site for the storage of radioactive waste is not made in the same way as the choice of a lead shielding, and it is because of this that methods to help make these choices are not identical.

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However, the history of decision-aiding techniques is full of general, overall models which, according to their authors, should improve on the inadequacies of previous ones without causing additional disadvantages. It is true that the more general and sophisticated the method, the more it can take into account all elements, (subjective or not), which affect choice. We should recognize, however, that its implementation is more and more difficult and is sometimes limited to the few units which developed it. By definition, a decision-aiding technique should facilitate the work of the decision maker ; if its mechanisms make it incomprehensible, this purpose is rarely achieved, and the use of a rougher but simpler method is preferable.

The ALARA procedure covers a wide range of decisions and the choice of a single decision-aiding method is not recommended. It should be noted that ICRP, which presented only the cost benefit method in its recommendation 26/4/, mentioned the existence of several methods in its recommendation 37/5/ and suggested that the most appropriate method be used.

The purpose of this first lecture is to introduce two rather simple and well known decision aiding techniques : the cost-effectiveness analysis (CEA) and the cost benefit analysis (CBA). These two techniques are relevant for the great part of ALARA decisions which need the use of a quantitative technique (for the simplest choices the engineering judgement may be enough). In an other lecture two more sophisticated decision aiding techniques will be introduced /6/ ; these particular techniques being relevant for particular ALARA decisions.

II - COST EFFECTIVENESS ANALYSIS

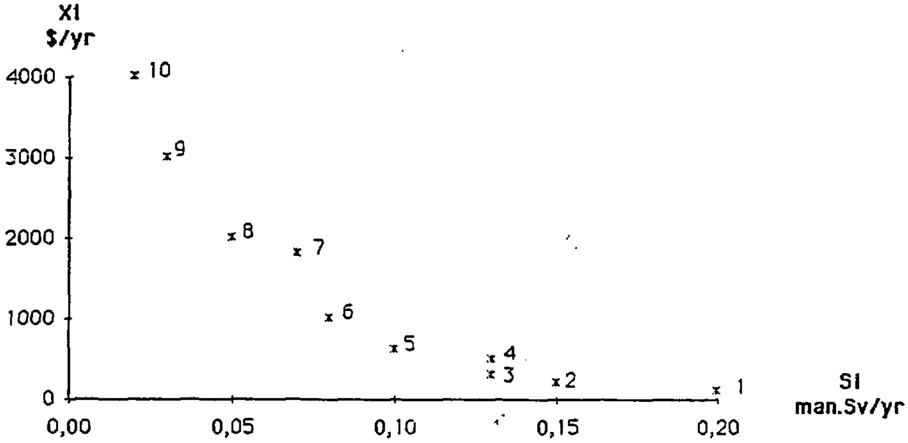
The ALARA procedure is used to find which option is the best compromise between the cost of protection Xi and the risk Ri (generally, the risk diminishes as the cost of protection increases), from a group of possible options Ai (choice of ventilation flowrate, screen thickness, etc.).

As an example we shall use in this lecture an hypothetical case of 10 protection options defined by their cost Xi and the residual risk Ri (if the option is choosen the protection cost is Xi and the residual risk Ri). One can express Xi in $ per year and for Ri the collective dose Si due to one year of exploitation can be choosen.

The following hypothetical values will be used :

Protection Option i	Collective dose Si (man Sv pear year)	Protection cost Xi ($ per year)
1	0.20	100
2	0.15	200
3	0.13	300
4	0.13	500
5	0.10	600
6	0.08	1 000
7	0.07	1 800
8	0.05	2 000
9	0.03	3 000
10	0.02	4 000

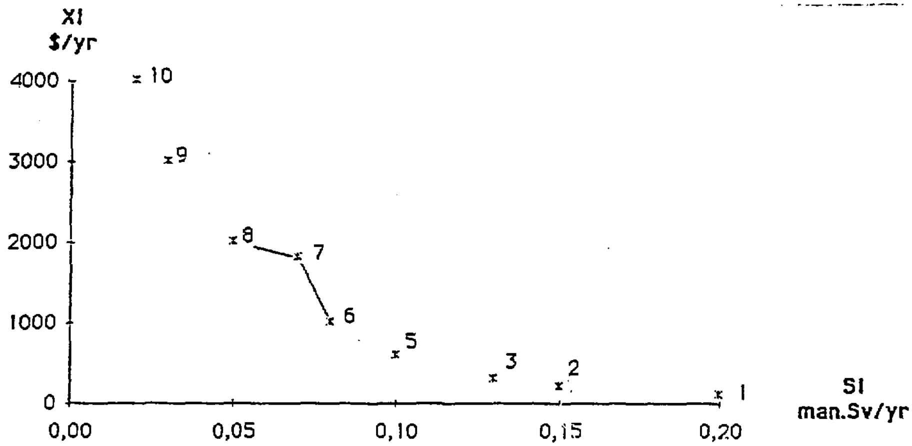
The most simple technique consists of plotting, on the same graph the cost Xi and the collective dose Si associated with each option i as follows :



II. 1 - Détermination of the cost effective options

Certain options may be eliminated immediately on the basis of this graph. Thus, if we compare option 4 with option 3, we see that option 4 is more expensive and leads to a same risk. Therefore option 4 is never advantageous when compared to option 3, and if the purpose of the ALARA procedure is to select one option among the ten possible, option 4 may be eliminated at once.

The elimination of option 4 stems more from good sense than from any methodology. The cost effectiveness analysis goes a little further and eliminates options which do not appear to be advantageous when they are compared to the two options on either side (that immediately less expensive and that immediately more expensive). If, for example, we analyze option 7, we note that for a small additional cost (from 7 to 8) we obtain a much higher effectiveness in terms of risk reduction than that obtained by going from option 6 to 7. This is shown by the break between the slope of the two lines joining points 6 and 7 and points 7 and 8.



Therefore option 7 is judged to be non "cost effective" and can be eliminated. Cost effective options are found mathematically after having eliminated the "totally dominated" option (option 4) by checking that successive slopes decrease evenly and that there is no break between slopes.

Slope estimation is made from a "cost effectiveness" ratio which is defined for each non-totally dominated option i with reference to the non-totally dominated option which precedes it, i-1, as follows :

$$\text{Cost effectiveness ratio of option } i = \left| \frac{X_i - X_{i-1}}{R_i - R_{i-1}} \right| = \left| \frac{\Delta X_i}{\Delta R_i} \right| = \alpha_i$$

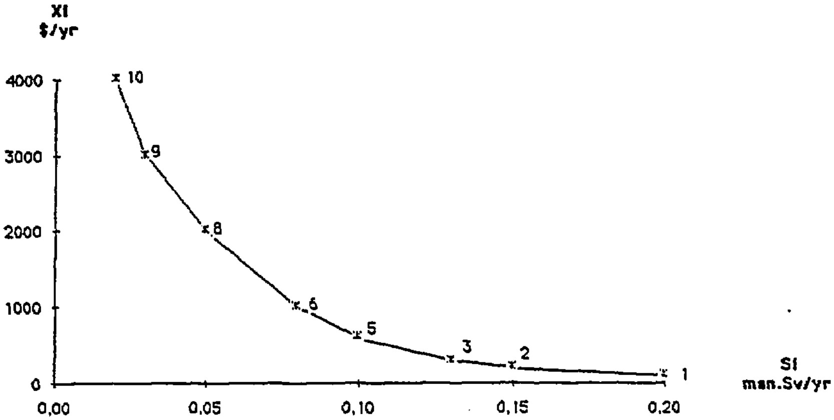
Therefore the following values are obtained :

Option i	Xi	Δ Xi	Si	Δ Si	α i
1	100	---	0.20	---	---
2	200	100	0.15	0.05	2000
3	300	100	0.13	0.02	5000
5	600	300	0.10	0.03	10000
6	1000	400	0.08	0.02	20000
7	1800	800	0.07	0.01	80000
8	2000	200	0.05	0.02	10000
9	3000	1000	0.03	0.02	50000
10	4000	1000	0.02	0.01	100000

Value α_7 is greater than value α_6, therefore option 7 is not cost effective and should be eliminated. After this elimination, the new value of α_8 becomes 33300 ($\Delta X = 1000$, $\Delta S = 0.03$) and all the residual options are "cost effective". It should be noted that the cost effectiveness ratio is never defined for the least expensive option, which is always cost effective.

All cost effective options make up what is called the lower part of the convex hull of the set of points, typifying the various options.

After this stage, one generally draws up the "cost effectiveness curve", which joins the "cost effective " options. (options 1,.2, 3, 5, 6, 8, 9 and 10)

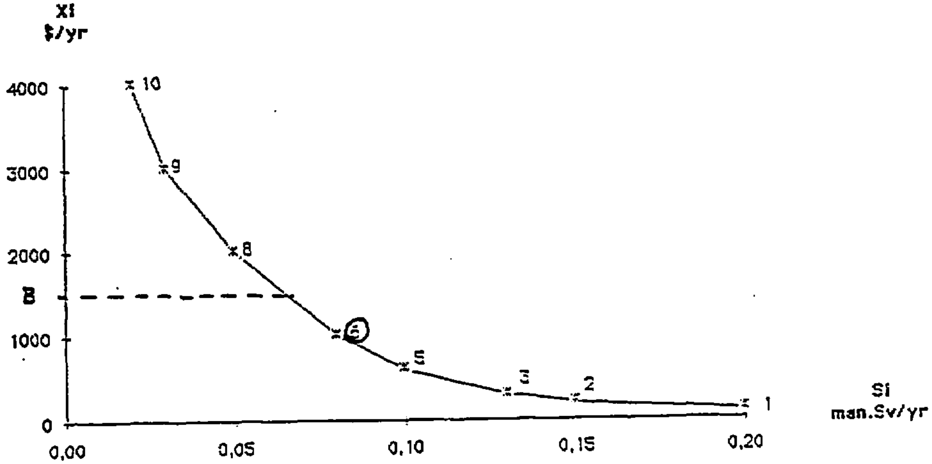


II.2 - Sélection procedures

The determination of cost effective options allows possible options to be sorted but never leads to a choice. Thus the previous graph has pre-selected 8 options (1, 2, 3, 5, 6, 8, 9 and 10) among the 10 possible options but cannot recommend one option among the 8. To do this, users of the cost effectiveness analysis have four different procedures available, one of them being only really valid.

II.2.1 - The budget limit

A simple selection procedure consists in adopting the option which corresponds to a present budget limit. Therefore, if budget B is available (1500 $ /yr as an example) option 6 will be chosen.



This simple procedure which generally (*) selects the option which corresponds to the budget limit and leads to minimum risk, is not strictly speaking an ALARA procedure since a comparison between costs and risks has not been carried out.

II.2.2 - A risk limit

The second procedure is equivalent to the first insofar as risk is concerned. If a risk limit is used, the least expensive cost effective option which corresponds to this limit shall be used. Therefore, if the limit which has been fixed is R (0,1 man.Sv/yr), option 5 shall be chosen.

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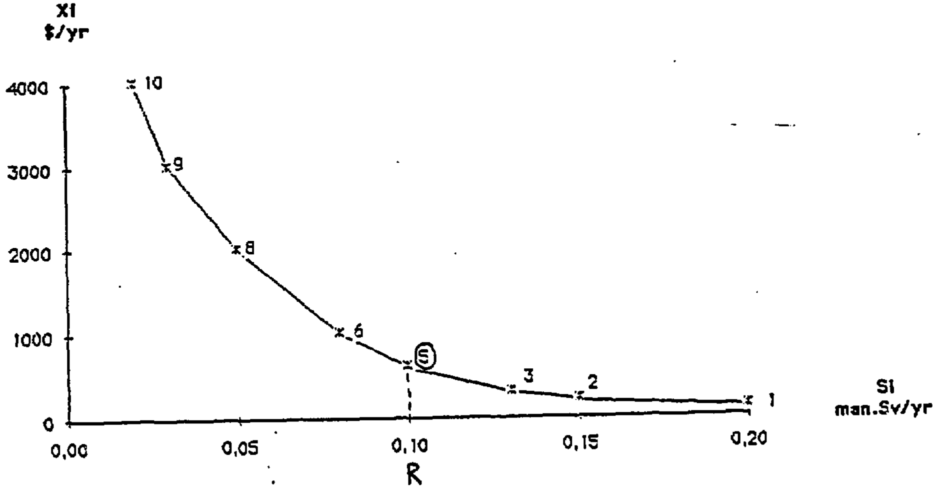
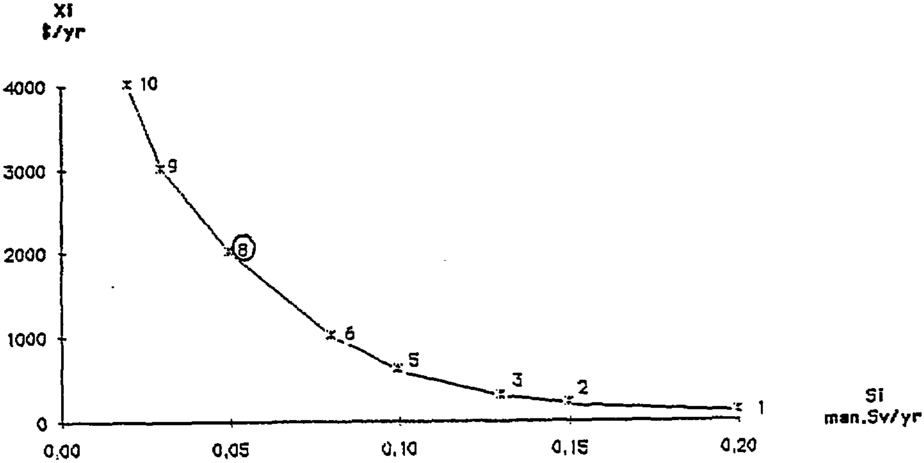
* the non-dominated options which are not cot effective (such as 7) may not be used since they do not appear on the curve (for B = 1900 $/ yr ; 7 is theoritically choosen).



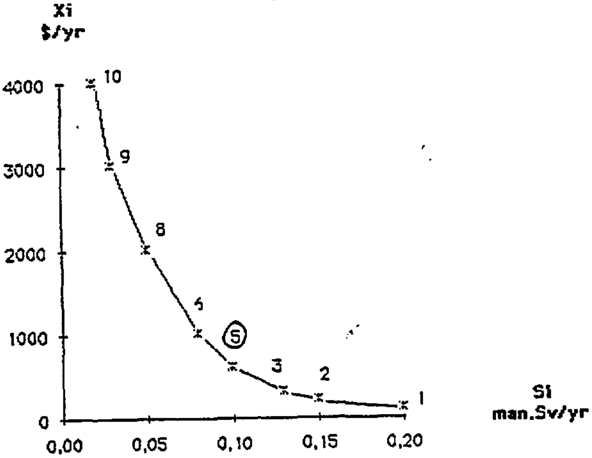
This procedure, which does not link costs and risks clearly, is not an ALARA procedure either.

II.2.3 - The "break point"

The third procedure finds whether the cost effectiveness curve shows a break point from which the effectiveness of options does not appear to be good (flat curve). This break point is easiest to find when there are a small number of cost effectiveness options. Here we can see that beyond option 8 costs seem too high from the effectiveness point of view, and therefore this "limit" option should be chosen.



This procedure, which combines costs and risks, may be considered in a first step an ALARA procedure. However, it is extremely dangerous. If it is based only on a visual reckoning (break in the slope of the curve), the result given depends entirely on the scale used. Therefore, if for example the same options are used but on a graph with the risk scale reduced by a factor of 2, the following result is obtained (new break point option : 5).



Therefore, only values which do not depend on the scale may be used, and the only solution consists in examining the evolution of cost effectiveness ratios associated with each option by determining the ratio of successive ratios. Therefore, the following results are obtained for the example :

Option i	α_i	α_i / α_{i-1}
1	---	-
2	2000	-
3	5000	2.5
5	10000	2
6	20000	2
8	33300	1.67
9	50000	1.5
10	100000	2

According to these values we can estimate that the greatest break point occurs between option 3 and option 2 ($\alpha_3 / \alpha_2 = 2.5$) and that the break point corresponds to option 2. However, this procedure does not compare realy costs and risks and is not recommended as an "pure" ALARA procedure.

II.2.4 - Referring to a preset α value

The final procedure consists in referring to a preset α value. The cost effectiveness ratios $\alpha_i = | \Delta X_i / \Delta S_i |$ give the monetary equivalent for each option i required to reduce the risk by one unit ($\alpha_i = \Delta X_i$ if $\Delta S_i = 1$). They therefore give the acceptable cost to reduce the risk by one unit when various possible options are implemented.

If in addition, the reference α value is available, the choice is simple, since when $\alpha_i \leqslant \alpha$, the option is viable and when $\alpha_i > \alpha$, the option is too expensive since it leads to expenditure higher than the reference.

Thus in the example, if the reference value alpha is 25000, option 6 should be adopted.

Finding this reference value requires choosing a risk indicator Ri which may be expressed in monetary terms. In general the man-Sievert, indicator of the collective dose, is used : therefore alpha corresponds to the cost of the man-Sievert.

II.3 - Single and multiple choices

The four procedures which have just been examined lead to the choice of one among all possible options. This is called a single choice. This procedure corresponds to a specific problem, e.g. an effluent pathway.

Multiple choices may also be encountered. In this case an option should be chosen for each of the choices offered, concerning, for example, different effluent pathways : a solution will be adopted for liquid and another one for a gaseous effluent concerning the same installation. To do this, there is often a tendency to carry out two different analyses and to define the combination of "local optimums" as the "general optimum", which assumes that the best solution for all choices is the combination of each of the solutions found for partial choices.

This practice, which is simple, is only valid if choices are INDEPENDENT, that is if cost or effectiveness of the various measures does not depend on choices which may have been made elsewhere. Clearly, if this is not the case, results will be erroneous. Thus, in a uranium mine (see /7/) in order to reduce the risks associated with radon products, galleries and stopes are ventilated using two types of fans. The efficiency of the fans used at the stopes depends on the effeciency of the gallery fan and choosing secondary ventilation for the stopes of 5 m ^{3} per second rather than 2 m ^{3} per second will reduce the risks less if the gallery fan is 30 m ^{3} per second rather than 20 m ^{3} per second.

In such situations, the options compared must be made independent by making what are called "combined options", which are general strategies combining all possible options. Thus, for the mine, a combined option will be paired ventilation (gallery, stope).

This solution, which is the only one guaranteeing the final result, multiplies the number of options to be compared. Thus, if we wish to compare four types of fan for the ventilation of the gallery and four other one the stopes, we should examine 16 (4 X 4) combined options. Generally, this disadvantage is mitigated by the fact that the examination of totally dominated options and non-cost effective options lead to a greater reduction.

Finally it should be noted that this problem is not specific to the cost effectiveness method and should be considered whatever the method used.

III - COST BENEFIT ANALYSIS

III.1 - Aggregative methods

If the comparison of protection options is made accordling to two criteria (e.g. cost of protection and collective dose) or more, it is not possible to classify these options directly to determine which is the best, since we have two or more values per option. However, if these various criteria can be translated into a single criteria, they may be combined or aggregated, and each option will have a single value. It would then be easy to classify options and to choose the best.

The concept of aggregating the various values associated with each option is the basis of most decision-aiding methods (including cost benefit analysis and decision analysis). If we accept this aggregation as possible, that is that the various values may be combined without prejudice, this procedure is recommended since it leads to single choices.

III.2 - Aggregation by cost

Each method of aggregation is different. In general, the most natural indicator for the problem should be used. Since the market has expressed a large number of products and services in monetary terms it is not surprising that aggregation by cost, or monetarization, should be the basis of the best known method of aggregation : cost benefit analysis. This analysis converts the various criteria into monetary terms so as to aggregate all these components by summation and to adopt the option which leads to minimum total cost.

III.3 - Cost benefit analysis

The ALARA procedure finds a compromise between the cost of protection and the health detriment.

If we admit that the collective dose S is a good indicator (or criteria) of the health risk, the costs and the collective doses associated with each protection option should be compared to find the best option. If a monetary equivalent for the man-Sievert (collective dose unit) is available, the risk may be changed into its monetary equivalent and the sum of the protection cost found, to establish the total cost.

If the cost of the man-Sievert is called α, the optimum option shall be that which minimizes the total cost :

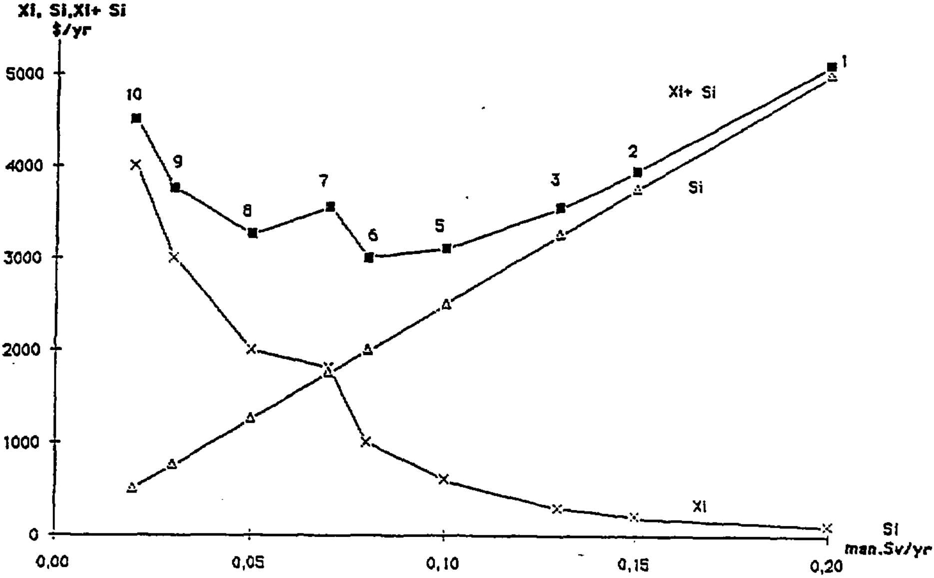
$Si * \Leftrightarrow$ minimum $(Xi + \alpha\, Si)$ or min $(Xi + Yi)$
where : Xi represents the protection cost of option i
Si the collective dose associated with option i
α the cost of the man-Sievert
i * the optimum option
γ i the cost of detriment

In general this minimization is illustrated by the following graph where the collective dose associated with each option is shown on the X axis, and the protection cost Xi, the cost of detriment α S and the total cost $(X + \alpha\, Si)$ are shown on the Y axis.

The application of the cost benefit analysis for the previous example gives the following results :

Option i	Xi $/yr	α Si $/yr	Xi+ α Si $/yr
1	100	5000	5100
2	200	3750	3950
3	300	3250	3550
4	500	3250	3750
5	600	2500	3100
6	1000	2000	3000
7	1800	2000	3550
8	2000	1250	3250
9	3000	750	3750
10	4000	500	4500

The option 6 which minimizes the total cost $(Xi + \alpha\, Si)$ corrresponds to the ALARA level and is the "analytical solution" as it is illustrated by the following graph (the option 4 being excluded of this graph).



One can notice that the two methods cost benefit analysis (CEA) cost effectiveness analysis (CEA) are very close.

CBA : Min (Xi + α Si)

$$= \frac{-dXi}{dSi} =$$

$$= \left| \frac{\Delta Xi}{\Delta Si} \right| = \alpha \text{ : CEA}$$

Therefore the result are the same, if the same value of α is chosen.

III - 4. the value of alpha

Cost benefit analysis or cost effectiveness analysis have the advantage of being easy to use. However they rely entirely on the man Sievert value alpha. This value is not easy to assess and a lecture is devoted on this problem /8/.

III - 5. Extended cost benefit analysis

III.5.1 - Principle

Although the cost benefit analysis (min $X_i + \alpha S_i$) is the method wich most minimizes the collective dose for a given cost and is therefore the most cost effective in terms of the objective risk, its use does not appear to be generally applicable to all ALARA procedures since the collective dose is not always the only health detriment indicator. Health risks have different forms which it is difficult to combine in a single risk :

- risk for neighbors (the public in general), workers,
- risk for present, future and remote generations,
- collective risks stemming from low, medium and high individual risks,
- risks due to the normal operation of the installation, to an incident, to an accident.

Thus, even if they theoretically lead to the same number of health effects, can two equivalent collective doses, one received by a neighbor following an accident and obtained from high individual exposure, and the other by workers following a routine inspection and obtained from low exposure, really be evaluated in the same way ?

III.5.2 - The NRPB proposition /see 9/

The NRPB in the United Kingdom, in its recommendations (10,11) concerning optimization, has extended the cost benefit analysis in order to differentiate the risks to the public from those to workers, and to take into account the level of individual risk. For this they use different values of alpha.

Category	Per caput dose (Sv/year)	alpha (£/man.Sv)
PUBLIC	$d < 5.10^{-5}$	2000
	$5.10^{-5} \leqslant d < 5.10^{-4}$	10000
	$5.10^{-4} \leqslant d < 5.10^{-3}$	50000
WORKERS	$d < 5.10^{-3}$	4000
	$5.10^{-3} \leqslant d < 1.5\ 10^{-2}$	20000
	$1.5\ 10^{-2} \leqslant d < 5.10^{-2}$	100000

Therefore the ALARA procedure minimizes the protection cost Xi associated with each option i, and the cost of detriment Yi which, however, is obtained from three factors Yi1, Yi2 and Yi3 which correspond for each category exposed to low per-caput doses Yi1, average doses Yi2 and high doses Yi3.

Therefore, to implement this extended cost benefit analysis, for each option i we must note the part of the collective dose Si which corresponds to the low per-caput doses (less than 5.10^{-5} Sv/year to the public) Si1, that corresponding to average per-caput doses (between 5.10^{-5} and 5.10^{-4} Sv/year) Si2, and that which corresponds to high per-caput doses (greater than 5.10^{-4} Sv/year) Si3. The analytical solution i is the option which minimizes the sum of :
(Xi + 2,000 Si1 + 10,000 Si2 + 50,000 Si3) if it concerns doses for individual members of the public.

This method, which allows individual doses which are close to the limit to be better taken into account, appears to be particularly appropriate when such doses are in question (hence generally for workers in certain nuclear fuel cycle installations such as uranium mines).

If the protection measures affect the public and workers simultaneously, then the three parts of the public collective dose Sp and the three parts of the workers collective dose Sw should be taken into account ; the recommended protection option is that which minimizes the following sum :

Xi + (2,000 Spi,1 + 10,000 Spi,2 + 50,000 Spi,2) +
(4,000 Swi,1 + 20,000 Swi,2 + 100,000 Swi,2)

or $\text{Min}\left(X_i + \sum_j \alpha_{p\,i,j} S_{p\,i,j} + \sum_j \alpha_{w\,i,j} S_{w\,i,j}\right)$

III.5.3. - A canadian proposition

An equivalent approach has been proposed by a Canadian working group /12/ which considers that the cost of health detriment Y is made up of two parts : $Y = \alpha S + \beta S$. To estimate which protection option should be adopted they carry out a cost effectiveness analysis to find the implicit value of β_i for each option with a fixed value of :

$$\beta_i = \left| \frac{\Delta X_i}{\Delta S_i} \right| - \alpha$$

Using a maximum value of β, \$1,000,000 per man-Sievert (1983 US \$) and the risk perception considered, they found a reference value β' which was used to find the ALARA protection option (see II.2.4).

III.5.4 - The ICRP formula

These two propositions comply with the formula introduced by ICRP publication 37, which laid down the cost of detriment Y by the following general formula :

$$Y = \alpha S + \beta \sum_j N_j f_j (H_j)$$

The Canadian formula fixed $f_j(H_j) = H_j$, the final result of β' being a compromise and the NRPB formula being the result of a three-step function f.

III.5.5 - Taking time into account

In addition to taking into account the level of individual doses, the second main reason which led to the extension of cost benefit analysis was the taking into account of the distribution of risks in time.

Management of long radioactive decay waste leads to the estimation of doses likely to be emitted in millions of years and the calculation of the emission of these doses to infinity does not appear to be realistic to some decision makers. Thus for example, a collective risk of 10^{-7} effect for the first year due to uranium 238 with a radioactive decay of 4.5 million years, would lead in theory to 325 health effects if the dose commitment is carried out to infinity ; but only 0.01 effect would be produced in the first 100,000 years, a period of time which separates us from the appearance of Neanderthal man. Should we take all these 325 effects into account, only retain part or ignore them completely ?

Some consider that we do not have the right to minimize or neglect the detriment which we are leaving for future generations. Others think that it is not realistic to take present and long-term future risks into account in the same way. Several propositions have been drawn up to take the risk distribution in time into cut-off account (see /13/) : time cut-off, de minimis level (time cut-off no longer takes health detriment into account after a given period of time, the de minimis level ignores detriment below a given value) but the formula which has the most supporters is the discounting of the cost of detriment (see /14/).

Discounting gradually reduces a monetary value in the course of time. The following formula is used :

$$Xf = \frac{Xp}{(1+r)^n}$$

where Xf represents the equivalent of a present value Xp after n years following discounting at an annual discounting rate r.

The higher the value of r, the more the value Xf decreases over time ; for example, the following values are obtained for different values of r after actualization of Xp equal to 1 (values rounded off to the nearest 10^{-3}).

	0.001	0.01	0.10
0	1	1	1
1	0.999	0.99	0.909
2	0.998	0.98	0.826
3	0.997	0.971	0.751
4	0.996	0.961	0.683
5	0.995	0.951	0.621
10	0.99	0.905	0.386
20	0.98	0.820	0.149
30	0.97	0.742	0.057
40	0.961	0.672	0.022
50	0.951	0.608	0.009
100	0.905	0.37	0
250	0.779	0.083	0
500	0.607	0.007	0
1000	0.368	0	0
2500	0.82	0	0
5000	0.007	0	0
10000	0	0	0

Thus, if a discount rate of one for a thousand is used, a man-Sievert estimated at 10,000 dollars for year 0 is only 9,900 dollars after 10 years, 3,680 dollars after 1,000 years and virtually nothing (0.456) after 10,000 years.

Taking time into account in the ALARA procedure transforms the cost of detriment Yi for each option i as follows, if discounting is used :

$$Yi = \sum_{i=0}^{\infty} \frac{Yi\,(t)}{(1+r)^{i}}$$

where Yi(t) is the non-discounted cost of detriment for year t, if option i is adopted (yi (t) = Si (t) for the simplified formula). The recommended protection option is that which minimizes the sum of Xi + Yi.

III.5.6 - Other extensions

Other extensions of cost benefit analysis have been considered but at present they have not led to concrete applications or recommendations. Their purpose is to integrate accidental situations, distinguishing the cost of detriment according to probability of risk-initiating events or taking non-probabilistic and non-mortal effects into consideration /15/.

While these attempts have not produced results, they underline the fact that certain ALARA techniques require extended full cost benefit analysis to better interpret the various factors which affect the choice. They also prove that beyond a certain point it is not easy to extend the cost benefit method, which in spite of everything requires all factors taken into account to be translated into monetary terms, and that a method which is better suited to this type of problem should be used. These specific methods will be presented in another lecture /6/.

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