RADIATION SHIELD OF THERAPEUTIC ELECTRON ACCELERATOR “CLINAC”

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It is anticipated that a therapeutic electron accelerator “Clinac” (manufactured by Varian Co., USA) will be installed at NSC KIPT. It has been suggested that the available compartment having thick concrete walls might be used as a medical treatment room. In this connection, the analysis has been made for correspondence of the compartment protection characteristics to the accelerator safe operation requirements. The protection capability was estimated for a mode of the accelerator operation at electron energy of 18 MeV with a target made of tungsten. Equivalent dose rates behind the shield were calculated with due regard for the direct bremsstrahlung from the target, and also, for the scattered photon emission and neutron radiation. To reduce the scattered radiation level in the entrance area, the variant of shielding maze has been proposed. The estimated radiation dose of the accelerator staff does not exceed the values permissible by the radiation safety standards. According to the calculations made, the concentration of ozone produced in the treatment room will be also below the MPC level.

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INTRODUCTION

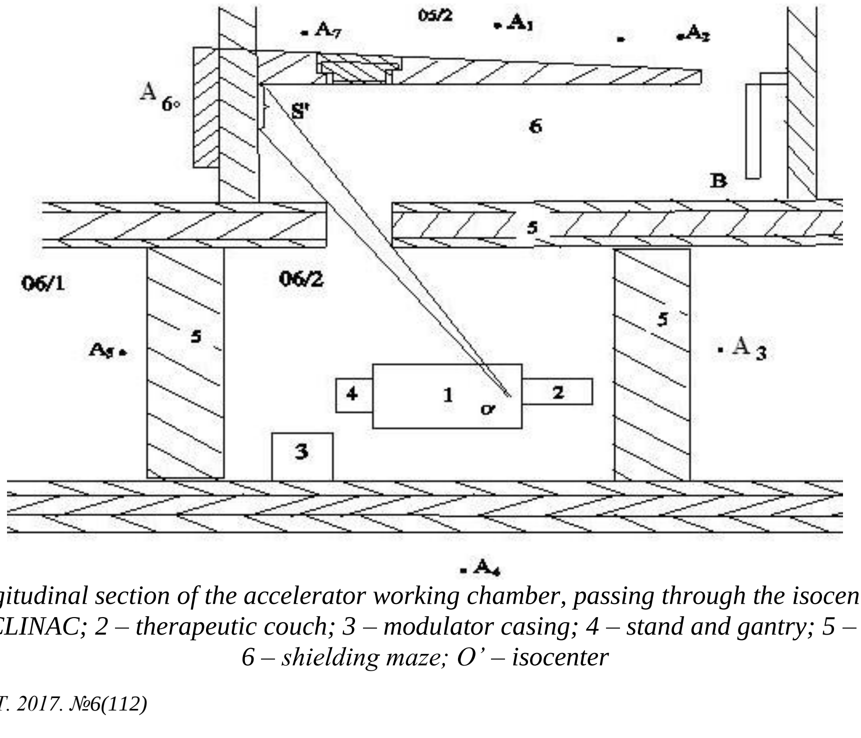
The National Science Center “Kharkiv Institute of Physics and Technology (NSC KIPT) is going to install an electron accelerator manufactured by Varian Co. (model Clinac 2300 C/D). On delivery, the Company provides only tabular standard protection data for the treatment room, which are intended for the use at the early stages of the therapeutic complex design. Therefore it was necessary to confirm its compliance with the regulatory requirements of a country where the accelerator is to be installed. In this connection, an analysis was performed to assess both the radiation protection of the intended accelerator chamber, as well as the ozone production during accelerator operation. The analysis was carried out with regard to the “Radiation safety rules for electron accelerators under No. 1442/23971 d/d 21 August, 2013”, to the recommendations on radiation shield calculations for electron accelerators, and also, other regulatory documents.

Fig. 1 shows the schematic of the intended Clinac working chamber at the level -4.800 is 6.9 m wide, 9 m long, the floor-ceiling height being 3.4 m. The side shielding of the facility will be provided by the existing 2 m thick concrete walls, and by the earth. At the top, the chamber is shielding by 1.2 m thick concrete constructions.

The installation control is assumed to be arranged in the adjacent premise at the level -4.800 separated from the accelerator chamber by the maze shielding against scattered radiation. The auxiliary operational areas are supposed to be located in the adjacent premises.

1. BREMSSTRAHLUNG SHIELDING CALCULATIONS

The analysis has been performed for the radiation shielding of the Clinac accelerator and its production of ozone at an electron energy of 18 MeV and a working load of 2000 Sv/week. For calculations, we have chosen the points A_1 – A_8 at mark -4.800, which are at service personnel location sites expected to have the highest radiation level (see Fig. 1), and also outside the building in the fill-up ground.



Longitudinal section of the accelerator working chamber, passing through the isocenter:
1 – accelerator CLINAC; 2 – therapeutic couch; 3 – modulator casing; 4 – stand and gantry; 5 – concrete shield; 6 – shielding maze; O’ – isocenter

Referring to Figure, we use the following notation: O and O^1 are the radiation source (accelerator head) and the isocenter, respectively; A_1 – is the point at the angle of radiation θ = 0 outside the maze shield; A_2 – is the point at the maze entrance, θ = 34°; A_3 – is the point behind the side shield of the vault; A_4 – is the point outside the building in the ground; A_5 – is the point at mark – 3.800 in an adjacent hall; A_6 – is the point outside the maze's entry; A_7 – is the point at θ = 20° in the hall, before the maze's entrance; A_8 – is the point on the ground floor, above the isocenter (at mark 1.000). The Clinac radiation characteristics used in the calculations are as follows.

- Maximum energy of accelerated electrons for the modes of exposure to electrons and bremsstrahlung 18 MeV;
- bremsstrahlung dose rate at the isocenter 720 Gy/h;
- bremsstrahlung dose rate external to the isocenter 0.72 Gy/h;
- neutron -to-bremsstrahlung dose ratio at the isocenter < 0.2%;
- shield materials – concrete, lead;
- beam size and possible beam directions are provided by Varian Co. on delivery of Clinac with a set of electronic applicators enabling the formation of six different fields measuring – 6×6 cm, 10×10 cm, 15×15 cm, 20×20 cm, 25×25 cm;
- feasible directions of the accelerator head: straight down – θ= 0°, and sideways – θ = 90°;
- radiation source- to- isocenter distance 1.05 m;
- accelerator operational mode (workload per week, equal to the product of the mean dose received by a single patient for the time of exposure by the number of patients) 2000 Sv/week.

The given below equivalent dose $\dot{H}$ rates at the points of interest correspond to the mode of facility operation with a tungsten target and a tantalum smoothing filter. Under these conditions, the bremsstrahlung is the dominant factor of radiation hazard, which governs the accelerator shield thickness. Noteworthy also is the production of harmful chemical substances (ozone and nitrogen oxides) in the air.

For a soft biological tissue, the relation between the absorbed and equivalent doses of bremsstrahlung is determined by the formula H(Sv)= 1.09 D(Gy). For simplicity, in our calculations, H was assumed to equal D.

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At the NSC KIPT, the design value of the standard reference dose rate RDR_A with the safety factor 2 at the workplaces of category "A" staff amounts to 4.1 µSv/h. The maximum workload *W* for the procedures without the smoothing filter (Field Flow Fractionation, FFF) has been determined by the Clinac supplier to be 2000 Sv/week at a 50-hour work week. The permissible bremsstrahlung dose rate *P* at a distance *R* is given by the expression

$$P(\theta)=\frac{1.0\cdot 10^{6}\,Wr^{2}b(\theta)}{T\cdot R^{2}}, \qquad (1)$$

where *W* is the workload (Sv/week), *r* is the radiation source-to-isocenter distance (m); T_x is the operational period of all the category "A" personnel shifts per week; *b(θ)* is the radiation yield factor in the *(θ)*-direction. In accordance to the data of refs. [2], [5], we put the solid angle value in the range from 0° to 14° to be b(θ)=1; and in the angular ranges from 14° to 20° and from 20° to 40° we put b(θ)=0.26 and b(θ)=0.1, respectively. For solid angles greater than 40°, *b(θ)* is taken to be 0.01.

The angular coordinates and the distances to the points of interest with respect to the point O, at which the electron accelerator target is located, are given in Table 1.

Table 1

Distances to the points of interest, angular coordinates and yield factors

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
R (m)	8	10	6	8	8	10	8.5	3.5
θ^0	0^0	34	90	0	90	40	20	180
b(θ)	1	0.1	0.01	1	0.01	0.1	0.26	0.01

Table 2 gives the calculated values for the equivalent dose rates (EDR) at unshielded control points, the necessary dose attenuation *K(X)*, the concrete shield thickness $X_{calc.}$, and also the thickness of the existing shield X_{actual}. Here and below, we use the attenuation of the bremsstrahlung dose rate for the concrete shield of density 2.3 g/cm^3.

Table 2

EDR at points of interest (µSv/h), the necessary attenuation K(x), shield thickness (required and existing)

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
$\dot{H}$, µSv/h	$6.9\cdot10^5$	$4.4\cdot10^4$	$1.2\cdot10^4$	$6.9\cdot10^5$	$6.9\cdot10^3$	$4.4\cdot10^3$	$1.6\cdot10^5$	$3.6\cdot10^4$
K(X)	$1.7\cdot10^5$	$1.1\cdot10^4$	$3\cdot10^3$	$1.7\cdot10^5$	$1.7\cdot10^3$	$1.1\cdot10^3$	$4\cdot10^4$	$8.8\cdot10^3$
$X_{calcul.}$, cm	240	190	160	240	152	145	207	185
X_{actual}, cm	300	270	200	300	200	200	250	120

The obtained shield thickness data for primary screening at points A_1 and A_4, X=240 cm, are in good agreement with the data of Table 2-1 for typical shield of the Clinac accelerator under standard procedures (X= 236.2 cm) at the concrete density ρ=2.355 g/cm^3.

It is evident from Table 2 that the existing shield thickness at the at mark -4.800 is sufficient for the primary and secondary screening of the personnel against the accelerator radiation. Point A_8 is found in the attic-floor room, where the coefficient of occasional presence of the personnel is equal to T=0.06, and the existing shield will suffice for the protection.

2. CONSIDERATION OF THE SCATTERED RADIATION

To calculate the scattered radiation contribution to the EDR at the entry to the treatment room (working chamber of the accelerator), the principal reflecting surface S_1 was chosen in accordance with the recommendations given in ref. [3]. In the calculations, the bremsstrahlung was assumed to be produced at the point O resulting from interaction of electron beam with the tungsten target, the primary collimator, the smoothing filter, the secondary collimator, and thereupon incidents on the scattering surface S_1.

The EDR of the scattered radiation at point B_1, scattered by the surface S_1, is determined according to ref. [3] by the formula

$$\dot{H}_{b_1} = \frac{1.0\cdot10^6\cdot Wr^2 b(\theta)}{T\cdot R^2}\,\frac{\alpha_1(\theta_{1,}E_0)\cdot S_1\cdot Cos\theta_1}{R_1^2}, \qquad (2)$$

where $\alpha_1(\theta_{1,}E_0)$ is the differential dose albedo for the bremsstrahlung with end-point energy E_0, incident on the scattering surface S_1 at an angle θ_1 relative to the normal to this surface. $\theta_{rad.}$ is the radiation angle, R is the distance from the radiation source to the scattering surface S_1 (m) in the maze of the treatment room, R_1 is the distance from the surface S_1 to the maze entry (point B_1). Using the parameters of the accelerator and the geometrical dimensions of the accelerator chamber, we obtain the initial data for calculating the EDR of the scattered radiation: R=7.2 m; R_1=11.2 m; $\theta_{rad.}$=30°; θ_1=60°; $\alpha(\theta,E)=3\cdot10^{-3}$; S_1=2.1 m^2; $b(\theta)$=0.01; r=1.05. Based on these data and formula (2), one can estimate the scattered radiation contribution to the EDR at point B ($H_в$ = 0.21 μSv/h). With account of the direct radiation contribution from point O at point B ($H_в$ = 0.34 μSv/h), the total dose rate at point B_1 is estimated to be H_Σ=0.55 μSv/h. Thus, the steel layer 6 mm thick will be sufficient for screening the door of the Clinac treatment room.

3. NEUTRON SHIELDING CALCULATION

In a working shift time, at an operating load of 2000 Sv/week and a 50-hour workweek, the mean EDR value of photoneutrons produced during accelerator operation, at a distance of 2 m from the target at the isocenter, will amount to

$$H_n = \frac{1.0\cdot10^6\cdot W\cdot r^2\cdot c}{T_n} = 4{,}41\cdot10^7\cdot c\,, \qquad (3)$$

where c is the ratio of the neutron EDR at the isocenter to the bremsstrahlung dose rate (c=0.2%); α is the neutron flux density-to-EDR conversion factor (α=1.7 μSv·cm^2·s/h).

So, the neutron flux density at the distance R=1 m (at the isocenter) will be H_n=5.2·10^4 n/cm^2·s.

The attenuation of photoneutron EDR in the concrete shielding can be estimated using the relation

$$К_н=\exp(d/\lambda), \qquad (4)$$

where d is the concrete shielding thickness (cm); λ is the photoneutron relaxation length in the concrete (equal to 16 cm).

Table 3 lists the values of neutron flux density at the calculation points without radiation shielding N_n, the neutron-induced dose rate $\dot{H}$, and also, the necessary dose rate attenuation K_n.

The data on the existing practical shield thickness X_{actual}, the required neutron shield thickness $D_{marg.}$, and the margin of neutron EDR attenuation $K_{marg.}$ are given in Table 4.

Table 3

Neutron flux density (n/cm^{2}s·), neutron-induced dose rate $\dot{H}$ (μSv/h) and the necessary neutron dose rate attenuation K_n

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
R(m)	8	10	6	8	8	10	8.5	3.5
N_n	$8.1\cdot10^2$	$5.2\cdot10^2$	$1.44\cdot10^3$	$8.1\cdot10^2$	$8.1\cdot10^2$	$5.2\cdot10^2$	$7.2\cdot10^2$	$4.2\cdot10^3$
$\dot{H}_n$	$1.38\cdot10^3$	$8.84\cdot10^2$	$2{,}45\cdot10^3$	$1.38\cdot10^3$	$1.38\cdot10^3$	$8.84\cdot10^2$	$1.22\cdot10^3$	$7.14\cdot10^3$
K_n	$3.37\cdot10^2$	$2.16\cdot10^2$	$6\cdot10^2$	$3.37\cdot10^2$	$3.37\cdot10^2$	$2.16\cdot10^2$	$3\cdot10^2$	$1.74\cdot10^2$

Table 4

Neutron shielding characteristics

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
$d(X)_{actual}$(cm)	300	270	200	300	200	200	250	120
$D_{concrete}$(cm)	94	86	103	94	94	86	92	120
K_{margin}	$3.9\cdot10^5$	$6.4\cdot10^5$	$4.3\cdot10^2$	$3.9\cdot10^5$	$7.5\cdot10^2$	$1.2\cdot10^3$	$1.9\cdot10$ 4	1

It is evident from the table that neutrons make practically no contribution to the EDR behind the shield, and their impact may be neglected.

4. CALCULATION OF OZONE CONCENTRATION AND FORBIDDEN PERIOD

Considering that at operation of an accelerator with energy up to 30 MeV the toxicity of air radiolysis products (ozone and nitrogen oxides) is mainly determined by ozone (ozone MPC is by a factor of 50 lower than the MPC of nitrogen oxides), the ventilation calculation is based on the provision of the desired ozone concentration reduction. In the “Radiation safety regulations for electron accelerators”, there are no instructions for calculating the ozone production by medical accelerators. There is a belief that when interacting with air, the bremsstrahlung of the accelerator produces far less radiolysis products than the electron beam does. It is assumed also that with the operating exhaust ventilation, the reduction in ozone concentration down to the permissible value occurs practically for a few seconds after the accelerator is turned off; and in this case, the forbidden period concept loses its practical meaning for the operating staff. For all that the patient stays all the time in the accelerator chamber (treatment room) with the accelerator being in operation. In view of this, the analysis has been performed to estimate the ozone production in the accelerator working chamber with the use of the data of practice guidelines [2, 3] and the available literary sources. In accordance with Supplement 2 to the "Radiation safety regulations for electron accelerators" (i. 2.16), the forbidden period of staff entrance to the working chamber is determined by the formula

$$T_{FORB} = \ln\left(\frac{C_{oz}}{MPC_{oz}}\right) / (K_{chamb} + \lambda_{chem}), \qquad (5)$$

where C_{oz} is the ozone concentration in the working chamber at the instant of radiation exposure, mg/m^3; MPC_{oz} is the maximum permissible ozone concentration, 0.1 mg/mm^3; $K_{chamb.}$ is the air change per hour in the accelerator working chamber, hour^{-1}; $\lambda_{chem.}$ is the coefficient characterizing the chemical instability of ozone, hour^{-1}, (λ_{chem}=1.2 h^{-1})

For determining the ozone concentration in the working chamber with the point radiator at its center, the chamber was assumed to be spherical with radius R.

The ozone concentration was calculated by the formula

$$C_{oz} = \frac{2.4 \cdot 10^2 \overline{\text{Đ}}}{\lambda + K_{chamb}} \left[1 - \exp\left\{-(\lambda + K_{chamb}) \cdot t\right\}\right], \qquad (6)$$

where $\overline{P}$ is the average absorbed dose rate in air, Gy/s; $K_{chamb.}$ is the air change in the irradiated volume, h^{-1}; t is the time of air irradiation, h; $\lambda=\lambda_{rad}+\lambda_{chem.}$ characterizes the radiation and chemical instabilities of ozone, h^{-1}.

λ_{rad} is calculated by the formula

$$\lambda_{rad}=34 \cdot \overline{P}^{\,0,6}, \text{ h}^{-}. \qquad (7)$$

The average absorbed dose rate in air for the chamber with the point radiator was determined through numerical integration of expression (1) over 4π. The angular distribution data are given in Section 1.

On exposure of a patient to radiation having the EDR equal to 12.1 Gy/min. (0.2 Gy/s) in the angular range from 0 to 14°, the maximum average EDR value in the treatment room of 211 m^3 in volume will make $\overline{P} = 0.0065$ Gy/s; and λ=1.66 h^{-1}; C_{oz}=0.042 mg/m$_3$.

Thus, even in the mode of operation without the smoothing filter at the patient dose of 20 Gy per run, the ozone concentration will not exceed the MPC value. Therefore, the forbidden period of entrance to the working chamber after the accelerator is turned off, loses its meaning. During the whole session of patient exposure, the ozone concentration in the chamber also will not exceed the MPC value.

CONCLUSIONS

The necessary design values for concrete shield thickness have been tabulated to provide safe operation of the installation with electron energy of up to 18 MeV. It follows from the present data that the existing radiation shield is sufficient to prevent the excess of the tolerable dose rate (TDR$_A$). For the treatment room protection, a 6 mm thick steel door must be installed in the shielding maze. During the irradiation session, the ozone concentration in the treatment room will not exceed the MPC value. Therefore, there is no need for setting a forbidden period for the staff to enter the treatment room.

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РАДИАЦИОННАЯ ЗАЩИТА ТЕРАПЕВТИЧЕСКОГО УСКОРИТЕЛЯ ЭЛЕКТРОНОВ "CLINAC"

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В ННЦ ХФТИ предполагается установить терапевтический ускоритель электронов "Clinac" (фирма Varian, США). В качестве процедурного кабинета предложено использовать имеющееся помещение с толстыми стенами из бетона. В связи с этим проведен анализ соответствия защитных характеристик помещения требованиям безопасной эксплуатации ускорителя. Оценка защиты проводилась для режима работы ускорителя с энергией электронов 18 МэВ и мишенью из вольфрама. Рассчитаны значения мощности эквивалентной дозы за защитой с учетом прямого тормозного излучения от мишени, а также рассеянного фотонного излучения и нейтронов. Для снижения уровня рассеянного излучения у входа в помещение предложен вариант защитного лабиринта. Полученная оценка дозовой нагрузки на обслуживающий персонал ускорителя не превышает значений, допускаемых нормами радиационной безопасности. Проведенный расчет наработки озона в процедурном кабинете показал, что его концентрация также не будет превышать допустимый уровень.

РАДІАЦІЙНИЙ ЗАХИСТ ТЕРАПЕВТИЧНОГО ПРИСКОРЮВАЧА ЕЛЕКТРОНІВ "CLINAC"

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У ННЦ ХФТІ передбачається встановити терапевтичний прискорювач електронів "Clinac" (фірма Varian, США). Як процедурний кабінет запропоновано використовувати наявне приміщення з товстими стінами із бетону. У зв'язку з цим проведено аналіз відповідності захисних характеристик приміщення вимогам безпечної експлуатації прискорювача. Оцінка захисту проводилася для режиму роботи прискорювача з енергією електронів 18 МеВ і мішенню із вольфраму. Розраховані значення потужності еквівалентної дози за захистом з урахуванням прямого гальмівного випромінювання від мішені, а також розсіяного фотонного випромінення і нейтронів. Для зниження рівня розсіяного випромінювання біля входу в приміщення запропонований варіант захисного лабіринту. Отримана оцінка дозового навантаження на обслуговуючий персонал прискорювача не перевищує значень, що допускаються нормами радіаційної безпеки. Проведений розрахунок напрацювання озону в процедурному кабінеті показав, що його концентрація також не перевищуватиме допустимий рівень.