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MONETARY VALUE OF THE MAN-SIEVERT FOR PUBLIC EXPOSURE VERSUS WORKER EXPOSURE

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SUMMARY

The implementation of cost-benefit analysis for the optimisation of radiation protection relies on the adoption of a monetary value of the man-sievert. From the economic point of view, the monetary value of the man-sievert can be seen as a function reflecting the individual and collective preferences associated with the level of exposures and the specificity of the exposure situations. It must thus integrate several dimensions:

- one dimension, which is independent of the exposure situation, is related to the potential health effects associated with the level of exposure;
- other dimensions are related to social and equity considerations, reflecting the characteristics of exposure situations: distribution of individual exposures, individual and social risk perception,…

In the case of occupational exposure, CEPN has developed a model to define the monetary values of the man-sievert according to the level of individual exposure. This model has been used by some European nuclear utilities for setting their own values to be used in the process of radiological protection optimisation for workers.

The question examined in this report concerns the establishment of this value for public exposure. For this purpose, two main differences between an individual exposure for a member of the public and for a worker are considered in terms of their influence on the willingness to pay for a reduction of exposure (reduction of the probability of radiation induced cancer):

- Difference in terms of initial individual level of exposure
  In practice, public exposure situations are characterised by lower levels of individual exposures than those observed for workers. According to the linear dose-effect relationship, in average, the members of the public are facing a lower probability of occurrence of potential radiation induced cancer than workers.
- Possibility to compensate the workers in case of radiation induced cancer
  In practice, compensation systems have been implemented for the workers exposed to ionising radiations and having developed a cancer. In the case of public exposure, such systems do not exist mainly due to the absence of a permanent individual monitoring of exposures and to the low level of exposures.

A theoretical model, based on the expected utility approach, is developed for evaluating how the willingness to pay for a reduction in the probability of a detriment varies either with the level of initial probability or with the existence of a compensation system. This model leads to the conclusion that given the lower probability for the public than for the workers (according to their individual level of exposure), and given the possibility for the workers to receive a compensation if they declare a radiation induced cancer, the willingness to pay should be higher when the probability is reduced for the public than for the workers.

A numerical application of the model based on a specific utility function is proposed and the evolution of the willingness to pay is analysed for different levels of relative risk aversion, initial probability, and compensation. From this numerical application, it appears that, when there is no compensation system implemented in case of a radiation

induced cancer, the difference between public and workers in terms of level of initial probability to develop a radiation induced cancer has nearly no impact on the willingness to pay (the latter of a member of the public - with the lowest initial probability - is from 2 ‰ to 2 % higher than the one for a worker).

The higher willingness to pay for the public is mainly related to the non existence of a compensation system compared with the workers. Depending on the level of compensation for workers and on the relative risk aversion coefficient, the willingness to pay for a reduction of probability of developing a radiation induced cancer for a member of the public should be between 2 and 6 times higher than that of a worker.

With the human capital approach, the monetary value of the health effects is given by valuing one year of loss of life expectancy with the Gross Domestic Product per capita per year. It leads to a monetary value of the radiation health effects per man-sievert for the public equal to 160 KF/man.Sv.

Furthermore, a recent survey conducted in France to evaluate the willingness to pay to reduce the probability of a radiation induced cancer in case of occupational exposure in nuclear power plants allowed to obtained a monetary value of the human life in case of death by cancer equal to 3 MF. According to this value, and using the probability of occurrence of a radiation induced health effect for the public presented above, the monetary value of the man-sievert obtained is: 220 KF/man.Sv.

Adopting a relative risk aversion coefficient between 2 and 3, and assuming that usually the compensation for a radiation induced cancer is greater than 50 %, the set of multiplying coefficients proposed is: 3, 5 and 6. The next table gives the resulting monetary values of the man-sievert when the different multiplying coefficients have been applied.

Basic monetary value of the man-sievert	**Multiplying coefficient**		
	3	**5**	**6**
160 KF/man.Sv	480 KF/man.Sv	800 KF/man.Sv	960 KF/man.Sv
220 KF/man.Sv	660 KF/man.Sv	1 100 KF/man.Sv	1 320 KF/man.Sv

In conclusion, it appears that the monetary value of the man-sievert to be applied in optimisation studies for the reduction of public exposures could be ranged between 500 KF/man.Sv and 1.3 MF/man.Sv.

1. INTRODUCTION

The implementation of cost-benefit analysis for the optimisation of radiation protection relies on the adoption of a monetary value of the man-sievert. From the economic point of view, the monetary value of the man-sievert can be seen as a function reflecting the individual and collective preferences associated with the level of exposures and the specificity of the exposure situations. It must thus integrate several dimensions:

- one dimension, which is independent of the exposure situation, is related to the potential health effects associated with the level of exposure;
- other dimensions are related to social and equity considerations, reflecting the characteristics of exposure situations: distribution of individual exposures, individual and social risk perception,…

In the case of occupational exposures, as already mentioned in the general framework part, a model has been developed to evaluate the monetary value of the man-sievert according to the level of individual exposure (Schneider et al., 1997). This model has been used by some nuclear utilities for setting their own values to be used in the process of radiological protection optimisation for workers (Lefaure, 1998). The question arising is how to evaluate this value for public exposure situations. For this purpose, two main differences between an individual exposure for a member of the public and for a worker have been considered in terms of their influence on the willingness to pay for a reduction of exposure (reduction of the probability of radiation induced cancer):

- <u>Difference in terms of initial individual level of exposure</u>
  In practice, public exposure situations are characterised by lower levels of individual exposures than those observed for workers. According to the linear dose-effect relationship, in average, the members of the public are facing a lower probability of occurrence of potential radiation induced cancer than workers.

- <u>Possibility to compensate the workers in case of radiation induced cancer</u>
  In practice, compensation systems have been implemented for the workers exposed to ionising radiations and having developed a cancer. In the case of public exposure, such systems do not exist mainly due to the absence of a permanent individual monitoring of exposures and to the low level of exposures (Derr et al., 1981).

The first part of this paper presents a theoretical model, based on the expected utility approach, to evaluate how the willingness to pay for a reduction in the probability of a detriment varies either with the level of initial probability or with the existence of a compensation system. Besides, since experimental studies have shown that the expected utility model has some weaknesses to evaluate risky situations, we discuss in a complementary analysis if the results are effected when a non expected utility model is used.

The second part of this paper deals with a numerical application of the model based on a specific utility function and analyses the evolution of the willingness to pay for different levels of relative risk aversion, initial probability, and compensation.

Finally, some recommendations are proposed for the monetary value of the man-sievert for public exposures.

2. THE THEORETICAL MODEL

To value the benefit associated with a reduction in the probability of a radiation induced cancer (i.e. reduction of the probability of detriment) either for members of the public or for workers, we basically use the framework developed by Jones-Lee (1974)[1]. In the present theoretical model, we have adjusted this general framework so that it fits either the expected utility model (E.U. in short) or a specific non expected utility model called the dual theory of choice under risk. We have done these adjustments in order to check the robustness of the results. Indeed, as indicated in the introduction, there now exist many ways of modelling risky choices and it is important to see to which extent a change in the selected model affects the properties of the monetary value of the man-sievert.

Whatever the selected model, the basic ingredients of the analysis are defined by:

- W_0 : total wealth of an individual in the absence of radiation induced cancer.

This total wealth includes not only the value of financial and physical assets, but also the implicit monetary value of life.

- L : the potential loss of wealth due to the occurrence of a radiation induced cancer.

- p_0 : the initial probability of the occurrence of a radiation induced cancer.

This probability is estimated by applying the linear dose-effect relationship to the initial level of individual exposure.

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1 Jones-Lee's model was developed in the framework of a state dependent utility function as being applied to identify the willingness to pay for a lower probability of death resulting from improvements in transport safety.

In the expected utility model, the individual values this initial position by:

$$p_0 U(W_0 - L) + (1 - p_0) U(W_0) \tag{1}$$

where the utility function of wealth (U) is an increasing and concave function.

Notice that in the E.U. model, the probabilities are not transformed; the individual's attitude towards risk is fully captured by the shape of the utility function.

To check the robustness of the results obtained in the E.U. model, it is useful to develop the same analysis in the framework of the dual theory of choice under risk (D.T.) because it does just the reverse of the E.U. model to capture the individual's risk attitude. Indeed in the D.T.'s model, the initial position is valued by:

$$h(p_0)(W_0 - L) + (1 - h(p_0))(W_0) \tag{2}$$

where h(p) is an increasing and concave function which besides satisfies the conditions[2]: h(0) = 0 and h(1) = 1

Clearly in D.T.'s model, the values of wealth are not transformed by the individuals. Their risk attitude is captured through the transformation function h(p) of the probability of occurrence of a radiation induced cancer.

Once the individual's initial welfare is obtained in each model one can turn to the valuation of a reduction in the probability of a radiation induced cancer. Whatever the model, we have to answer the following question: how much wealth is the individual willing to give up in order to face a lower probability of developing a radiation induced cancer, which is denoted p ($p < p_0$).

The amount of wealth the individual is willing to give up is denoted V. As a result in the E.U. model, V is solution of:

$$p\ U(W_0 - L - V) + (1 - p)\ U(W_0 - V) = p_0\ U(W_0 - L) + (1 - p_0)\ U(W_0) \tag{3}$$

while in D.T.'s model, V is given by:

2 This function is depicted in appendix 1.

$$h(p)(W_0 - L - V) + (1 - h(p))(W_0 - V) = h(p_0)(W_0 - L) + (1 - h(p_0))(W_0) \tag{4}$$

Whatever the model, V clearly depends among other things upon the value of the initial probability (p_0), the importance of the fall in probability (p_0 - p) and of course also the amount of the potential loss (L).

Our objective now is to specify in each model how V is affected by the parameters.

2.1. Analysis of the willingness to pay function in the expected utility model

As indicated above, we now discuss in the framework of the E.U. model how the willingness to pay v is affected either by the initial value of p_0, or by the existence of a compensation in case of detriment. Each point is developed separately in the following two sub-sections.

2.1.1. The impact of the initial level of the probability of radiation induced cancer

To see how V responds to the initial baseline probability p_0, we first differentiate V with respect to p from equation (3), and we obtain after simplification:

$$\frac{dV}{dp} = \frac{U(A) - U(B)}{pU'(A) + (1 - p)U'(B)} \tag{5}$$

where $A = W_0 - L - V$

$B = W_0 - V$

Examination of equation (5) reveals that $\frac{dV}{dp}$ is negative. The intuition behind this result is very simple: the stronger the reduction in the probability of radiation induced cancer, the more wealth the individual is willing to pay in order to benefit from this advantage.

For our purpose later on, we essentially need to evaluate $\frac{dV}{dp}$ around $p = p_0$ since we are going to be concerned with small probability changes[3] around an initial radiation induced cancer probability either for workers or for the public. When p is close to p_0, V is close to zero and then we obtain:

$$\left(\frac{dV}{dp}\right)_{p=p_0} = \frac{U(C) - U(D)}{p_0 U'(C) + (1 - p_0) U'(D)} \tag{6}$$

where $C = W_0 - L$

$D = W_0$

This expression will be central in the discussion about the monetary value of the man-sievert. Indeed consider now that the initial probability of occurrence of a radiation induced cancer is no longer p_0 but p_1 with $p_1 < p_0$ and that for this new group this probability p_1 is going to be reduced by the same amount as in the other group[4]. All other things being assumed identical, we have:

$$\left(\frac{dV}{dp}\right)_{p=p_1} = \frac{U(C) - U(D)}{p_1 U'(C) + (1 - p_1) U'(D)} \tag{7}$$

Notice that (6) end (7) have the same numerator. The difference between the two expressions lies in the denominator. Since C is smaller than D we have by concavity of U that $U'(C) > U'(D)$ and since p_1 is smaller than p_0, the denominator in (7) is smaller than the denominator in (6). Hence in absolute values we have:

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3 Since the initial levels of probabilities to develop a radiation induced cancer are very low, and because the final probabilities are necessarily non negative, the changes in the probabilities must necessarily be infinitesimal.

4 In our case, p_1 is the initial probability of a radiation induced cancer associated with the individual exposure of a member of the public, while p_0 plays the same role but for the workers.

$$\left| \left(\frac{dV}{dp} \right)_{p=p1} \right| > \left| \left(\frac{dV}{dp} \right)_{p=p0} \right| \qquad (8)$$

This result is central for what follows: it means that, ceteris paribus, the willingness to pay (W.T.P.) for a given small reduction in p is larger when p is initially low. If the cost of the technology necessary to obtain a given reduction in probability is the same at p_0 as at p_1, then <u>under the expected utility model</u>, funds to reduce the probability of radiation induced cancer should be allocated in priority to group with a low probability of radiation induced cancer.

This result is a consequence of risk aversion (concavity of U) in the E.U. model. Indeed under risk neutrality (U linear in wealth) we would have:

$$\left| \left(\frac{dV}{dp} \right)_{p=p_1} \right| = \left| \left(\frac{dV}{dp} \right)_{p=p_0} \right| = \left| C - D \right| = L \qquad (8')$$

so that W.T.P. would then be a constant whatever the initial probability of occurrence of a radiation induced cancer.

We now turn to the other potential justification for a difference in the willingness to pay, i.e., the possibility to compensate the worker who is developing a radiation induced cancer.

2.1.2. The impact of compensation for workers

As indicated in the introduction, it is sometimes argued that the monetary value of man-sievert should be lower for workers than for the public, because in case of radiation induced cancer a compensation (I) is paid to workers while no such scheme exists in case of a radiation induced cancer for the public. To check if such a statement holds true in the E.U. model, we now introduce the possibility of a compensation in case of occurrence of a radiation induced cancer so that V is now defined by:

$$pU(W_0 - L + I - V) + (1-p)U(W_0 - V) = p_0 U(W_0 - L + I) + (1 - p_0)U(W_0) \qquad (9)$$

and we wonder how increases in I affect V. In order to do that, we differentiate (9) with respect to I and V and we obtain:

$$\frac{dV}{dI} = \frac{pU'\left(W_0 - L + I - V\right) - p_0 U'\left(W_0 - L + I\right)}{pU'\left(W_0 - L + I - V\right) + \left(1 - p\right)U'\left(W_0 - V\right)} \tag{10}$$

While the denominator in (10) is positive, the numerator is sign ambiguous. Indeed, the numerator is a difference between two products that involve each a probability and a level of marginal utility. When we compare p $U'(W_0\text{-}L\text{+}I\text{-}V)$ with p_0 $U'(W_0\text{-}L\text{+}I)$, we have:

- $p<p_0$
- $U'(W_0\text{-}L\text{+}I\text{-}V) > U'(W_0\text{-}L\text{+}I)$ because of decreasing marginal utility.

Since we know nothing a priori upon the importance of the difference between the two levels of marginal utility (we only know its sign), it is impossible to determine if the numerator of equation (10) is positive or negative (or even zero). Hence in the E.U. model and under risk aversion it is not clear that the possibility of compensation should reduce the WTP for a lower radiation induced cancer probability. In fact under risk neutrality, dV/dI is clearly negative (yielding the intuitive result) but this conclusion cannot be extended to all risk averse utility functions. Nevertheless in the numerical examples developed below, dV/dI turns out to be negative for the specific class of risk averse utility functions we have used. This means that the willingness to pay to reduce the probability of radiation induced cancer is greater for non compensated individuals (public in our case) than for compensated ones (workers).

2.2. Analysis of the willingness to pay function in the model of dual theory of choice under risk

Because of the controversy around the ability of the E.U. model to value risky situations, we now proceed to the analysis of the willingness to pay function V in the framework of the dual theory of choice under risk.

2.2.1. The impact of the initial level of the probability of radiation induced cancer

To establish the link between V and p in D.T.'s model, we slightly rewrite equation (4), which, after obvious simplifications, becomes:

$$V = \left(h\left(p_0\right) - h\left(p\right)\right)L \tag{11}$$

It easily follows from (11) and from the concavity of h(p) that the lower the initial probability of radiation induced cancer, the higher the W.T.P. to reduce this probability by a given amount.

Indeed let $p = p_0 - \varepsilon$ and let us consider another initial probability p_1 ($p_1 < p_0$) that is also reduced by ε. Then V becomes V* where:

$$V^* = \left(h\left(p_1\right) - h\left(p_1 - \varepsilon\right)\right)L \tag{12}$$

Because h is concave in p, it is true that:
$h(p_1) - h(p_1 - \varepsilon) > h(p_0) - h(p_0 - \varepsilon)$ whenever $p_1 < p_0$.

Thus in this case $V^* > V$.

This result is very important because it shows the robustness of the property already described in the E.U. model. While E.U. and D.T. are very different models of choice under risk, they both predict that decision makers should value more a given reduction in radiation induced cancer probability when the initial probability is low. In other words both models predict that, ceteris paribus, priority should be given to reductions in the probability of occurrence of a radiation induced cancer for the public.

2.2.2. The impact of compensation for workers

We now turn to the impact of compensation on WTP. Once there is a possibility of compensation I, the definition of V in the D.T.'s model becomes:

$$h(p)(W_0 - L + I - V) + (1 - h(p))(W_0 - V) = h(p_0)(W_0 - L + I) + (1 - h(p_0))(W_0) \tag{13}$$

Again, obvious simplifications enable us to rewrite (13) as:

$$V = (h(p_0) - h(p))(L - I) \tag{14}$$

Because by assumption $p < p_0$, $h(p_0) > h(p)$ and thus $\frac{dV}{dI}$ is negative in D.T.'s model, implying that for this class of model, we do obtain without ambiguity that the willingness to pay to reduce a given probability of radiation induced cancer is greater when the individual are not compensated (public) than when they are compensated (workers).

2.3. Synthesis

While being very different, the two models of choice under risk considered here (E.U. and D.T.) lead to very similar conclusions about the relationship between the willingness to pay on the one hand and the values of p_0 or I, on the other hand:

- In both models, a lower initial probability should induce ceteris paribus a greater willingness to pay for a given reduction of probability.
- While the conclusions are less clear-cut for the impact of a compensation in the E.U. model, there seems nevertheless a general tendency to find a negative influence of the level of the compensation I on the value of the willingness to pay V.

<u>Remark</u>:

The fact to consider that a lower probability of developing a radiation induced cancer should increase the willingness to pay for a given reduction of this probability could lead to a questioning of the system of monetary values of the man-sievert developed for the radiation protection of workers. Indeed, the latter consider that an increasing monetary value of the man-sievert should be adopted when individual exposure increases (this means an increasing WTP to reduce exposures when the individual probability of developing a radiation induced cancer increases). In order to better understand this "contradiction", it has to be reminded that, in case of worker exposures, the objective of radiation protection optimisation is not only to reduce the collective exposure, but also the dispersion of individual exposures within a given group of workers. This objective results from the particularity of occupational exposure situations where lot of protection actions modify the dispersion of individual exposures and may lead to increase the exposures of a few individuals in order to reduce that of others. In order to favour a reduction of the dispersion of individual exposures, it is necessary to adopt, within a given group of workers, a greater monetary value of the man-sievert when the reduction of exposure concerns individuals having a higher level of individual exposures than for those with lower level of individual exposures. In case of public exposures to radioactive releases of nuclear installations, the situation is slightly different. Usually, the radiation protection actions will reduce the source of exposure, and all individuals will benefit from the same proportional reduction of exposures. In such situations, it is then not necessary to consider the dispersion of individual exposures within the members of the public. Even if this dispersion had to be considered, this would mean that an increasing value should be adopted for increasing levels of public individual exposures, but this should be done independently of the determination of the basic monetary value of the man-sievert.

3. NUMERICAL APPLICATION

In the preceding section, we have developed general models dealing with the relationship between the willingness to pay V, the level of probability of radiation induced cancer p and the existence of a compensation I. While these models produce a direction for the relationship, they do not offer guidance about orders of magnitude. In the present section, we use widespread information on the shape of the utility function in the E.U. model in order to compare the willingness to pay for workers on the one side, and for the public, on the other side.

In order to proceed to the numerical application, we need besides characteristics of utility functions, information on the initial probability of radiation induced cancer and on the potential loss. Each of these elements is discussed in turn in the following section.

3.1. Basic assumptions

3.1.1. Utility function and relative risk aversion coefficient

From the theoretical point of view, various functional forms of utility functions have been studied which reflect different attitudes towards risk. Many experimental studies have also been developed to estimate the risk aversion coefficient of individual decision makers by presenting them lotteries (i.e. a set of probabilities associated with different losses of wealth) and by letting them rank these lotteries (Blake, 1996 ; Friend et al., 1975 ; Hansen et al., 1982 ; Levy, 1994 ; Mehra et al., 1985 ; Szpiro, 1986 ; Weber, 1970). These studies usually show that the absolute risk aversion decreases with wealth. As far as relative risk aversion is concerned, they seem to support the idea of an almost constant coefficient of relative risk aversion[5].

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[5] Formally, absolute risk aversion at a given wealth level W_0 is defined by: $A_a = -\dfrac{U''(W_0)}{U'(W_0)}$. Relative risk aversion is the degree of absolute risk aversion multiplied by W_0, that is: $A_r = -W_0 \dfrac{U''(W_0)}{U'(W_0)}$.

As a consequence, two potential functional forms of the utility function emerge:

- either the utility function is logarithmic: $U(W) = \ln W$; implying that the coefficient of relative risk aversion is equal to unity,
- or the utility function is a power function defined by: $U(W) = \frac{1-\beta}{\beta} W^{\beta}$ with $\beta < 1$.

  This function exhibits positive and decreasing absolute risk aversion while the coefficient of relative risk aversion (A_r) amounts to $1-\beta$.

Notice that fundamentally, the logarithmic utility function is a special case of the power function which is obtained by choosing $\beta = 0$. In this paper, the calculation will thus be made using the second utility function, except in the case of a relative risk aversion factor equal to 1, where the first one will be used.

3.1.2. Range of probabilities for public and workers

The value of the initial probability of radiation induced cancer for public and workers has been evaluated on the basis of the dose-effect relationship (ICRP, 1991). Two situations have been considered for assessing this probability: the exposure to the individual dose limits and a lower individual exposure level reflecting better the main actual situations. In both situations, the initial probability of a radiation induced cancer corresponds to the lifetime risk (excess number of fatal cancers).

a) <u>Exposure to the individual dose limit</u>

- If we assume a member of the public exposed at the annual dose limit (1 mSv/year) during 75 years, his lifetime dose is equal to 75 mSv, and his lifetime risk is equal to $4.\ 10^{-3}$.

- If we assume a worker exposed at the annual occupational dose limit (20 mSv/year) from age 18 to 65 years, his lifetime dose is equal to 960 mSv, and his lifetime risk is equal to $4.\ 10^{-2}$.

For this situation, the willingness to pay will be evaluated for a reduction of probability equal to $1.\ 10^{-3}$ for the public and for the workers. The results for this situation are presented in Appendix 2

b) Exposure to an average individual level

- If we assume a member of the public exposed at 0.1 mSv/year during 75 years, his lifetime dose is equal to 7.5 mSv, and his lifetime risk is equal to 4. 10^{-4}.

- If we assume a worker exposed at 5 mSv/year from age 18 to 65 years, his lifetime dose is equal to 240 mSv, and his lifetime risk is equal to 10^{-2}.

For this situation, the willingness to pay will be evaluated for a reduction of probability equal to 1. 10^{-4} for the public and for the workers.

3.1.3. Level of wealth and loss of wealth

The initial level of wealth is supposed to be the same for a member of the public and a worker: W_0 = 6 MF (rounded value). It is based on two components:

- The monetary value of life, evaluated with the human capital approach[6]: 5.7 MF (GDP/capita x average life expectancy of the general population = 135 KF x 42 years)
- The average individual financial wealth: 0.5 MF (total private capital of households/number of inhabitants = 28. 10^9 / 58. 10^6)

The loss of wealth in case of a radiation induced cancer is evaluated on the basis of its associated loss of life expectancy (GDP/capita x loss of life expectancy due to a radiation induced cancer = 135 KF x 16 years): L = 2 MF (rounded value).

Three levels of compensation for the workers have been selected:
- 0 % of the loss (I = 0 MF), so that L - I = 2 MF
- 50 % of the loss (I = 1 MF), so that L - I = 1 MF
- 75 % of the loss (I = 1.5 MF), so that L - I = 0.5 MF

These assumptions reflect the current compensation system applied for workers in France for radiation induced cancers (EDF, 1997).

6 Another solution could be to evaluate the monetary value of life using the contingent valuation approach. This approach is discussed later in § 3.3.

3.2. The main results

The utility function : $U(W) = (1\text{-}ß)/ß \,.\, W^{ß}$ has been studied with four different coefficients of relative risk aversion ($A_r = 1\text{-}ß$)[7]:

- $A_r = 0.5 \Rightarrow ß = 0.5$; $U(W) = \sqrt{W}$
- $A_r = 1 \Rightarrow ß = 0$; $U(W) = Log(W)$
- $A_r = 2 \Rightarrow ß = -1$; $U(W) = -2/W$
- $A_r = 3 \Rightarrow ß = -2$; $U(W) = -1.5/W^2$

The willingness to pay "V" to reduce the probabilities by ε was calculated by solving a slightly different version of the preceding equation (9):

$$p_i U(W - L + I) + (1 - p_i)U(W) = (p_i - \varepsilon)U(W - L + I + V) + (1 - (p_i - \varepsilon))U(W - V)$$

Where, as before:

- W : total wealth of an individual in the absence of radiation induced cancer.
- L : the potential loss due to the occurrence of a radiation induced cancer.
- p_i : the initial probability of the occurrence of a radiation induced cancer, either for the public (p_i=p_0) or for the workers (p_i=p_1).
- ε : reduction in the initial probability of a radiation induced cancer (so that $p = p_i - \varepsilon$ in equation (9)).

In each of the following subsections, we present in the tables the willingness to pay attached either by a member of the public or by a worker to a reduction of the probability of radiation induced cancer equal to 1/10 000 and an initial probability corresponding to an exposure at the average individual level of exposure. The set of probabilities is then:
p_0 = 4/10000 ; $p_0 - \varepsilon$ = 3/10000 (Public)
p_1 = 100/10000 ; $p_1 - \varepsilon$ = 99/10000 (Workers)

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7 It can be easily shown that with such a utility function, $A_r = -W\dfrac{U''(W)}{U'(W)} = 1 - \beta$.

The Appendix 2 presents the case of a reduction of probability equal to 1/1000, and an initial probability corresponding to an exposure at the annual dose limit.

3.2.1. Comparison between public and workers, both with no compensation system

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer: $L_0 = L_1 = 2$ MF (no compensation)

Table 1. Comparison of the willingness to pay for a given reduction of probability between public and workers, both with no compensation system

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0002201872	0.0002432376	0.000299872	0.000374697
Workers non compensated	0.000219713	0.000242075	0.000296318	0.000366351
Ratio Public/Workers	1.002	1.005	1.012	1.023

It appears that, when there is no compensation system implemented in case of a radiation induced cancer, the variation of the willingness to pay for a given reduction of probability with the initial level of probability is quite low. The willingness to pay of a member of the public (with the lowest initial probability) is from 2 ‰ to 2% higher than the one for a worker.

3.2.2. Comparison between public with no compensation system and workers with 50% of compensation

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer:
  - $L_0 = 2$ MF (no compensation for public)
  - $L_1 = 1$ MF (compensation of workers: 50% of loss)

Table 2. Comparison of the willingness to pay for a given reduction of probability between public non compensated and workers with 50% of loss compensated

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0002201872	0.0002432376	0.000299872	0.000374697
Workers compensated at 50 % of loss	0.0001044557	0.0001091757	0.000119477	0.0001310511
Ratio Public/Workers	2.108	2.228	2.510	2.859

When there is a compensation of 50 % of the loss due to a radiation induced cancer, the willingness to pay of a worker for the reduction of probability is quite lower than in the situation where no compensation can be obtained. As a result, the willingness to pay of a member of the public (non compensated) is very different that that of a worker (compensated), being between 2 and 2.8 times greater.

3.2.3. Comparison between public with no compensation system and workers with 75% of compensation

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer:
  - $L_0 = 2$ MF (no compensation for public)
  - $L_1 = 0.5$ MF (compensation of workers: 75% of loss)

Table 3. Comparison of the willingness to pay for a given reduction of probability between public non compensated and workers with 75% of loss compensated

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0002201872	0.0002432376	0.000299872	0.000374697
Workers compensated at 75 % of loss	5.106488E-5	5.212965E-5	5.444250E-5	5.685609E-5
Ratio Public/Workers	4.312	4.663	5.508	6.590

With 75% of loss compensated for the workers, the difference between the willingness to pay for a member of the public and a worker is quite important, being between 4 and 6.5 higher for the public.

Figure 1 summarises the results obtained for the different values of the relative risk aversion coefficient.

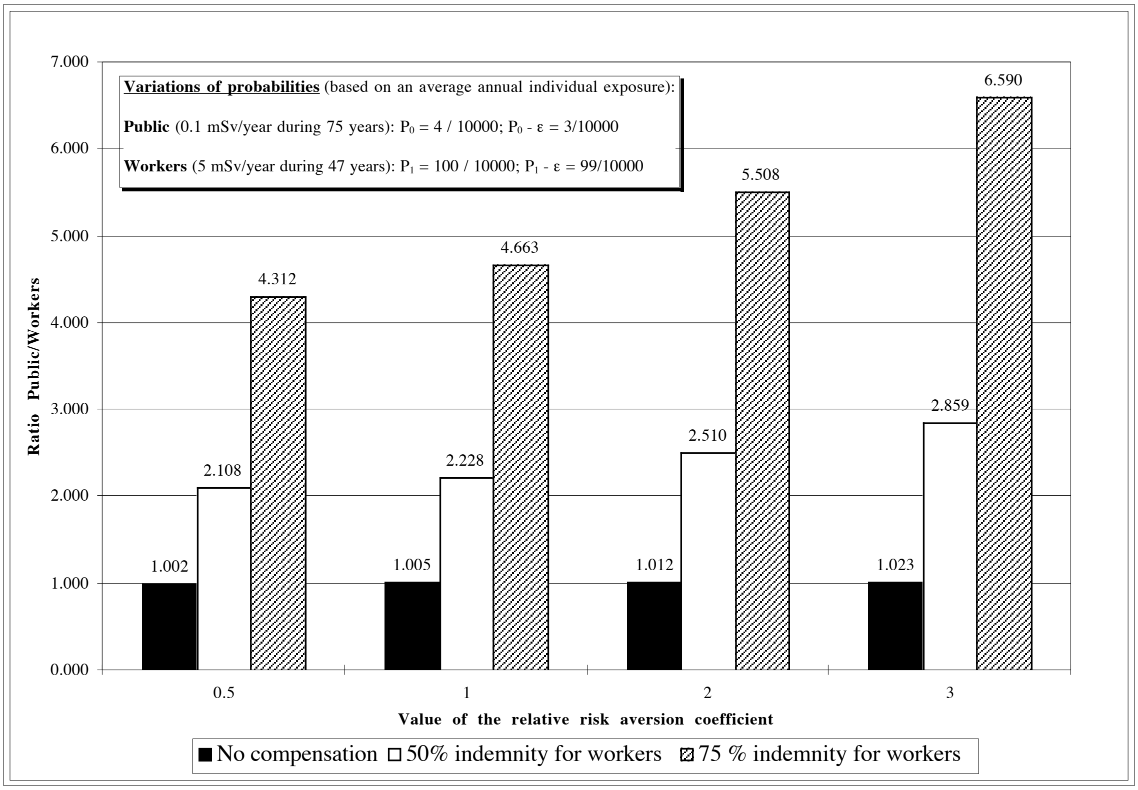

Figure 1. **Ratio of the WTP for a small reduction of probability of occurrence of a radiation induced cancer according to increasing values of the relative risk aversion coefficient**

3.3. Calculation of the monetary value of the man-sievert for the public

As noted in the introduction, the monetary value of the man-sievert integrates several dimensions:

- The first dimension is related to the monetary value of the potential health effects associated with an exposure of one man-sievert. This "basic" value can be obtained either by the "Human Capital approach", or by the "Revealed Preferences approach".

- The other dimensions are related to social and equity considerations reflecting the characterisation of the exposure situations. The ratios obtained previously between the WTP for a reduction of probability of a radiation induced cancer between public and workers, give an indication of the multiplying factor which could be applied to the "basic" monetary value of the man-sievert.

3.3.1. Calculation of the "basic" monetary value of the man-sievert related to the monetary value of the potential health effects

a) Human Capital Approach

With this approach, the monetary value of the health effects is given by valuing one year of loss of life expectancy with the Gross Domestic Product per capita per year. The following assumptions are:

- Average loss of life expectancy associated with a radiation induced health effect (fatal cancer and hereditary effect) : 16 years
- GDP per capita per year: 135 KF
- Monetary value of one radiation induced health effect: 135 * 16 = 2.2 MF
- Probability of occurrence of a radiation induced health effect for the public: 7.3 10^{-2} Sv^{-1}
- Monetary value of the radiation health effects per man-sievert for the public: 2.2 x 7.3 x 10^{-2} = 160 KF/man.Sv

b) Revealed Preference Approach

A recent survey conducted in France to evaluate the willingness to pay to reduce the probability of a radiation induced cancer in case of occupational exposure in nuclear power plants allowed to obtained a monetary value of the human life in case of death by cancer equal to 3 MF (Leblanc et al., 1997).

According to this value, and using the probability of occurrence of a radiation induced health effect for the public presented above, we obtain the following monetary value of the man-sievert: 3 x 7.3 x 10^{-2} = 220 KF/man.Sv

3.3.2. Application of the multiplying coefficient to the basic monetary value of the man-sievert

The rounded values of the multiplying coefficients obtained in the numerical application according to the different situations (compensation or no compensation) and to the different relative risk aversion coefficients are the following:

Table 4. Rounded values of the multiplying coefficients according to the different situations and to the four relative risk aversion coefficients

	Ar = 0.5	Ar = 1	Ar =2	Ar =3
No compensation	1	1	1	1
Compensation of 50 % for the workers	2.1	2.2	2.5	2.9
Compensation of 75 % for the workers	4.3	4.7	5.5	6.6

Adopting a relative risk aversion coefficient between 2 and 3, and assuming that usually the compensation for a radiation induced cancer in greater than 50 %, the following set of multiplying coefficients is proposed: 3; 5 and 6.

The "basic" monetary value of the man-sievert in case of public exposure is between 160 and 220 KF/man.Sv. Table 5 gives the resulting monetary value of the man-sievert when the different multiplying coefficients have been applied.

Table 5. Proposal for the monetary values of the man-sievert in case of public exposure

Basic monetary value of the man-sievert	**Multiplying coefficient**		
	3	**5**	**6**
160 KF/man.Sv	480 KF/man.Sv	800 KF/man.Sv	960 KF/man.Sv
220 KF/man.Sv	660 KF/man.Sv	1 100 KF/man.Sv	1 320 KF/man.Sv

Under the preceding assumptions, it appears that the monetary value of the man-sievert to be applied in optimisation studies for the reduction of public exposures could be ranged between 500 KF/man.Sv and 1.3 MF/man.Sv.

4. CONCLUSION

The theoretical model used to evaluate the willingness to pay to reduce the probability of occurrence of a radiation induced fatal cancer shows that, given the lower probability for the public than for the workers (according to their individual level of exposure), and given the possibility for the workers to receive a compensation if they declare a radiation induced cancer, the willingness to pay should be higher when the probability is reduced for the public than for the workers.

It appears, from the numerical application, that the difference between public and workers in terms of level of initial probability to develop a radiation induced cancer has nearly no impact on the willingness to pay (the latter of a member of the public - with the lowest initial probability - is from 2 ‰ to 2% higher than the one for a worker).

The higher willingness to pay for the public is mainly related to the non existence of a compensation system. Depending on the level of compensation for workers and on the relative risk aversion coefficient, the willingness to pay for a reduction of probability of developing a radiation induced cancer for a member of the public should be between 2 and 6 times higher than that of a worker.

Considering a basic monetary value of the man-sievert ranged between 160 KF/man.Sv and 220 KF/man.Sv (based on human capital approach or revealed preference approach), and a multiplying coefficient between 3 and 6, the resulting monetary value of the man-sievert to be applied in optimisation studies for the reduction of public exposures is ranged between 500 KF/man.Sv and 1.3 MF/man.Sv.

REFERENCES

Blake D. (1996), **Efficiency, Risk Aversion and Portfolio Insurance: an Analysis of Financial Asset Portfolios Held by Investors in the United Kingdom**, The Economic Journal, Vol. 106, September 1996, pp. 1175-1192.

Derr P., Goble R., Kasperson R. E., Kates R. W. (1981), **Worker/public Protection: The Double Standard**, Environment, Vol. 23, N°7, September 1981.

EDF-Service de Radioprotection (1997), **Le risque attribuable**, juillet 1997 - N°11.

Friend I., Blume M. (1975), **The Demand for Risky Assets**, American Economic Review, vol. 65, pp. 900-922.

Hansen L. P., Singleton K .J. (1982), **Generalized Instrumental Variables Estimation of Non-linear Expectations Models**, Econometrica 50, September 1982, pp. 1269-1286.

ICRP (1991), **1990 Recommendations of the International Commission on Radiological Protection,** ICPR publication 60, Pergamon press, Oxford.

Jones-Lee M. (1974), **The Value of Changes in the Probability of Death or Injury**, Journal of Political Economy, 82, pp. 835-849.

Leblanc G., Schneider T. (1997), **Enquête de révélation des préférences pour le système de valeurs monétaires de l'homme-sievert**, CEPN-R-253, Octobre 1997.

Lefaure C. (1998), **Valeurs monétaires de l'homme-sievert - Du concept à la pratique : résultats d'une enquête internationale**, CEPN-R-254, Septembre 1998.

Levy H. (1994), **Absolute and Relative Risk Aversion: An Experimental** Study, Journal of Risk and Uncertainty, Vol. 8, pp. 289-307.

Mehra R., Prescott E. C. (1985), **The Equity Premium - a puzzle**, Journal of Monetary Economics, Vol. 15, pp. 145-161.

Schneider T., Schieber C., Eeckhoudt L., Gollier C. (1997), **Economics of Radiation Protection: Equity Considerations**, Theory and Decision, 43, pp. 241-251.

Szpiro G. (1986), **Measuring Risk Aversion: an Alternative Approach**, The Review of Economics and Statistics, Vol. LXVIII n°1, February 1986.

Weber W. E. (1970), **The Effect of Interest Rates on Aggregate Consumption**, American Economic Review, Vol. 60, September 1970, pp. 591-600.

Yaari M.E. (1987), **The Dual Theory of Choice Under Risk**, Econometrica, 55, pp.95-115.

APPENDIX 1
THE FUNCTION OF TRANSFORMATION OF PROBABILITIES IN THE DUAL THEORY OF CHOICE UNDER RISK

The function of transformation of probabilities, h(p), used in the dual theory of choice under risk is an increasing and concave function which satisfies the conditions:
h(0) = 0 and h(1) = 1

It is depicted in Figure 1.

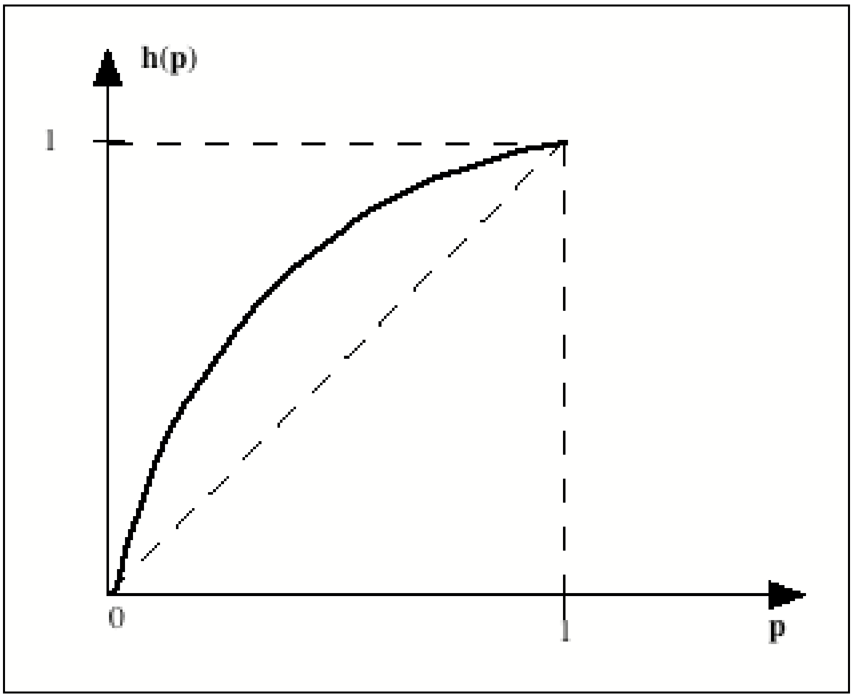

Figure A1-1. Function of transformation of probabilities, h(p)

APPENDIX 2
NUMERICAL APPLICATION CONSIDERING AN INITIAL LEVEL OF EXPOSURE EQUAL TO THE INDIVIDUAL ANNUAL LIMIT

1. Estimation of the initial probability of developing a radiation induced cancer

If we assume a member of the public exposed at the annual dose limit (1 mSv/year) during 75 years, his lifetime dose is equal to 75 mSv, and his lifetime risk is equal to $4. 10^{-3}$ (initial probability: $p_0 = 4/1000$).

If we assume a worker exposed at the annual occupational dose limit (20 mSv/year) from age 18 to 65 years, his lifetime dose is equal to 960 mSv, and his lifetime risk is equal to $4. 10^{-2}$ (initial probability: $p_1 = 40/1000$).

For this situation, the willingness to pay will be evaluated for a reduction of probability equal to $1. 10^{-3}$ for the public and for the workers.
(Public: $p_0 - \varepsilon = 3/1000$; Worker: $p_1 - \varepsilon = 39/1000$)

2. Comparison between public with no compensation system and workers with no compensation system

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer: $L_0 = L_1 = 2$ MF (no compensation)

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0022035	0.00242865	0.0029872	0.0037199
Workers non compensated	0.002182704	0.00238577	0.00285912	0.0034289
Ratio Public/Workers	1.008	1.018	1.045	1.085

3. Comparison between public with no compensation system and workers with 50% of compensation

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer:
  - $L_0 = 2$ MF (no compensation for public)
  - $L_1 = 1$ MF (compensation of workers: 50% of loss)

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0022035	0.00242865	0.0029872	0.0037199
Workers compensated at 50 % of loss	0.00104162	0.00108563	0.0011795209	0.0012831401
Ratio Public/Workers	2.112	2.237	2.533	2.899

4. Comparison between public with no compensation system and workers with 75% of compensation

Assumptions:

- Initial wealth: $W_0 = W_1 = 6$ MF
- Loss in case of a radiation induced cancer:
  - $L_0 = 2$ MF (no compensation for public)
  - $L_1 = 0.5$ MF (compensation of workers: 75% of loss)

WTP	Ar = 0.5	Ar = 1	Ar = 2	Ar = 3
Public non compensated	0.0022035	0.00242865	0.0029872	0.0037199
Workers compensated at 75 % of loss	0.000509979	0.000520201	0.000541391	0.000563610
Ratio Public/Workers	4.315	4.669	5.518	6.600

5. Synthesis

It appears that the values of the ratio between the public WTP and the workers WTP are not very different between the two sets of probabilities (one, presented in section 3, corresponding to an average individual level of exposure, and the one presented here, corresponding to an exposure at the annual individual limit).

- When both public and workers are not compensated, the WTP for public is not very different from that of workers, with a ratio being at maximum equal to 2%.
- When workers are compensated at 50% of their loss, the ratio of the WTP for public and workers is between 2 and 3
- When workers are compensated at 75% of their loss, the ratio of the WTP for public and workers is between 4 and 6

The following Figure presents these ratio for the two sets of probabilities and the four different values of the relative risk aversion coefficient.

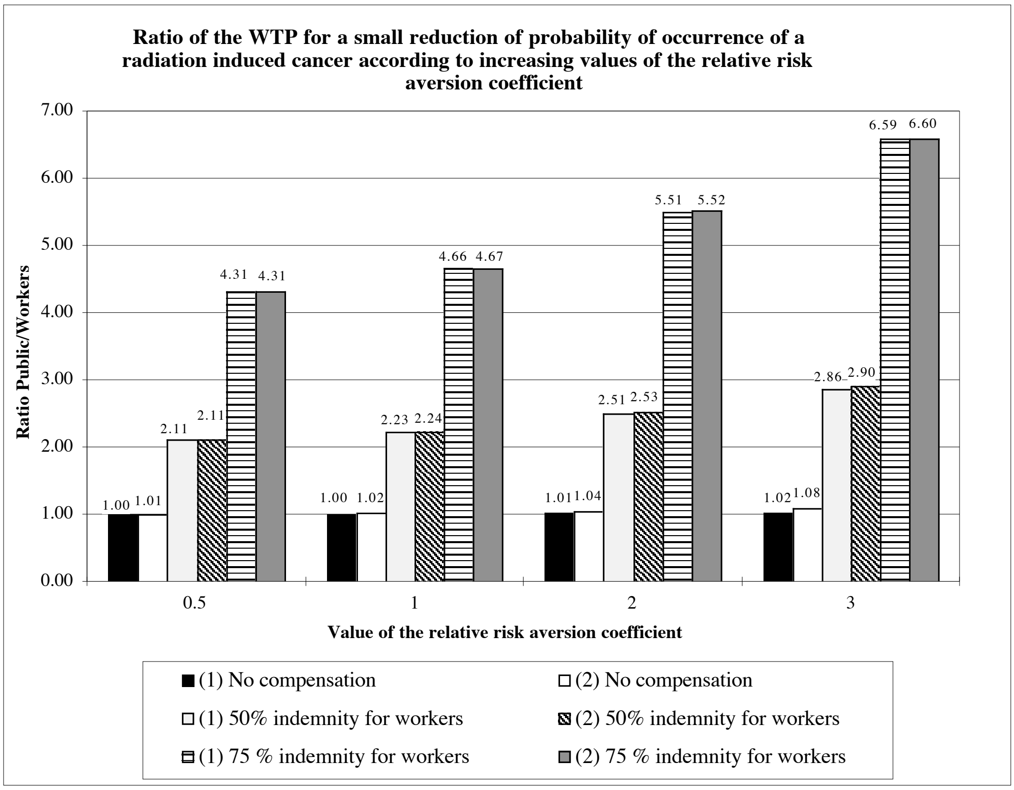

Figure A2-1. Ratio of the WTP of public and workers -
(1) Initial probabilities based on an exposure at the annual dose limit
(2) Initial probabilities based on an average annual individual exposure