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# Calculation of the Parameters of the Effects of Uranium Radiation on Humans in Emergencies at Nuclear Plants

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**Abstract**—Human radiation exposures from uranium via the skin or lungs during emergencies at nuclear plants are considered. The effective dose that can accumulate in humans and the dose coefficient of uranium are calculated. Models developed by the authors, which describe air pollution in a factory shop and uranium penetration through the skin are used. The effective doses accumulated in humans through the skin and via inhalation are compared. The effect of uranium on the skin is estimated and the skin layer most affected by radiation is determined.

*Key words:* uranium hexafluoride, penetration through skin, inhalation penetration, dose coefficient, mathematical model.

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We analyze the following physical situation. The air in an operating room contains $UF_6$ (gas), $UOF_4$ (gas), $UO_2F_2$ (gas), HF (gas), $UO_2F_2$ (aerosol), HF (aerosol), and $H_2O$ vapor. The following processes are considered. $UF_6$ (gas) and $UOF_4$ (gas) interact with $H_2O$ vapor and undergo hydrolysis. Gaseous $UO_2F_2$ and HF are transformed into aerosols. Gases diffuse and are deposited at the boundaries of the room under consideration, whereas aerosol particles move and are driven by the force of gravity and the resistance force of the medium. The air in the operating room is assumed to be contaminated as a result of a short-term ejection of uranium hexafluoride (i.e., an emergency is considered).

Uranium atoms can penetrate into the bodies of people in a contaminated room in two ways. First, uranium-containing substances $UF_6$ (gas), $UOF_4$ (gas), and $UO_2F_2$ (gas) are deposited diffusively on the skin. Some uranium atoms penetrate the skin, travel via blood circulation, and then are distributed throughout the entire body (penetration through the skin). Secondly, people inhale uranium-containing substances: $UF_6$ (gas), $UOF_4$ (gas), $UO_2F_2$ (gas), and $UO_2F_2$ (aerosol). The inhaled uranium atoms are involved in blood circulation and then are distributed throughout the organism (inhalation penetration).

To estimate the negative effects of uranium on a human organism, it is useful to have four types of models. The first are those describing the contamination of the air in the operating room. Here we use the approximate models developed in [1, 2]. The models of the second type describe the penetration of uranium through skin. We apply the integral model developed in [3]. The third type of model describes uranium penetration through respiratory organs. We use the model recommended by the ICRP (International Commission on Radiological Protection) [3]. The fourth type of model describes human metabolism. The ICRP compartment model [4] is applied here.

In this study we calculated the effective dose accumulated in a person due to the penetration through skin and the dose coefficient for uranium through the skin. The contributions of the skin and inner organs to the accumulation of the effective dose are compared. In addition, the effect of uranium on the skin (which serves as a barrier in this mechanism of penetration) is estimated and the skin layer subjected to the maximum radiative effect is selected. The effective dose accumulated in a person due to penetration via inhalation and the dose coefficient for uranium during penetration via inhalation are calculated. The effective doses accumulated in a person due to penetration through skin and inhalation penetration are compared.

Since diffusion deposition is a slow process and skin is a good protective barrier, it follows from the most general considerations that the amount of uranium penetrating an organism through the skin during a specified time interval is much smaller than that that is inhaled. However, it is necessary to take into account the fact that respiratory organs can be protected by a respirator, while the initial $UF_6$ concentration in an emergency can be so high that penetration through the skin can have a disastrous effect. Therefore, a detailed study of penetration through the skin is an urgent problem.

## 1. PENETRATION OF URANIUM THROUGH THE SKIN IN AN EMERGENCY

Let us assume that $j(t)$ is the gaseous uranium flux density on the skin surface at the instant $t$, $N(t)$ is the number of uranium atoms deposited on the skin surface in the time interval $[0, t]$, $A(t)$ is the activity of the uranium deposited on the skin in the time interval $[0, t]$, $N_1(t)$ is the number of uranium atoms penetrated through from skin and involved in blood circulation in the time interval $[0, t]$, $N_2(t)$ is the number of uranium atoms removed from the body in urine in the time interval $[0, t]$, $N_{\mathrm{T}}(t)$ is the number of uranium atoms located at the instant $t$ in an organ or tissue T (T = s for skin), $N'_{\mathrm{T}}(t)$ is the number of $\alpha$-particles emitted in the time interval $[0, t]$ by the uranium atoms located in an organ or tissue T, $H_{\mathrm{T}}(t)$ is the equivalent dose accumulated in the time interval $[0, t]$ in an organ or tissue T, $E(t)$ is the effective dose accumulated in the time interval $[0, t]$ in the human body, and $\varepsilon(t)$ is the dose coefficient of uranium. Then $N(t) = \int_0^t d\tau\, Sj(\tau)$, $A(t) = A_{\mathrm{sp}} m_0 N(t)$, $N'_{\mathrm{T}}(t) = \int_0^t d\tau\, A_{\mathrm{sp}} m_0 N_{\mathrm{T}}(\tau)$, $H_{\mathrm{T}}(t) = \dfrac{K_\alpha}{m_{\mathrm{T}}} W_\alpha N'_{\mathrm{T}}(t)$, $E(t) = \sum_{\mathrm{T}} K_{\mathrm{T}} H_{\mathrm{T}}(t)$, and $\varepsilon(t) = \dfrac{E(t)}{A(t)}$. Here, $S$ is the skin surface area, $A_{\mathrm{sp}}$ is the specific activity of uranium, $m_0$ is the uranium atomic mass, $K_\alpha$ is the dimensionless weighting coefficient for $\alpha$-radiation, $m_{\mathrm{T}}$ is the mass of an organ or tissue T, $W_\alpha$ is the $\alpha$-particle energy, and $K_{\mathrm{T}}$ is the dimensionless weighting coefficient for the organ or tissue T. In addition, we introduce the following designations: $E_{\mathrm{T}}(t) = K_{\mathrm{T}} H_{\mathrm{T}}(t)$, $\varepsilon_{\mathrm{T}}(t) = \dfrac{E_{\mathrm{T}}(t)}{A(t)}$, $E_{\mathrm{o}}(t) = \sum_{\mathrm{T} \neq \mathrm{s}} K_{\mathrm{T}} H_{\mathrm{T}}(t)$, and $\varepsilon_{\mathrm{o}} = \dfrac{E_0(t)}{A(t)}$.

The approximate model developed in [1] (which describes the air contamination in an operating room) gave the following expression for $j(t)$: $j(t) = n_0 \sqrt{\dfrac{D}{\pi}} \dfrac{1}{\sqrt{t}} e^{-\delta t}$. Here, $n_0$ is the initial uranium concentration in the gas mixture in the operating room, $D$ is the diffusion coefficient, and $\delta$ is a constant characterizing the hydrolysis rate. Then, $N(t) = n_0 S \sqrt{\dfrac{D}{\delta}} \operatorname{erf}(\sqrt{\delta t})$ (erf is the error function).

The integral model developed in [3] (which describes uranium penetration through the skin) yielded the following expression for $N_{\mathrm{s}}(t)$: $N_{\mathrm{s}}(t) = \int_0^t d\tau\, Sj(\tau)(1 - e^{-\lambda(t-\tau)})(C_1 e^{-\lambda_1(t-\tau)} + C_2 e^{-\lambda_2(t-\tau)})$. Here, $\lambda$ is a constant characterizing the uranium penetration rate through the skin surface in bulk, $\lambda_1$ and $\lambda_2$ are constants characterizing the rate of uranium extraction from the skin bulk, and $C_1$ and $C_2$ are dimensionless constants. Then,

$$
\begin{aligned}
N_{\mathrm{s}}(t) &= n_0 S C_1 \Big( e^{-\lambda_1 t} \sqrt{\frac{D}{\delta - \lambda_1}} \operatorname{erf}(\sqrt{(\delta - \lambda_1)t}) \\
&\quad - e^{-(\lambda + \lambda_1)t} \sqrt{\frac{D}{\delta - \lambda - \lambda_1}} \operatorname{erf}(\sqrt{(\delta - \lambda - \lambda_1)t}) \Big) \\
&\quad + n_0 S C_2 \Big( e^{-\lambda_2 t} \sqrt{\frac{D}{\delta - \lambda_2}} \operatorname{erf}(\sqrt{(\delta - \lambda_2)t}) \\
&\quad - e^{-(\lambda + \lambda_2)t} \sqrt{\frac{D}{\delta - \lambda - \lambda_2}} \operatorname{erf}(\sqrt{(\delta - \lambda - \lambda_2)t}) \Big);
\end{aligned}
$$

$$
\begin{aligned}
N'_{\mathrm{s}}(t) &= n_0 A_{\mathrm{sp}} m_0 S C_1 \Big( \frac{1}{\lambda_1} \sqrt{\frac{D}{\delta}} \operatorname{erf}(\sqrt{\delta t}) \\
&\quad - \frac{1}{\lambda_1} \sqrt{\frac{D}{\delta - \lambda_1}} e^{-\lambda_1 t} \operatorname{erf}(\sqrt{(\delta - \lambda_1)t}) - \frac{1}{\lambda + \lambda_1} \sqrt{\frac{D}{\delta}} \operatorname{erf}(\sqrt{\delta t}) \\
&\quad + \frac{1}{\lambda + \lambda_1} \sqrt{\frac{D}{\delta - \lambda - \lambda_1}} e^{-(\lambda + \lambda_1)t} \operatorname{erf}(\sqrt{(\delta - \lambda - \lambda_1)t}) \Big) \\
&\quad + n_0 A_{\mathrm{sp}} m_0 S C_2 \Big( \frac{1}{\lambda_2} \sqrt{\frac{D}{\delta}} \operatorname{erf}(\sqrt{\delta t}) \\
&\quad - \frac{1}{\lambda_2} \sqrt{\frac{D}{\delta - \lambda_2}} e^{-\lambda_2 t} \operatorname{erf}(\sqrt{(\delta - \lambda_2)t}) - \frac{1}{\lambda + \lambda_2} \sqrt{\frac{D}{\delta}} \operatorname{erf}(\sqrt{\delta t}) \\
&\quad + \frac{1}{\lambda + \lambda_2} \sqrt{\frac{D}{\delta - \lambda - \lambda_2}} e^{-(\lambda + \lambda_2)t} \operatorname{erf}(\sqrt{(\delta - \lambda - \lambda_2)t}) \Big).
\end{aligned}
$$

Within the integral model [3], $N_1(t) = \int_0^t d\tau\, Sj(\tau) C(1 - e^{-\lambda_3(t-\tau)})$. Here, $\lambda_3$ is a constant determining the rate of uranium penetration through skin into blood and $C$ is a dimensionless constant. Then,

$$
\begin{aligned}
\frac{d}{dt} N_1(t) &= \int_0^t d\tau\, Sj(\tau) C \lambda_3 e^{-\lambda_3(t-\tau)} \\
&= n_0 S C \lambda_3 e^{-\lambda_3 t} \sqrt{\frac{D}{\delta - \lambda_3}} \operatorname{erf}(\sqrt{(\delta - \lambda_3)t}).
\end{aligned}
$$

The ICRP compartment model [4] yields the functions $N_2$, $N_{\mathrm{T}}$, and $N'_{\mathrm{T}}$ ($\mathrm{T} \neq \mathrm{s}$) as a solution to the Cauchy problem for a system of linear ordinary differential equations with constant coefficients. The above-determined quantity $\dfrac{d}{dt} N_1(t)$ is substituted into the right-hand side of the system.

The constants $\lambda_3$ and $C$ were chosen so as to make the law of uranium removal with urine, which was established within the models under consideration, fit in the best way to the experimental one [5]. As a result,

**Table 1.** Distribution over human organs for the doses accumulated over $t = 50$ yr after penetration through skin in an emergency

Emergency, penetration through skin, integral and compartment models; $n_0 = 1 \times 10^{21}$ m$^{-3}$, $t = 50$ yr;
$N'_{\mathrm{T}}$ is the number of accumulated decays and $A$ is the penetration activity through skin

| Organ or tissue T | $N'_{\mathrm{T}}$ | Dose in organ: $E_{\mathrm{T}}$, Sv | Dose in inner organs: $E_{\mathrm{o}}$, Sv | $A$, Bq | $\varepsilon_{\mathrm{s}} = \frac{E_{\mathrm{s}}}{A}$, Sv/Bq | $\varepsilon_{\mathrm{o}} = \frac{E_{\mathrm{o}}}{A}$, Sv/Bq | $\varepsilon = \varepsilon_{\mathrm{s}} + \varepsilon_{\mathrm{o}}$, Sv/Bq |
|---|---|---|---|---|---|---|---|
| Kidney | $3.6 \times 10^6$ | $3.98 \times 10^{-6}$ | $2.25 \times 10^{-5}$ | $1.5 \times 10^4$ | | $1.5 \times 10^{-9}$ | $1.51 \times 10^{-9}$ |
| Trabecula bone surface | $1.3 \times 10^6$ | $1.08 \times 10^{-6}$ | | | | | |
| Trabecula bone bulk | $4.05 \times 10^7$ | $1.08 \times 10^{-6}$ | | | | | |
| Cortico–cancellous bone surface | $1.04 \times 10^6$ | $3.39 \times 10^{-6}$ | | | | | |
| Cortico–cancellous bone bulk | $1.73 \times 10^8$ | $2.98 \times 10^{-7}$ | | | | | |
| Liver | $7.44 \times 10^6$ | $1.97 \times 10^{-6}$ | | | | | |
| Soft tissues | $6.48 \times 10^7$ | $1.07 \times 10^{-5}$ | | | | | |
| Skin | $1.96 \times 10^8$ | $1.74 \times 10^{-7}$ | | | $1.14 \times 10^{-11}$ | | |

the following values were obtained: $\lambda_3 = 0.57$ day$^{-1}$ and $C = 8 \times 10^{-4}$.

The quantities $A(t)$, $N'_{\mathrm{s}}(t)$, $E_{\mathrm{s}}(t)$, $\varepsilon_{\mathrm{s}}(t)$, and $\frac{d}{dt}N_1(t)$ were calculated from explicit formulas, and the above-mentioned Cauchy problem was solved numerically using Mathcad 2000 Professional software. The quantities $E_{\mathrm{T}}(t)$ ($\mathrm{T} \neq \mathrm{s}$), $E_{\mathrm{o}}(t)$, $\varepsilon_{\mathrm{o}}(t)$, and $\varepsilon(t)$ were calculated using the $N'_{\mathrm{T}}(t)$ ($\mathrm{T} \neq \mathrm{s}$), $A(t)$, and $\varepsilon_{\mathrm{s}}(t)$ values. According to the recommendations of the Ministry of Health of the Russian Federation, SRS-99 [6, p. 9], we considered the case $t = 50$ yr. The calculation results are listed in Table 1.

## 2. ESTIMATION OF URANIUM EFFECTS ON THE SKIN

Skin is known to be an effective barrier that hinders substances deposited on it from penetrating into the body. This means that the skin cover is strongly negatively affected if the deposited substance is radioactive or chemically toxic. To estimate this effect quantitatively, it is necessary to take into account the complex structure of skin. The structure of human skin was described in [7, 8]. This description was based on separation into several layers with characteristic properties. The main zone of radiation-induced tumors is known to be formed by the reproductive cells of the skin basal layer (although cells can also be reproduced in the skin's top layers) [8]. To estimate the equivalent dose accumulated in the basal layer, we assumed that the radioactive materials under consideration are distributed throughout the skin according to the exponential law: $n(z) = n_0 e^{-\mu z}$ ($n(z)$ is the uranium concentration at a depth $z$ and $n_0$ is the uranium concentration in the upper skin layers).

A similar law was obtained experimentally for a number of materials that penetrate through the skin in humans [7]. The quantity $\mu$ was found from the experimental data modeling an emergency [5]. According to these data, the uranium concentration at the depth $z = 300$ μm is lower than the surface concentration by a factor of 100: $\mu \approx 1.535 \times 10^{-2}$ μm$^{-1}$. In this case, the ratio of the uranium content in the basal layer of thickness $\Delta z = 50$ μm, located at the depth $z = 70$ μm [7], to its total content in the skin is $\frac{N_{\mathrm{b}}}{N_{\mathrm{s}}} = \frac{e^{-\mu z} - e^{-\mu(z + \Delta z)}}{1 - e^{-\mu L}} \approx 0.183$ ($L = 2000$ μm is the distance from the skin surface to the fatty tissue). Using these data, one can easily show that the equivalent dose in the basal layer exceeds the total equivalent dose in the skin by a factor of six. Thus, this layer can be considered as critical due to the large equivalent dose accumulated in it and the sensitivity of its reproducing cells to radiation.

## 3. INHALATION PENETRATION OF URANIUM IN EMERGENCY

Let us assume that $n_{\mathrm{g}}(z, t)$ is the uranium concentration in the gas mixture in an operating room at the height $z$ at the instant $t$, $n_{\mathrm{a}}(z, t)$ is the uranium concentration in the aerosol mixture in the operating room at the height $z$ at the instant $t$, $N(t)$ is the number of uranium atoms inhaled in the time interval $[0, t]$, and $A(t)$ is the activity of the uranium inhaled in the time interval $[0, t]$. Then $\frac{d}{dt}N(t) = q(n_{\mathrm{g}}(z_0, t) + \xi_{\mathrm{a}} n_{\mathrm{a}}(z_0, t))$ at $t \in [0, t_0)$, $\frac{d}{dt}N(t) = 0$ at $t \in (t_0, +\infty)$, $N(t) = \int_0^t d\tau\, q(n_{\mathrm{g}}(z_0, \tau) + \xi_{\mathrm{a}} n_{\mathrm{a}}(z_0, \tau))$ at $t \in [0, t_0]$, $N(t) = \int_0^{t_0} d\tau\, q(n_{\mathrm{g}}(z_0, \tau) + \xi_{\mathrm{a}} n_{\mathrm{a}}(z_0, \tau))$ at $t \in (t_0, +\infty)$, $A(t) = A_{\mathrm{sp}} m_0 N(t)$, $N'_{\mathrm{T}}(t) =$

**Table 2.** Distribution over human organs for the doses accumulated over $t = 50$ yr after inhalation penetration in an emergency

Emergency, inhalation penetration, integral and compartment models; $n_0 = 1 \times 10^{21}$ m$^{-3}$, $t = 50$ yr;
$N'$ is the number of accumulated decays and $A$ is the penetration activity through skin

| Organ or tissue T | $N'_T$ | Dose in organ: $E_T$, Sv | Dose in inner organs: $E$, Sv | $A$, Bq | $\varepsilon = \frac{E}{A}$, Sv/Bq |
|---|---|---|---|---|---|
| Kidney | $1.82 \times 10^{10}$ | $2 \times 10^{-2}$ | $1.1 \times 10^{-1}$ | $1.13 \times 10^{5}$ | $9.73 \times 10^{-7}$ |
| Trabecula bone surface | $6.6 \times 10^{9}$ | $5.38 \times 10^{-3}$ | | | |
| Trabecula bone bulk | $2.05 \times 10^{11}$ | $1.7 \times 10^{-2}$ | | | |
| Cortico–cancellous bone surface | $5.27 \times 10^{9}$ | $1.49 \times 10^{-3}$ | | | |
| Cortico–cancellous bone bulk | $8.78 \times 10^{11}$ | $9.91 \times 10^{-3}$ | | | |
| Liver | $3.77 \times 10^{10}$ | $1.43 \times 10^{-2}$ | | | |
| Soft tissues | $3.31 \times 10^{11}$ | $4.21 \times 10^{-2}$ | | | |

$\int_0^t d\tau\, A_{sp} m_0 N_T(\tau)$, $H_T(t) = \frac{K_\alpha}{m_T} W_\alpha N'_T(t)$, $E(t) = \sum_T K_T H_T(t)$, and $\varepsilon(t) = \frac{E(t)}{A(t)}$. Here, $z_0$ is the height at which a person's mouth is located, $t_0$ is the instant at which the person leaves the emergency room, $q$ is the volume of the air inhaled per unit time, and $\xi_a$ is the coefficient of the aerosol delay in the respiratory channel [3].

The approximate model developed in [2], which describes the air contamination in an operating room, yields fairly cumbersome expressions for $n_g(z, t)$, $n_a(z, t)$, and $N(t)$.

The ICRP compartment model gives the functions $N_T$ and $N'_T$ as a solution to the Cauchy problem for a system of linear ordinary differential equations with constant coefficients. The above-found value of $\frac{d}{dt}N(t)$ is substituted into the right-hand side of the system.

The quantities $A(t)$ and $\frac{d}{dt}N(t)$ were calculated from the explicit formulas (with numerical integration over the radii of aerosol particles). The above-mentioned Cauchy problem was solved numerically using the Mathematica 4.2 package. The quantities $E_T(t)$, $E(t)$, and $\varepsilon(t)$ were calculated using the $N'_T(t)$ and $A(t)$ values. According to the recommendations of the Ministry of Health of the Russian Federation, (SRS-99 [6, p. 9]), we considered the case $t = 50$ yr. The calculation results are given in Table 2.

The obtained dose coefficient of uranium during inhalation penetration, $\varepsilon = 9.73 \times 10^{-7}$ Sv/Bq, differs somewhat from the values of $\varepsilon = 4.9 \times 10^{-7}$ Sv/Bq (reported in SRS-99 [6]) and $5.9 \times 10^{-7}$ Sv/Bq [4]. This discrepancy may be related to the use of somewhat different AMAD activity median aerodynamic diameter of the aerosol particles in the above-mentioned sources.

## CONCLUSIONS

The results of this study suggest the following. First, despite the fact that in the case of penetration through the skin the basal skin layer is especially strongly affected by α-particles, it is the uranium that penetrates the body that plays a key role in the effective-dose accumulation. The component of the dose coefficient that is determined by the skin is smaller than the component determined by the inner organs by a factor of about 130. Secondly, the dose coefficient for the penetration through the skin is smaller than that during inhalation penetration by a factor of about 600. Thirdly, the dose coefficient calculated within the models is in good correspondence with the data on ε in the literature [4, 6].

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