YEARS OF LIFE LOST DUE TO EXTERNAL RADIATION EXPOSURE

Jagoš J. Raičević (1)*, Milan J. Merkle* (2)*, Joachim Ehrhardt* (3)*,*
Marko M. Ninković (1)
(1) *Institute for Nuclear Sciences "Vinča" P.O.Box 522, 11000 Belgrade, Yugoslavia*
(2) *Faculty of Electrical Engineering P.O.Box 816, 11001 Belgrade, Yugoslavia*
(3) *Forschungszentrum Karlsruhe, GmbH IKET, Bau 433, P.O.Box 3640, 76021 Karlsruhe, Germany*

ABSTRACT

A new approach(1) for calculation of the years of life lost per excess death (YLL) due to stochastic health effects is applied to external exposure pathways. The short-term external exposures are due to the passage of radioactive cloud (CL) and due to the skin and clothes contamination (SK). The long-term external exposure is the one from the radioactive material deposited on ground (GR). Three nuclides, ^{131}I, ^{137}Cs and ^{239}Pu with extremely wide range of the half-life are considered to examine its possible influence on the calculated YLL values. For each of these nuclides, the YLL is found as a decreasing function of the age at exposure and presented graphically in this paper. Another negative correlation is established between the fully averaged YLL and the duration of the nuclide's half-life has been found for protracted exposure (GR). On the other hand, the YLL for the short-term external exposures (CL and SK) practically does not depend on the nuclide's half-life. In addition, a weak YLL dependence of the dose was commented.

Key words: radiation, radiation exposure, life lost, , ^{131}I , ^{137}Cs , ^{239}Pu

INTRODUCTION

Following a nuclear accident, certain amount of radioactive material reaches a human environment. Due to exposure to such low doses, a number of stochastic somatic health effects may occur in the observed population, which can be assessed by various models(2). Each death causes a certain loss of life, which is in this paper called the years of life lost per excess death, and abbreviated with the YLL. External exposure pathways can be divided into the short and long term exposures. The short-term exposures are due to the passage of the radioactive cloud (CL) and due to the skin and clothes contamination. The long-term one is exposure to radioactive material deposited on the ground (GR). Due to its ability to assess the YLL for both, short and long term radiation exposure, the method established in (1) is used. This method is also applicable to internal exposure pathways - however, it is out of the scope of this paper. It should be noted that YLL depends on many factors; however, in this paper dependence *YLL(a)*, where a is age at exposure is considered only. This paper is organized as follows. The next section describes the model for calculation of the survival function by means of the probability of radiation induced death. The third section presents the YLL curves for particular exposure pathways, giving also the table with fully averaged YLL values.

MATERIALS AND METHODS

Let us introduce two age parameters: a - the age at exposure and l - natural duration of life, which an individual would experience in case of no irradiation. The mean number of years of life lost per excess death, for a given pair (a,l) is defined as (1)

$$YLL(a,l) = \frac{l - a - \int_0^{l-a} S(t,a)\ dt}{1 - S(l-a,a)} \tag{1}$$

where $S(t,a)$ is the survival function, defined by

$$S(t,a) = \exp\left(-\int_0^t r(u,a)\ du \right) = \exp\left[-R(t,a) \right] \tag{2}$$

In the above expression $r(t,a)dt$ is probability of radiation induced death within time interval $(t, t+dt)$, given that the observed individual was alive at the time t. The function $R(t,a)$ in (2) is the age at exposure dependent probability of death up to the moment t. The function $r(t,a)$ depends also on the other parameters (nuclide and target organ); these dependencies are at the moment omitted due to simplicity.

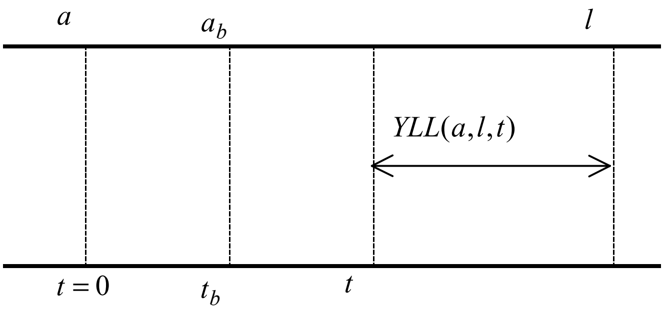

Figure 1. Age and time parameters

Legend:

$t=0$ – time of the accident, t_b - time of irradiation, t - time of radiation induced death, a - age at the accident, a_b - age at irradiation, l - age at natural death, $YLL(a,l,t)$ - loss of life

Averaging the $YLL(a,l)$ defined by (1) with respect to <u>l</u> gives

$$YLL(a) = \int_0^{l_m} p(l\,|\,a) \;\; YLL(a,l) \;\; dl \tag{3}$$

where $p(l\,|\,a)$ is the conditional probability density of <u>l</u>, for a given <u>a</u>:

$$p(l\,|\,a) = \frac{p(l)}{\int_a^{l_m} p(l) \;\; dl} \tag{4}$$

and $p(l)$ is the probability density function for <u>l</u>. In this paper the $p(l)$ is used from (3) with the age distribution maximum value of $l_m = 95$ years. It is also possible to find the joint distribution function for a given pair (a,l), denoted by $p(a,l)$. In that case, averaging the $YLL(a,l)$ using the $p(a,l)$ would bring the same result as averaging *YLL(a)* with respect to <u>a</u> – the fully averaged mean *YLL* as

$$YLL \;\;=\;\; \int_0^{l_m} da \;\; \int_a^{l_m} p(a,l) \;\; YLL(a,l) \;\; dl \tag{5}$$

where the joint density function of (a,l) is given by

$$p(a,l) = \begin{cases} \dfrac{p(l)}{L_0}, & a < l \\ 0, & a \geq l \end{cases} \tag{6}$$

and the parameter L_0 is the life expectancy for newborn, i.e. $L_0 = \int_0^{l_m} lp(l)dl$. Let $w(t,a)$ denotes the probability of death up to time <u>t</u>, for an individual who, being at age <u>a</u> at time $t = 0$, was short term irradiated by a unit dose. The time and age scenario is presented in Figure 1. An observed individual is irradiated at time t_b. The dose delivered within time interval $(t_b, t_b + dt_b)$ might cause death, say at some later moment <u>t</u>. Probability of death due to irradiation with a unit dose at time t_b in time interval $(t, t+dt)$ is $\dot{w}(t - t_b, a + t_b)dt$. If irradiation is continuous, probability of death within time interval $(t, t+dt)$ is sum of all exposure intervals, i.e.

$$r(t,a) \;\; dt = \int_0^{t} \dot{H}(t_b, a_b)\dot{w}(t - t_b, a_b)dt_b \;\; dt \tag{7}$$

where $\dot{H}(t_b, a + t_b)dt_b$ is dose delivered in time interval $(t_b, t_b + t_b)$. The age at exposure a_b can be expressed as a sum of the age at the accident <u>a</u> and the time of exposure, calculated from the beginning of the accident, i.e. $a_b = a + t_b$. The first derivative of the dose $\dot{H}$ is with respect to time t_b, while $\dot{w}(t - t_b, a + t_b)$ is derivative with respect to time <u>t</u>. According to (2), function $R(t,a)$ can be defined by

$$R(t,a) = \int_0^t r(u,a)du = \int_0^t \dot{H}(t_b,a_b)\dot{w}(t-t_b,a_b)dt_b \qquad (8)$$

as the time and age dependent probability of radiation induced death due to continuous exposure up to the moment t. The complete set of parameters which are involved in the function $R(t,a)$ includes also the nuclide name n, the cancer type specified through so-called target organ o, and the type of the exposure p, which in fact defines the model of the processes. Consequently, these parameters would appear in the corresponding YLL values. However, due to simplicity, these parameters are omitted, and only time and age parameters are kept. When real data are used, the function $R(t,a)$ is in the order of magnitude of 10^{-3} or smaller, and from (2) and (9) we have

$$S(t,a) = \exp[-R(t,a)] \approx 1 - R(t,a) \qquad (9)$$

which, taking $R(0,a) = 0$, yields

$$YLL(a,l) = \frac{\int_0^{l-a} R(t,a)dt}{R(l-a,a)} \qquad (10)$$

The above expression is used for the YLL calculation. One should note that $YLL(a,l)$ is not an observable quantity, since it depend on the stochastic variable l.

RESULTS

According to (11), (3) and (5), assessment of the YLL values is reduced to calculation of the probability $R(t,a)$. Further on, due to (9), the whole calculus of the YLL is reduced to estimation of the corresponding organ and nuclide dependent equivalent dose $H(t,a)$ for each particular exposure pathway. As a consequence, the analytical form of the YLL determined by the dose model. In this paper the COSYMA (2) dose model is used, where the time and age dependencies are incorporated in the dose conversion factors. According to such an approach, it was shown that initial activities play no important role in the YLL assessment. The probabilities $w(t,a)$ are used from (3) and they are not nuclide and exposure pathway dependent; besides the time and age at exposure, they also depend on the target organ.

Short-term external exposures – CL and SK. Let us at first define the function $R(t,a)$ for short-term external exposures - irradiation from the radioactive cloud as it passes overhead (CL) and the irradiation from the contaminated skin and clothes (SK). The radiation dose is received within the short time interval and for the purpose of this analysis the cumulative dose received is used rather than time dependent dose. From this point of view, the specific dose model regarding the CL and SK cases is not relevant for the YLL calculus. The only important is total dose received within the pathway specific time interval. According to that, the cumulative dose is a step function of time,

$$H(t)=\begin{cases}0, & t<t_k\\ H, & t\geq t_k\end{cases} \qquad (11)$$

where $t_k = t_c$ or $t_k = t_s$ in case of CL or SK, respectively. Accordingly, t_c is radioactive cloud travelling time and t_s is time of an individual's exposure to contamination of his skin and/or clothes. Both times, t_c and t_s, are in the range of some hours, up to some days, whereas time resolution of the model is one year. So, for analysis of the late effects it may be assumed with a good proximity $t_k = 0$.
Let us again consider time and age scenario presented in Figure 1, and let us consider the CL case (the analysis of the SK case is identical). An individual at age $\underline{a}$ is irradiated during the passage of the radioactive cloud at $t_b = t = 0$. After that single irradiation some of individuals who would have died at age $\underline{l}$ if not irradiated, die at time $\underline{t}$ due to radiation exposure, suffering a loss of lifetime $Y(a,l,t)$, as indicated in Figure 1. If someone dies before the age of the natural death $\underline{l}$, that must be due to irradiation, and the difference $(l-t)$, denoted in Figure 1 as $YLL(a,l,t)$ is the loss of life in a population with a fixed pair of parameters (a,l). Since stochastic effects are considered only, the case $t=a$ is not treated, since it deals with the deterministic effects.
Under the condition $t_c = 0$, the time derivative of the step dose function defined by (12) is the impulse function $\delta(t)$, i.e.

$$\dot{H}(t,a) = H \quad g(a) \qquad (12)$$

where $g(a)$ is the age dependent correction factor for exposure pathway CL. Substituting the above equation in (9), we obtain

$$R(t,a) = H \quad g(a) \quad \dot{w}(t,a) \qquad (13)$$

where *H* is dose received during the passage of the radioactive cloud. Similar consideration brings the same formula for the SK case. In particular, the $R(t,a)$ for CL case can be estimated as follows: the probability of death up to time $\underline{t}$ due to short-term unit exposure at $t=0$ is $w(t,a)$, where $\underline{a}$ is the age at exposure. Multiplying this quantity with the applied dose *H*, the $R(t,a)$ is obtained. Substitution into the YLL formula, using $w(0,a)=0$, gives

$$YLL(a,l) \;=\; \frac{1}{w(l-a,a)} \int_0^{l-a} w(t,a)\;\, dt \qquad (14)$$

Substitution of (14) in (3) gives the mean number of the years of life lost $YLL(a)$ as a function of the age at the exposure; this function is presented in Figure 2. One can see from (14) that YLL for a fixed pair of (a,l), depends on the probabilities $w(t,a)$ only, being independent on the dose at all. To be more precise, the dose independence in (14) is valid until the condition (9) is valid. Since the risk function $R(t,a)$ is proportional with the dose rate (see (8)), for the small dose and dose rates, the exponential function in (9) can be approximated with the linear function.

Table 1. Averaged YLL in case of the short term external exposure (CL or SK)

Target organ	Averaged YLL (years)	Target organ	Averaged YLL (years)
Breast	14.6	Remainder	12.4
Bone surface	28.2	Stomach	10.6
Lung	11.4	Colon	10.9
Bone marrow	28.9	Liver	11.9
Thyroid	14.1	Pancreas	10.6

The loss of life is in this paper calculated among those ones who will certainly die (per excess death). If someone died, the severity of an event, which caused death, plays no role to the number of his/her loss of life. For example, the loss of life for someone who died in a car accident is not depending on the severity of that accident. Certainly, we assume such kind of event were no many people are involved (say, we consider low doses). If someone dies due to the short-term exposure, the radiation dose is not related (at the small doses) with the size of the loss of life (if death occurs). It will only influence the number of effects. This statement is usually most difficult to understand.

According to above, the curve in Figure 2 represents the loss of life as a function of the age at the accident, for all nuclides. At small ages, the YLL values are much greater for effects with a small latency period (bone marrow and bone surface) than for the other ones. Except for the small latency period effects, there is some kind of plateau, starting in the region of small ages, up to 30 - 40 years.

Since the time of exposure is limited to some minutes or hours, and having in mind the time resolution of one year, the nuclide characteristics are not relevant in this case. Therefore, no big differences would be expected among different nuclides, and our calculus confirmed that conclusion.

Long-term external exposure – GR. Radioactive material deposited on ground may remain a long period of time. That implies continuous irradiation not only those alive at the time of the accident, but also the subsequent generations. In this paper the YLL for so called living generations is considered, i.e. the YLL for those ones which were alive at the time of the accident is calculated. The YLL for so called following generations would be subject of an another paper. The external irradiation from the activity deposited on the ground is called in this paper also groundshine, and abbreviated by the GR. In this case the radiation dose is function of time and age at exposure (besides the nuclide dependency). Time and age model parameters are presented on Figure 1.

According to the model, the problem of finding the YLL is in general reduced to calculation of the function $R(t,a)$ as defined by equation (8), i.e. to the calculation of nuclide specific, time and age dependent equivalent dose $H(t,a)$. In this paper the dose model used in the European PRA code system COSYMA$^{(2)}$ is used, where dose calculation is performed by the multiplication of the initial nuclide concentration with the time, age and nuclide specific dose conversion factors. Let $\dot{g}_{gr}(t,a)$ denotes time and age dependent differential-dose-conversion factors (DDCF's). These DDCF's are organ and nuclide dependent and contain all information concerning the temporal behavior of nuclides on ground surface. If C_0 denotes an initial activity concentration of deposits, an individual who at the time of the accident was at the age a, will in time interval $(t_b, t_b + t_b)$ receive radiation dose

$$dH(t_b, a+t_b) \;=\; C_0 \;\; \dot{g}(t_b, a+t_b) \;\; dt_b \tag{15}$$

Substituting (15) in (8) and (10), the YLL for a fixed pair of (a,l) can be found by

$$YLL(a,l) = l - a - FL(a,l) \tag{16}$$

where

$$FL(a,l) = \frac{\int\limits_0^{l-a} t \;\; dt \;\; \int\limits_0^{t} \dot{g}_{gr}(t_b, a+t_b)\dot{w}(t-t_b, a+t_b)dt_b}{\int\limits_0^{l-a} \; dt \;\; \int\limits_0^{t} \dot{g}_{gr}(t_b, a+t_b)\dot{w}(t-t_b, a+t_b)dt_b} \tag{17}$$

where $\dot{g}_{gr}(t_b, a+t_b)$ is differential dose conversion factor (DDCF) for groundshine and $(a+t_b)$ is the age at the exposure since $\underline{a}$ is the age at the accident. While the nuclide dependence remains (within DDCFs), the initial concentration of deposit vanishes after abbreviation of C_0. In this sense, the initial concentration will much more affect the number of stochastic health effects, than life shortening. Clearly, increasing the doses above the value, which satisfies (9), initial concentration C_0 will appear in the YLL expressions.

Table 2. Averaged YLL in case of the protracted external exposure (GR)

Target organ	Averaged YLL (years)			Target organ	Averaged YLL (years)		
	^{131}I	^{137}Cs	^{239}Pu		^{131}I	^{137}Cs	^{239}Pu
Breast	14.5	12.9	12.4	Remainder	12.1	10.3	9.4
Bone surface	27.5	20.2	17.0	Stomach	10.2	8.8	8.2
Lung	11.2	9.8	9.1	Colon	10.6	9.2	8.5
Bone marrow	27.3	18.4	14.5	Liver	11.6	10.3	9.6
Thyroid	13.9	12.0	11.2	Pancreas	10.3	8.9	8.3

Let us consider three nuclides with a wide range of the half-life: ^{131}I (half-life 8 days), $^{137}C_s$ (30 years) and $^{239}P_u$ (10 000 years). Iodine and cesium are chosen as important nuclides in NPP accident, while plutonium is taken due to its extremely long half-life. Numerical calculations for ^{131}I show almost no differences between the YLL obtained for the GR and CL. Such result could be expected, since short living nuclides have a "chance" to produce some health effects during a short period of time. Indeed, a few months after the accident, all available ^{131}I is decayed, and there is no any protracted exposure from it. Therefore, the YLL values for iodine ^{131}I will be, in case of exposure pathway GR, close to CL ones. As a result, there is no difference between the YLL curves for iodine ^{131}I in case of short and long term external exposure. That is common for all short-lived nuclides - the smaller half-life, the closer YLL to the CL case.

Figure 3 presents the YLL for $^{137}C_s$, giving a function $YLL(a)$, where $\underline{a}$ is age at the beginning of exposure, which is in fact the age at the accident, since we at the moment do not consider any kind of the countermeasures. Model takes into account the natural deaths, and the aging of the observed population with respect to the time of the continuous exposure. For an individual with a fixed age at the accident $\underline{a}$ $(a \in (0, l_m))$ the age at the exposure is always $a_b = a + t_b$ where time of the exposure t_b can take any value from the interval $(0, l_m)$, depending on the age at the accident, and the age at natural death $\underline{l}$.

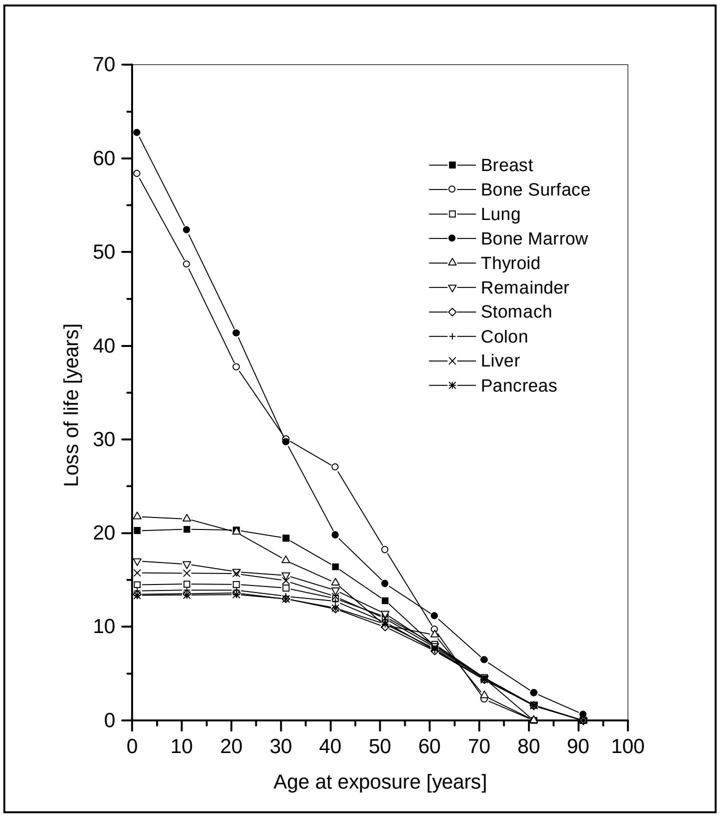

Figure 2. Loss of lifetime versus age at exposure (nuclide independent). Exposure pathways - CL and SK.

Since the YLL curves from Figure 2 are not nuclide dependent, they are valid for $^{137}C_s$ also. Comparison of the YLL values from Figs 3 and 4 shows decrease of the YLL with a protraction of exposure. Although this decrease affects more effects with a small latency, it influences all other target organs, keeping the type of the curves unchanged (for non-bone organs some kind of "plateau" remains for small ages). The radiation induced lethal cancer can be generated at any time during the period of exposure. The protraction of exposure therefore may cause some additional lethal effects due to irradiation at later ages, postponing effectively the age at death, and resulting to the reduction of the average loss of life. One should notice that, besides of the YLL reduction, the number of lethal effects is expanded, due to the protraction of radiation exposure. Finally, Figure 4 presents the YLL obtained for an extremely long half-life nuclide - $^{239}P_u$. A further decrease of the YLL values for bone organs continues, reducing the YLL gap between "bone" organs and other ones. One could recognize this gap as the lowest one with respect to the further half-life increase. Fully averaged YLL values for external exposure to radioactive material deposited on the ground are presented in Table 2. Comparison of the YLLs from tables 1 and 2 numerically confirm*s the above discussion. For example, the protraction of exposure reduces the YLL caused by leukemia (target organ bone marrow), to about 60 and 100 percents of values obtained for the short-time exposure for $^{137}C_s$, and $^{239}P_u$ respectively.

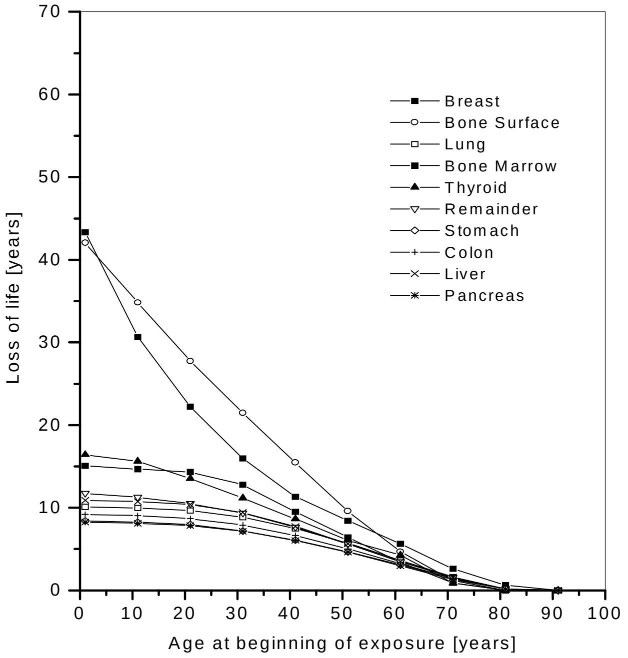

Figure 3. Loss of lifeteime versus age at the beginning of exposure. Exposure pathway GR. Nuclide ^{137}Cs .

CONCLUSIONS

In this paper the new concept for calculation of the years of life lost per excess death - YLL, is applied to external exposure pathways, which are usually considered in the accident consequence assessment. These are the short term exposures to the radioactive cloud as it passes overhead (CL) and to radioactive material deposited on skin and clothes (SK), and the continuous external exposure to radioactive material deposited on the ground (GR). A short analysis indicates no nuclide dependencies in the YLL when short-term external exposures are considered. On the other hand, the YLL for protracted exposure depends on the nuclide's half-life. It is obtained from the curves presented (YLL vs. age at the beginning of exposure), as well from the calculated fully averaged YLL values, presented in the Table 2. Continuous exposure to radioactive material deposited on the ground involves some additional effects, which result in the reduction of the calculated YLL. In order to examine the nuclide's half-life influence on the calculated YLL, three nuclides with a wide range of half-life are considered: I—131 (half-life 8 days), Cs-137 (30 years) and Pu-239 (10.000 years). As a result, the shortening of the nuclide's half-life brings closer the corresponding YLL value obtained for the CL case (which is nuclide independent). Increase of the nuclide's half-life leads in general to decrease of the YLL. That results from the fact that protraction of exposure may postpone the occurrence of lethal health effects due to exposure at later ages. It is emphasized that, although the protraction of exposure may lead to significant increase of the number of stochastic health effects, it also decreases the mean averaged YLL. That means the average loss of life decreases within the observed population due to some additional lethal cases, which appear due to exposure at higher ages.

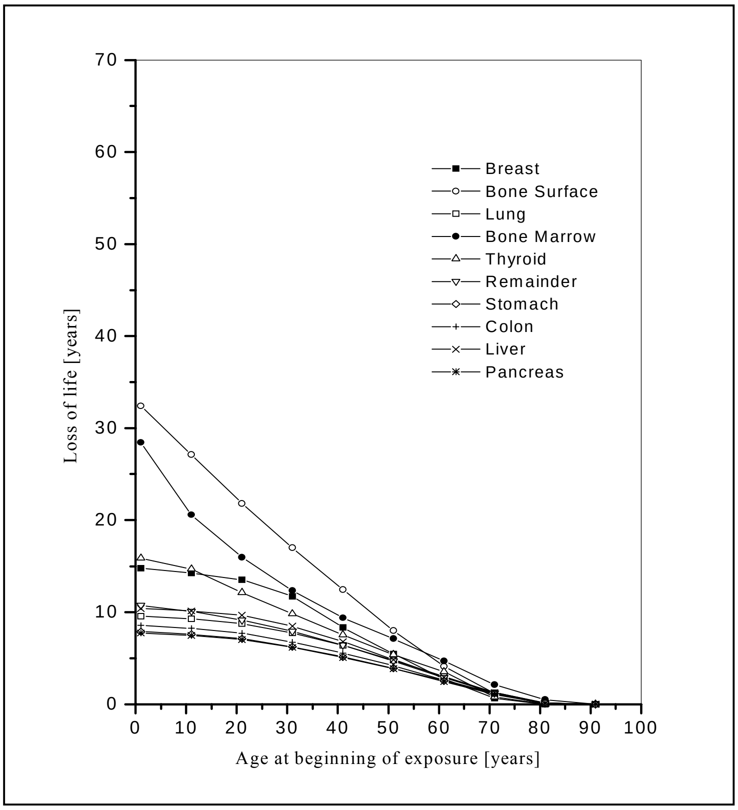

Figure 4. Loss of lifetime versus age at the beginning of exposure. Exposure pathway GR. Nuclide ^{239}Pu.

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