YEARS OF LIFE LOST DUE TO EXTERNAL RADIATION EXPOSURE

by

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

Key words: years of life lost, radiation risk, stochastic health effects, external radiation exposures

INTRODUCTION

Following a nuclear accident, certain amount of radioactive material reaches human environment. After the end of countermeasures, the affected population returns to their normal activities. Depending on the exposure pathway and many other factors, this population (at least a part of it) is still exposed to a certain level of radiation. Exposure to low doses may cause a number of stochastic somatic health effects in the observed population, which can be assessed by various models [1-4]. 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*. Many attempts have been made to obtain a quantitative assessment of this quantity (see for example [5, 6]). After all, the quantity years of life lost in [7] was redefined.

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 (SK). The long-term one is the exposure to the radioactive material deposited on the ground (GR). Due to its ability to assess the *YLL* for both, short and long term radiation exposures, the method established in [7] is used (the method may be used for internal exposure pathways – what is out of the scope of this paper). It should be noted that *YLL* depends on many factors; however, in this paper the years of life lost dependence on the age at the exposure is considered only – *YLL*(a), where a is the age at the exposure.

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, also giving the table with fully averaged *YLL* values.

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MATERIALS AND METHODS

Let us introduce two age parameters: a – the age at the exposure and l – the 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 [7]

$$YLL(a,l) = \frac{l - a - \int_0^{l-a} S(t,a)\,\mathrm{d}t}{1 - S(l-a,a)} \quad (1)$$

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

$$S(t,a) = \exp[-\int_0^t r(u,a)\,\mathrm{d}u] = \exp[-R(t,a)] \quad (2)$$

In the above expression, $r(t, a)\,\mathrm{d}t$ is the probability of radiation induced death within time interval $(t, t + \mathrm{d}t)$, given that the observed individual was alive at the time t. The function $R(t, a)$ in eq. (2) is the age at the exposure dependent probability of death up to the moment t. The function $r(t, a)$ also depends on the other parameters (the nuclide and the target organ); these dependencies are at the moment omitted due to simplicity. Averaging the $YLL(a, l)$ defined by eq. (1) with respect to l gives

$$YLL(a) = \int_0^{l_m} p(l|a)\, YLL(a,l)\,\mathrm{d}l \quad (3)$$

where $p(l|a)$ is the conditional probability density of l for a given a:

$$p(l|a) = \frac{p(l)}{\int_a^{l_m} p(l)\,\mathrm{d}l} \quad (4)$$

and $p(l)$ is the probability density function for l. In this paper the $p(l)$ is used from [8] 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 a – the fully averaged mean YLL as

$$YLL = \int_0^{l_m} \mathrm{d}a \int_a^{l_m} p(a,l)\, YLL(a,l)\,\mathrm{d}l \quad (5)$$

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

$$p(a,l) = \begin{cases} \dfrac{p(l)}{L_0}, & a \le l \\ 0, & a > l \end{cases} \quad (6)$$

and the parameter L_0 is the life expectancy for newborn, *i. e.*

$$L_0 = \int_0^{l_m} l\,p(l)\,\mathrm{d}l \quad (7)$$

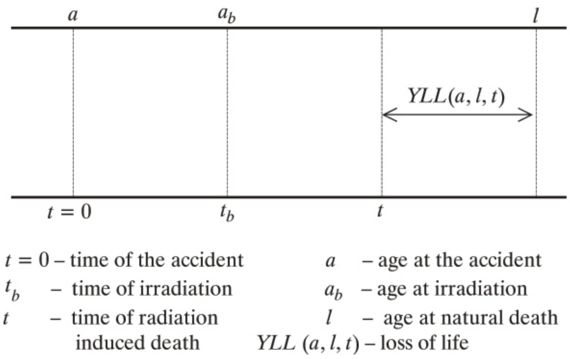

Figure 1. Age and time parameters

Let $w(t, a)$ denotes the probability of death up to the time t, for an individual who, being at the age a at time $t = 0$, was short term irradiated by a unit dose. The time and age scenario is presented in fig. 1. An observed individual is irradiated at time t_b. The dose delivered within the time interval $(t_b, t_b + \mathrm{d}t_b)$ might cause death, say at some later moment t. Probability of death due to irradiation with a unit dose at time t_b in the time interval $(t, t + \mathrm{d}t)$ is $\dot{w}(t - t_b, a + t_b)\mathrm{d}t$, where $w(t, a)$ is the probability of death up to time t for an individual who is at the age a irradiated at time $t = 0$. If the irradiation is continuous, probability of death within the time interval $(t, t + \mathrm{d}t)$ is the sum of all exposure intervals, *i. e.*

$$r(t,a)\,\mathrm{d}t = \int_0^t \dot{H}(t_b,a_b)\,\dot{w}(t-t_b,a_b)\,\mathrm{d}t_b\,\mathrm{d}t \quad (8)$$

where $\dot{H}(t_b, a + t_b)\,\mathrm{d}t_b$ is the dose delivered in the time interval $(t_b, t_b + \mathrm{d}t_b)$. The age at the exposure a_b can be expressed as a sum of the age at the accident a and the time of the 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 t. According to eq. (2), the function $R(t, a)$ can be defined by

$$R(t,a) = \int_0^t r(u,a)\,\mathrm{d}u = \int_0^t \dot{H}(t_b,a_b)\,w(t-t_b,a_b)\,\mathrm{d}t_b \quad (9)$$

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 $R(t, a)$ also includes the nuclide name n, the cancer type specified through the 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 eq.(2) and (9) we have

$$S(t,a) \quad \exp[\quad R(t,a)] \quad 1 \quad R(t,a) \qquad (10)$$

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

$$YLL(a,l) \quad \frac{\overset{l\ \ a}{} R(t,a)\,\mathrm{d}t \ _{0}}{R(l \quad a,a)} \qquad (11)$$

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

RESULTS

According to eqs. (11), (3), and (5), assessment of the *YLL* values is reduced to calculation of the probability $R(t,a)$. Further on, due to eq. (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* is determined by the dose model. In this paper the COSYMA [4] 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 the 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; beside the time and age at the exposure, they also depend on the target organ.

Short-term external exposures – CL and SK

Let us first define the function $R(t,a)$ for short-term external exposures – the 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 the 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 one is the total dose received within the pathway specific time interval. According to that, the cumulative dose is a step function of time,

$$H(t) \quad \begin{matrix} 0, t \quad t_k \\ H, t \quad t_k \end{matrix} \qquad (12)$$

where $t_k = t_c$ or $t_k = t_s$ in case of CL or SK, respectively. Accordingly, t_c is the radioactive cloud travelling time and t_s is the 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 the time resolution of the model is one year. So, for the analysis of the late effects it may be assumed with a good proximity that $t_k = 0$.

Let us again consider the time and age scenario presented in fig. 1, and let us consider the CL case (the analysis of the SK case is identical). An individual at the age a is irradiated during the passage of the radioactive cloud at $t_b = 0$. After that single irradiation some of the individuals who would have died at the age l if not irradiated, die at time t due to the radiation exposure, suffering a loss of lifetime $Y(a,l,t)$, as indicated in fig. 1. If someone dies before the age of the natural death l, it must be due to the irradiation, and the difference $(l-t)$ denoted in fig. 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 eq. (12) is the impulse function $\delta(t)$, *i. e.*

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

where $g(a)$ is the age dependent correction factor for the exposure pathway CL. Substituting the eq. (13) in (9), we obtain

$$R(t,a) \quad H\,g(a)\,\dot{w}(t,a) \qquad (14)$$

where H is the 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 t due to the short-term unit exposure at $t = 0$ is $w(t,a)$, where a is the age at the 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

$$YLL(a,l) \quad \frac{1}{w(l \quad a,a)} \ \overset{l\ \ a}{\underset{0}{}} w(t,a)\,\mathrm{d}t \qquad (15)$$

Substitution of eq. (15) in eq. (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 fig. 2. One can see from eq. (15) that *YLL* for a fixed pair of (a,l), depends on the probabilities $w(t,a)$ only, being independent on the dose. To be more precise, the dose independence in eq. (15) is valid until the condition eq. (10) is valid. Since the risk function $R(t,a)$ is proportional with the dose rate, see eq. (9), for the small dose and dose rates, the exponential function in eq. (10) can be approximated with the linear function. If the doses in-

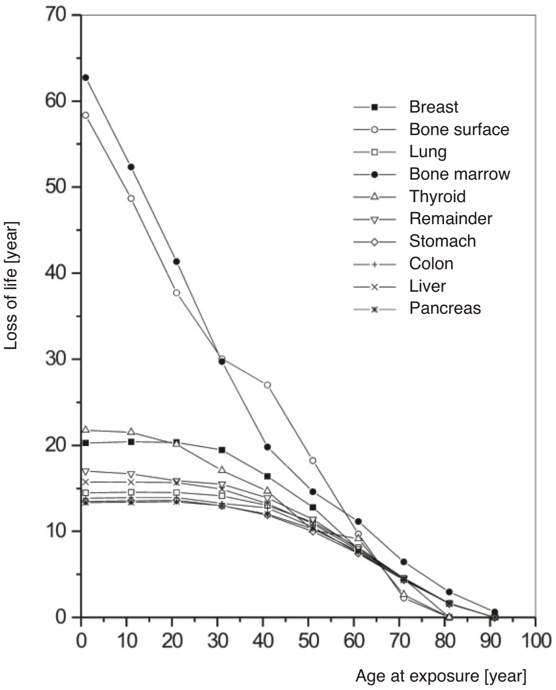

Figure 2. Loss of lifetime versus age at exposure nuclide independent). Exposure pathways – CL and SK

crease, the next term have to be taken into account in the surviving function

$$S(t,a) \quad \exp[\ R(t,a)] \quad 1 \quad R(t,a) \quad \frac{R^2(t,a)}{2} \qquad (16)$$

and the *YLL* becomes dose and nuclide dependent. However, stochastic health effects are those ones which stem from the small doses; therefore, eq. (10) *i. e.* eq. (11) is used for the estimation of the *YLL* in this paper. Nevertheless, it remains the fact that eq. (16) offers a suitable tool for the dose investigations with respect to the *YLL*.

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 that 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 does not depend on the severity of that accident. Certainly, we assume such kind of event where 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 affect the number of effects only. This statement is usually most difficult to understand.

According to the above, the curve in fig. 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 the effects with a small latency period (bone marrow and bone surface) than for the other ones. The *YLL* for other health effects express a very weak dependence on the age at the exposure in the region of small ages, up to 30-40 years. On the other hand, it should be noted that the time resolution in the model is one year. Having in mind that in this case the time of the exposure is limited to some hours or days, the nuclide's half-life is not relevant in this case. Therefore, no significant differences would be expected among different nuclides, and our calculus confirmed that conclusion.

Long-term external exposure – GR

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

According to the model, the problem of finding the *YLL* is in general reduced to the calculation of the function $R(t, a)$ as defined by eq. (9), *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 [4] is used, where the 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). These DDCF are organ and nuclide dependent and contain all the information concerning the temporal behavior of nuclides on the 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 the time interval (t_b, t_b + dt_b) receive the radiation dose

$$\mathrm{d}H(t_b, a \quad t_b) \quad C_0\, \dot{g}(t_b, a \quad t_b)\, \mathrm{d}t_b \qquad (17)$$

Substituting eq. (17) in eqs. (9) and (11), the *YLL* for a fixed pair of (a, l) can be found by

$$YLL(a,l) \quad l \quad a \quad FL(a,l) \qquad (18)$$

where

$$FL(a,l) = \frac{\int_0^{l-a} t \, \mathrm{d}t \int_0^t \dot{g}_{gr}(t_b, a+t_b)\,\dot{w}(t-t_b, a+t_b)\,\mathrm{d}t_b}{\int_0^{l-a} \mathrm{d}t \int_0^t \dot{g}_{gr}(t_b, a+t_b)\,\dot{w}(t-t_b, a+t_b)\,\mathrm{d}t_b} \qquad (19)$$

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 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 affect the number of stochastic health effects much more than life shortening. It should be noted that the increase of doses would make assumption eq. (10) not valid. That will cause the necessity of using the nonlinear approximation given by eq. (16), what will involve the initial concentration C_0 and consequently the dose dependence into the *YLL* expressions. That is the reason why the approximation of small doses, given by eq. (10), is so important in understanding the independency of the years of life lost with the radiation doses.

Let us consider three nuclides with a wide range of half-life: ^{131}I (8 days), ^{137}Cs (30 years), and ^{239}Pu (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 the 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 exposures. That is common for all short-lived nuclides – the smaller the half-life, the closer *YLL* to the CL case.

Figure 3 presents the *YLL* for ^{137}Cs, giving a function *YLL*(a), where a is the age at the beginning of the exposure, which is in fact the age at the accident, since we at the moment do not consider any kind of the countermeasures. The 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 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 the natural death l.

Since the *YLL* curves from fig. 2 are not nuclide dependent, they are also valid for ^{137}Cs. Comparison of the *YLL* values from figs. 3 and 4 shows

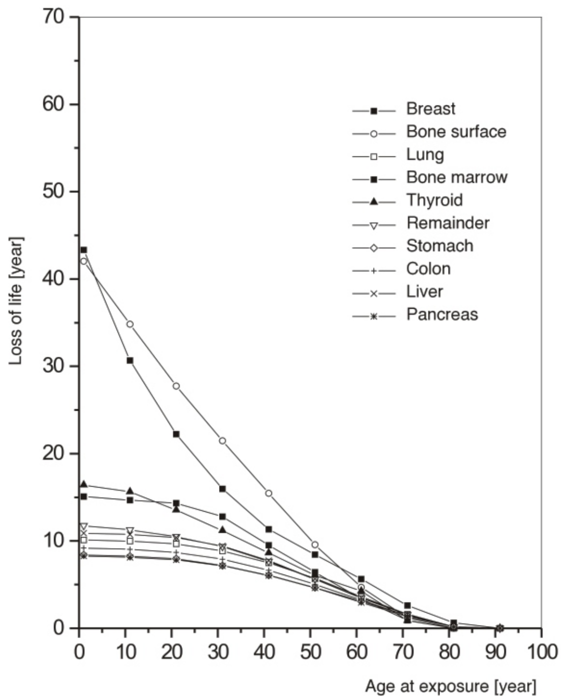

Figure 3. Loss of lifetime versus age at the beginning of exposure. Exposure pathway GR. Nuclide ^{137}Cs

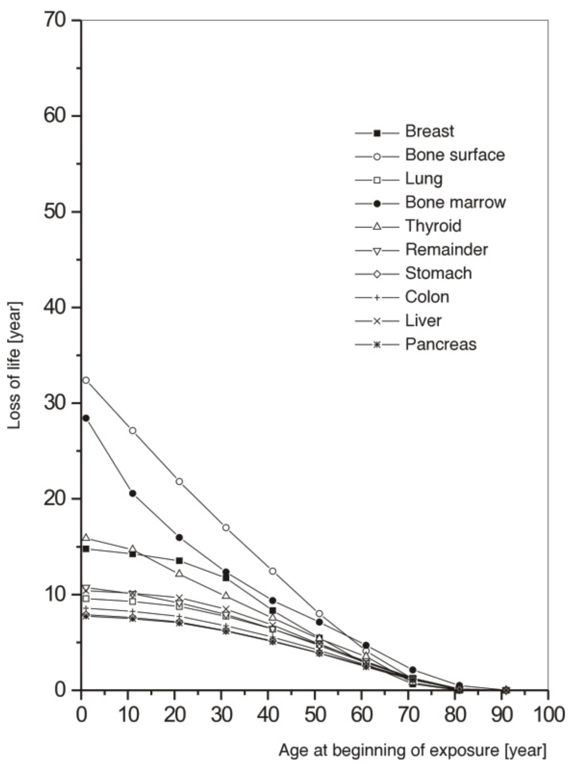

Figure 4. Loss of lifetime versus age at the beginning of exposure.Exposure pathway GR. Nuclide ^{239}Pu

decrease of the *YLL* with a protraction of the exposure. Being more evident in case of small latency effects, this effect also appears for other target organs, keeping the type of the curves unchanged.

The radiation induced lethal cancer can be generated at any time during the period of the exposure. Therefore, the protraction of the exposure may cause some additional lethal effects due to irradiation at the later ages, postponing effectively the age of death, and resulting into the reduction of the average loss of life. One should notice that beside the *YLL* reduction, the number of lethal effects is expanded due to the protraction of the radiation exposure. Finally, fig. 4 presents the *YLL* obtained for an extremely long half-life nuclide – ^{239}Pu. 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 the external exposure to the radioactive material deposited on the ground are presented in tab. 2. Comparison of the *YLLs* from tabs. 1 and 2 numerically confirms the above discussion. For example, the protraction of the 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}Cs and ^{239}Pu respectively.

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

Target organ	Averaged *YLL* [year]	Target organ	Averaged *YLL* [year]
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

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

Target organ	Averaged *YLL* [year]			Target organ	Averaged *YLL* [year]		
	^{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

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 the radioactive material deposited on skin and clothes (SK), and the continuous external exposure to the 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 the protracted exposure depends on the nuclide's half-life. It is obtained from the curves presented (*YLL vs*. age at the beginning of the exposure), as well from the calculated fully averaged *YLL* values, presented in the tab. 2.

Continuous exposure to the 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: ^{131}I (8 days), ^{137}Cs (30 years), and ^{239}Pu (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). The increase of the nuclide's half-life leads in general to the decrease of the *YLL*. That results from the fact that protraction of the exposure may postpone the occurrence of lethal health effects due to the exposure at later ages. It is emphasized that although the protraction of the 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 the exposure at later ages.

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СКРАЋЕЊЕ ЖИВОТА УСЛЕД СПОЉАШЊЕГ ИЗЛАГАЊА РАДИОАКТИВНОМ ЗРАЧЕЊУ

У раду је приказан нови метод израчунавања скраћења живота до кога долази услед појаве стохастичких ефеката у популацији изложеној малим дозама зрачења преко спољашњих путева излагања. При томе се скраћење посматра само код оних особа код којих долази до појаве ефекта. Разматрана су краткотрајна спољашња излагања пролазећем радиоактивном облаку и услед контаминације делова тела и одеће, као и дуготрајно спољашње излагање услед боравка на контаминираном земљишту. Ради испитивања утицаја дужине времена полураспада на скраћење живота, одабрана су три радионуклида са јако великим опсегом времена полураспада (^{131}I, ^{137}Cs и ^{239}Pu). За сваки од ових радионуклида израчунате су вредности скраћења живота, као опадајуће функције од старости у тренутку излагања. Израчунате вредности су и графички приказане. За континуирана излагања, показана је негативна корелација усредњене вредности скраћења живота са временом полураспада посматраног радионуклида. С друге стране, таква корелација не постоји за краткотрајна излагања. У раду је посебно посматрана и анализирана слаба зависност скраћења живота од примењене дозе зрачења.