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Shadow radiation shield required thickness estimation for space nuclear power units

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Abstract

The paper concerns theoretical possibility of visiting orbital transport vehicles based on nuclear power unit and electric propulsion system on the Earth's orbit by astronauts to maintain work with payload from the perspective of radiation safety.
There has been done estimation of possible time of the crew's staying in the area of payload of orbital transport vehicles for different reactor powers, which is a consistent part of nuclear power unit.

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Keywords: orbital transport vehicles, nuclear power unit, radiation safety

1. Introduction

Implementation of The Lunar Program, aimed to the creation of long duration lunar bases, will allow to create and work out necessary technical means for solution of more ambitious aims such as, for example, expedition to Mars. The deployment and exploitation of the lunar bases will require large-scale goods traffic to the circumlunar orbit.

Work [1] shows that The Orbital Transport Vehicle (OTR) with The Nuclear Power Unit (NPU) of 1MW electrical output and 5-year design life is the most cost-effective and technically achievable mean for provision of such goods traffic. The nuclear reactor of NPU is the source of energy.

An active zone of the NPU reactor is the source of ionizing radiation which is composed of neutrons and gamma.

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Works [2, 3] show the general view of a construction of space-adopted high power NPU on the basis of nuclear reactor. The radiation shadow shielding is applied for decreasing of radiation load from reactor on the materials of the engine and equipment of NPU. This shield is a block directly near the reactor with specified Radiation Cone Angle in which systems and aggregates of OTV are disposed. Apart from this, radiation-sensitive elements are protected by distance, i. e. they are placed in the most distant from the reactor areas.

Work [2] states that the usage of electronic component base is possible with the reactor radiation load of 25 krad and 10^{11} neutrons/cm^2.

This work estimates possibility of visiting by astronauts the space nuclear power units on the Earth's orbit for realization of routine work with safe radiation load. NPU with a gas-turbine heat exchanger by Closed Brayton Cycle (CBC) power conversion system was considered as an example [4].

2. Reactor as the source of neutrons and gamma

On the distances much larger than the active zone of reactor the flows of neutrons and gamma decrease with high accuracy inversely to squared distance, like for a dotted source.

$$\varphi(r,E) = N(E)\cdot L(E)\cdot \frac{1}{4\cdot \pi r^2}, \tag{1}$$

N(E) – intensity of radiation source , *L(E)* – function of decreasing of flow in material of radiation shielding, *r* – distance from the source.

If we know the value of flow *φ(R,E)* in the dot of detection, which was placed on the distance *R* from the source, then according to (1) the flow on the distance r is

$$\varphi(r,E) = \frac{\varphi(R,E)\cdot R^2}{R^2}, \tag{2}$$

Since leaks of ionizing radiation are proportional to reactor's heat power, the flows of neutrons and gamma (that are produced by reactor) in the shadow of shielding are equal to

$$\varphi(r,E) = \frac{P}{P_0}\cdot\frac{\varphi(R,E)\cdot R^2}{R^2}, \tag{3}$$

φ(R,E) – the flow in the dot of detection at the reactor's heat power P_0.

Thus if we know the value of flow of neutrons or gamma from the reactor's active zone, which is working at the specified power in definite dot, it is possible to estimate the value of flows in other dots, which are lying on the ray with the beginning in the center of the reactor's active zone and crossing this dot.

Forced fissions of atomic nucleus of ^{235}U are the main source of neutrons in the reactor's active zone. Specified value of heat power of the reactor allows to estimate amount of forced fissions of uranium nucleus per second. Power output (including energy of gamma from fission and decay of fission products, neutrons from fission, reaction's products, β-radiation from β-fissions of fission products, and neutrino) accounts for about 200 MeV per one fission of ^{235}U. So, 1W/200 MeV of fission of ^{235}U accounts for 1 W of power output in the reactor's active zone. The amount of fissions per 1 W is equal $3.1\cdot10^{10}$ fission/W·s, because 1 MeV = $1.602\cdot10^{-6}$ erg, and 1 erg = 10^7 J. On the average ~ 2.5 neutrons are released in case of the forced fission of ^{235}U. One of them has to provoke a forced fission of another uranium nucleus for maintaining of chain reaction. The rest 1.5 neutrons leave the active zone or are absorbed by reactor's regulating elements and by other construction's elements. This amount of neutrons can be considered the highest estimation of neutron's leak value, which is equal $3.1\cdot10^{10}$ fission/W·s ·1.5 neutron/fission = $4.7\cdot10^{10}$ neutron/W·s. The electrical output of NPU, necessary for OTV with 5-year design life, is equal 1 MW [1]. Efficiency of gas-turbine heat exchanger by Closed Brayton Cycle (CBC) power conversion system is about 30% [4], so the maximum of neutron's leak from the reactor's active zone doesn't exceed $4.7\cdot10^{10}$ neutron/W·s ·$3\cdot10^6$ W=$1.4\cdot10^{17}$ neutron/s.

Neutron fission spectrum can be accurately described by formula [5].

$$N(E) = 0.77 \cdot \sqrt{E} \cdot e^{-0.776 \cdot E} \tag{4}$$

The neutron fission spectrum according (4) is represented in Table 1.

Table 1. Neutron fission spectrum, normalized to unity

Energy, MeV	Quantity of neutrons, n/(MeV·n·fis)
0.01	$1 \cdot 10^{-3}$
0.10	0.015
0.50	0.129
1.00	0.185
2.00	0.294
2.50	0.103
5.00	0.223
7.00	0.039
10.0	0.011

Gamma-radiation of the reactor's active zone is usually divided into momentary and delayed (radiation of fission products) forms. During the fission of ^{235}U about 10 MeV is emitted momentary per fission in the form of gamma-radiation. Energy of photons, which are emitted during fission of nuclear fuel's fission products, is lower than those of momentary photons. Therefore, delayed γ-radiation is absorbed in the active zone and doesn't contribute in leak value significantly. So, leak of γ-radiation energy from the reactor's active zone doesn't exceed 10 MeV/fis·$3.1 \cdot 10^{10}$ fis/W·s=$3.1 \cdot 10^{11}$ MeV/W·s. The leak of energy at heat power of 3 MW is equal to $3.1 \cdot 10^{11}$MeV/(W·s) · $3 \cdot 10^{6}$ W=$9.3 \cdot 10^{17}$ MeV/s.

Photon fission spectrum can be described by the exponential dependence [5] in energy limit from 1 to 4.5 MeV.

$$\chi_{\gamma}(E_{\gamma}) = 8 \cdot \exp(-1.1 E_{\gamma}) \cdot, \tag{5}$$

$\chi_{\gamma}\left(E_{\gamma}\right)$ – photon spectrum, ph/MeV·fis, Eγ – photon energy, MeV.

Photon spectrum according (5) is represented in Table 2.

Table 2. Photon spectrum

Energy, MeV	Quantity of photon, ph/(MeV·fis)
1.00	4.85
1.25	0.58
1.50	0.44
2.00	0.59
3.00	0.54
4.00	0.18
5.00	0.06

3. Estimation of necessary shield thickness

Classical material for protection from neutron radiation is boron carbide (B4C). Series of calculation of neutron fluence and the absorbed dose of photons in silicon of different thicknesses were made for estimation of necessary boron carbide shield thickness. Modeling of radiation transfer was conducted using Monte-Carlo method. The reactor active zone was imitated by dotted isotropic source of neutrons and gamma with the spectrums from Table 1 and Table 2 and weight that corresponds to the above estimated leaks for reactor with 3 MW heat power and 5-year design life. The shield is a truncated cone with angle α=24º at the top (Fig. 1), as stated in [2], that ensures radius of the shadow ~ 10 m in fifty meters from the source of neutrons and gamma.

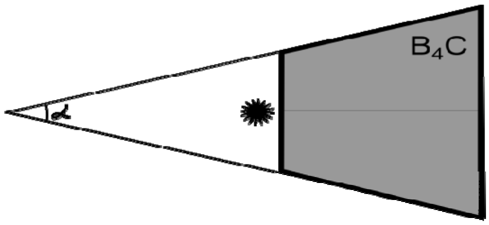

Fig. 1. Location of the dotted source and radiation shadow shielding

The source is placed directly near the shield. The dot of detection is located on the axis of the radioactive shield cone in 50 meters from the source of radiation next to the shield. Results of calculation of neutron fluence are shown in Fig. 2.

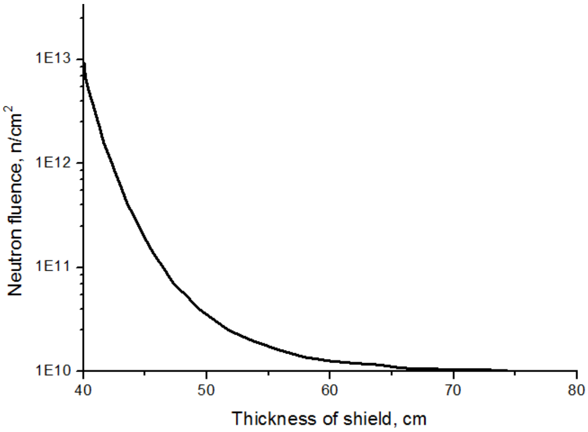

Fig. 2. Neutron fluence in the dot of detection depending on shield thickness (data obtained in the simulation)

Obtained regressive ratio of neutron fluence is:

$$\Phi_0 = 2 \cdot 10^{16} \cdot e^{-0.168 \cdot h} \tag{6}$$

h $[cm]$ – the thickness of the cone shield.

From the obtained regressive ratio follows that for decreasing of neutron fluence to the level of 10^{11} n/cm^2 the shield thickness should be:

$$h = \frac{\ln(10^{11}) - \ln(2 \cdot 10^{16})}{-0.168[cm^{-1}]} = 73[cm], \tag{7}$$

Unnormalized spectrums of neutrons and photons obtained in the dot of detection are shown in Table 3.

Table 3. Spectrum of neutrons and photons in the dot of detection

Photon energy, MeV	Photon fluence, ph/cm^2	Neutron energy, MeV	Neutron fluence, n/cm^2
0.15	$1.37\cdot10^{12}$	0.01	$5.16\cdot10^{8}$
0.20	$7.62\cdot10^{11}$	0.10	$9.59\cdot10^{9}$
0.30	$8.00\cdot10^{11}$	0.50	$1.72\cdot10^{10}$
0.40	$8.27\cdot10^{11}$	1.00	$2.60\cdot10^{10}$
0.50	$7.82\cdot10^{11}$	2.00	$1.51\cdot10^{10}$
0.60	$7.95\cdot10^{11}$	2.50	$6.74\cdot10^{9}$
0.80	$1.39\cdot10^{12}$	5.00	$2.44\cdot10^{10}$
1.00	$3.71\cdot10^{12}$	7.00	$9.39\cdot10^{9}$
2.00	$7.37\cdot10^{12}$	10.0	$3.18\cdot10^{9}$
3.00	$4.76\cdot10^{12}$	-	-
4.00	$4.04\cdot10^{12}$	-	-
6.00	$2.40\cdot10^{12}$	-	-

With the shield of such thickness total rated dose of absorbed primary and secondary photons in silicon is equal 4.86 Mrad, which don't meets the requirements stated in [2]. In order to reduce value of the absorbed dose required layer of heavy material, such as tungsten.

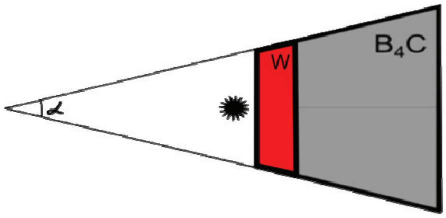

Fig. 3. Location of the dotted source and components of radiation shadow shielding

Series of calculation of the absorbed dose of photons in silicon of different thicknesses of tungsten layer were made for estimation of necessary tungsten shield thickness. Results of calculation of the absorbed dose are shown in Fig. 4.

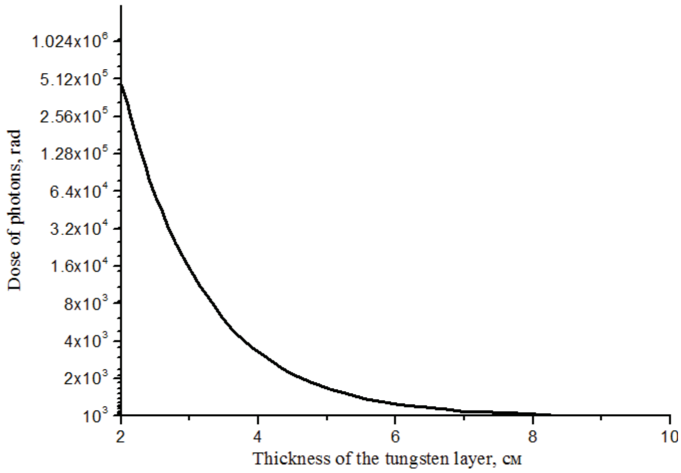

Fig. 4. Absorbed dose of photons in the dot of detection depending on tungsten layer thickness (data obtained in the simulation)

Obtained regressive ratio of neutron fluence is:

$$D_\gamma = 5 \cdot 10^6 \cdot e^{-0.742 \cdot x}, \tag{8}$$

x [cm] – the thickness of the tungsten layer.

From the obtained regressive ratio follows that for decreasing of photons dose to the level of 25 krad the tungsten layer thickness should be 7.2 cm.

As a result, the radiation shield is a truncated cone with angle at the top equal to 24º, and consisting of a tungsten, boron carbide layers, with thicknesses 7.2 cm and 73 cm correspondingly.

4. The maximum possible time of staying in payload area OTV

Calculation of equivalent dose from reactor's radiation at phases of convergence and docking was done on the strength of next assumptions [6]:

- The phase of convergence begins at the distance in 10 km from OTV and it consists of two parts: near guidance 1 (10 km to the aim, initial relative speed is 15 m/s) and near guidance 2 (1 km to the aim, initial relative speed is 1.5 m/s);
- The phase of docking begins in 100 m with initial speed 0.3 m/s;
- Motion is uniformly accelerated on each phase;
- Trajectory of convergence is not out of region of the shadow of radiation shield of NPU;
- Reactor works at standby with heat power 320 kW [4].

The time of near guidance 1 is T_1 = 17 min, time of near guidance 2 is T_2 = 19 min, and time of docking is T_3 = 11 min on the assumption of these supposition.

Equivalent dose rate in the dot, which is lining on the axis shadow cone behind the shield and is in the distance r from the center of the active zone, is equal On the distances much larger than the active zone of reactor the flows of neutrons and gamma decrease with high accuracy inversely to squared distance, like for a dotted source.

$$\dot{H} = \varphi(E) \cdot \mu(E), \tag{9}$$

φ(E) – flow of neutrons or photons [$cm^{-2} \cdot s^{-1}$], *μ(E)* – dose factor for neutrons or photons [cm·Sv]. The value of dose factor [7] are in Table 4.

In according to (3), (9) equivalent dose rate is equal

$$\dot{H} = \frac{P}{P_0} \cdot \frac{\varphi(R,E) \cdot R^2)}{r^2} \cdot \mu(E) \tag{10}$$

Equivalent dose of neutrons or photons, got at the time of convergence and docking is

$$H(E) = \sum_1^3 \int_0^{T_n} \varphi\big(r(t), E\big) dt \cdot \mu(E) \tag{11}$$

It is follows from (3) and (11), that value of equivalent dose is

$$H(E) = \sum_1^3 \int_0^{T_n} \frac{P}{P_0} \cdot \frac{\varphi(R,E) \cdot R^2}{\left(S_n - \frac{(V_n + V_{n+1})}{2} \cdot t\right)^2} dt \cdot \mu(E) \tag{12}$$

V_n- initial speed of phase of convergence n, S_n – distance from the beginning of phase of convergence n to the science payload OTV.

Calculated equivalent dose, got at the time of guidance 1, 2 and docking is equal 0,003 rem. The equivalent dose rate in the area of paylod OTV is equal 0,05 rem/hour for 320 kW reactor heat power. For example, equivalent dose level 10 rem is 20 percent of the maximum tolerated dose [8] and achieved in 200 hours for 320 kW reactor heat power.

Table 4. Flux to dose conversation factor values

Energy of photons, MeV	Flux to dose conversation factor, 10^{-12} Sv·cm^2	Energy of neutrons, MэB	Flux to dose conversation factor, 10^{-12} Sv·cm^2
0.15	0.752	0.01	18
0.20	1.00	0.10	59
0.30	1.51	0.20	99
0.40	2.00	0.50	188
0.50	2.47	1.00	282
0.60	2.91	2.00	383
0.80	3.73	3.00	432
1.00	4.48	5.00	474
2.00	7.49	7.00	490
4.00	12.0	10.0	499
6.00	16.0	-	-

5. Conclusion

According to estimations, the time of crew's possible staying in payload area OTV will make approximately 200 hours for reactor plant operation mode with thermal power of 320 kW and approximately 20 hours for thermal power of 3 MW. Biological radiation shield can increase crew's staying time in payload area.

Thus, it is possible to increase team safety while approaching OTV in case of its routine maintenance.

References

[1]Kosenko A.B., Sinyavskiy V.V. Technical and economic efficiency of employing a reusable space tug based on a nuclear electric propulsion system to support intensive cargo traffic for lunar exploration. *J. Space technology and technology*. 2013;№2:72-84.

[2]Masson L.S. A Power Conversion Concept for the Jupiter Icy Moons Orbiter, NASA/TM—2003;212596.

[3]Sinyavskiy V.V. Advanced technology for nuclear electric propulsion orbital transfer vehicle Hercules. *J. Space technology and technology*. 2013;№3:26-43.

[4]Karevsky A.V., Popov S.A. Features a joint operation of the system of energy conversion and electric rocket engines as part of a nuclear power installation. EUCASS-2013. Munich, 2013.

[5]Gusev N.G., Klimanov V.A., Mashcovich V.P. et al. Protection against Ionizing Radiation. Moscow:Energoatomizdat. 1989

[6]Lebedev A.A., Socolov V.B. "Meeting in orbit". Moscow:Mechanical Engineering. 1969.

[7]Sanitary norms and rules 2.6.2523-09. *Radiation safety standards.* RSS-99/2009. 2009

[8]Vorobiev E.I., Kovalev E.E. *Radiation safety of crews of aircraft.* Moscow:Energoatomizdat. 1983