Calculational aspects of integrated design of optimum radiation protection of space nuclear power systems

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ABSTRACT

The analysis of missions of spacecrafts[1] has shown, that the space nuclear power systems (SNPS) are competitive for electric power requirements about 50 kW and more. Space nuclear power offers significant increases in available power for spacecraft, independent of sunlight intensity. It is a key element in earth orbit applications, enables the use of high power active sensors, such as radar. However, high powers and long-lived operational life's of SNPS and a large sizes of a radar reduce in increase of a mass of radiation shield. Therefore the creation of shield with minimally possible mass is one of the most important problems of a practical designing of SNPS.

1. INTRODUCTION

A complex approach to optimization of shield of SNPS are being carried out at the Institute of Physics and Power Engineering[2]. One of the basic ideas in this approach is that the creation of optimum of radiation shield system is not only the task of the shielding designers, but developers of all subsystems of a SNPS. The calculated aspects of such technology are submitted in this report. The classification of subsystems SNPS as the objects of optimization of radiation shield is presented too. The techniques of calculation and optimization in developed approach are being chosen according to iterative character of the designing process. At each stage of this process the information about the spacecraft subsystems be-

comes more definite. The accuracy of the radiation transport calculations and the carefulness of the shield's optimization are heighten with a deepening of designing too.
The calculated techniques of optimization and the codes used on various design stages are described.

2. SPACECRAFT SUBSYSTEM, WHICH DEFINE MASS AND GABARIT CARACTERISTICS OF THE RADIATION SHIELDING

When we choice the optimum configuration of the radiation shielding SNPS, it is needed take into consideration other subsystems of the spacecraft. The scheme of such spacecraft is shown on figure 1. The basic subsystems which determine the radiation conditions and mass characteristics of the shielding are: nuclear reactor; shielded object (payload); radiation shielding; scattering – large-scale overall dimensions subsystem situated outside a shadow limit of the shielding (for example antenna); additional radiation source – the installation components which is taken out shield limit (for example: activated coolant); communications – elements of the installation the mass of which must be taken into account during we are choosing the optimum distance between reactor and payload (for example: boom, cable, pipeline).

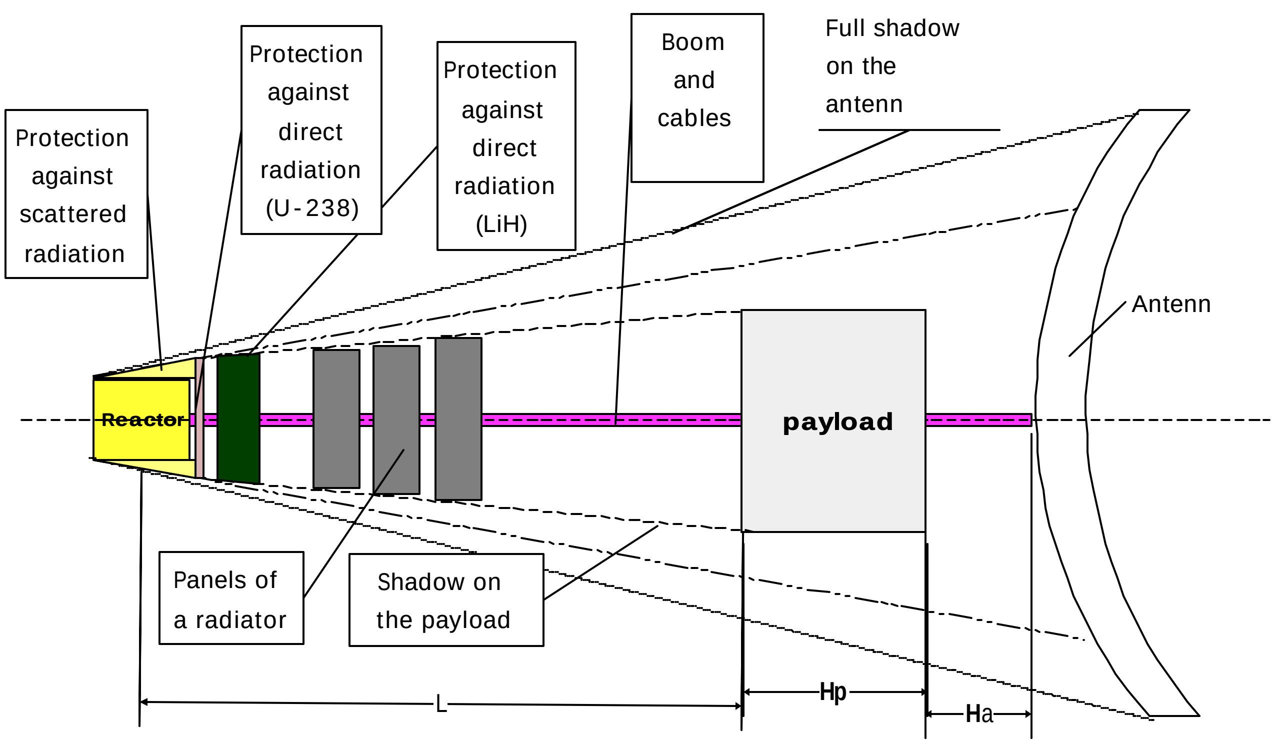

Figure.1. Arrangement of the spacecraft with antenna.

3. THE METHODS OF THE CALCULATION AND OPTIMIZATION

The designing of the shielding as a subsystem SNPS is an iteration process. On earch step the information about installation subsystem is done more precise. This increases the accuracy of calculations of the reactor radiation field and the detaility of mass shielding optimization. In this report we describe two ways for designing. For example, let us consider spacecraft with radar-antenna (fig.1).

Stage 1. To define the arrangement installation and radiation shielding.

Stage 2. To define the project parameters of the radiation shielding.

For the first stage we designed code OPTI. It calculates operatively the optimum disposition of the spacecraft subsystems, optimum structure and mass of the shielding. A brief description of this code is presented below. The input data contain a parameters for seven types of the spacecraft subsystems, which determine mass and overall dimensions characteristics of the shielding. The list of the input data for such objects is shown in table. The code OPTI uses this data.

Table. Input data

The object of the spacecraft	Parameters
Nuclear reactor	Overall dimensions, powerful, resources, parametrical description of the neutron and photon field around the reactor and shielding [a)]
Payload	Overall dimensions, limited neutron fluence and limited photon doze
Radiator	Powerful of the activated sources , distribution of activated coolant in the pipeline and radiator
The system of the moving apart and electro communication.	A mass as a function of distance between the reactor and payload [b)]
Scattering (large-scale overall dimensions construction)	Mass, geometry, cross sections of scattering for neutrons and photons
Equipment	Axial overall dimensions, effective cross sections of attenuation for neutrons and photons
Radiation shielding	The distance from the reactor, meaning of components of the doses on payload and effective cross sections [c)]

[a]Calculating on code RAPID[3] or MCNP[4].

[b]The data of the designer.

[c] Calculate for definite reactor.

Varied parameters: the distance between reactor and payload, shadow angel, the thickness of the shielding layers.
Objective function – summary mass of the shielding, system of the moving apart and communications.
Restriction functionals – neutron fluence, photon doze, radiation heating of the shielding and et.
Methods for the estimation of the radiation functional and optimization algorithemes – engineering methods; parametrical discription of the radiation functional, which is given from RAPID and MCNP calculations; methods of the Lagrange factor and procedures for one-dimension optimization.
Already at the beginning stage the worked out instrument allows to define the optimum disposition of the subsystem power installation and spacecraft, thickness and mass of the shielding layers, shadow angel. This permits to decrease the spacecraft mass on several hundred kg. The scheme of the spacecraft with radar antenna and nuclear power installation NPS-50 is shown in fig.1. The start composition was the composition in which the shadow cone is oriented on large-scale overall dimensions element of the spacecraft – antenna. This results in some profits. Firstly, the optimum arrangement of the spacecraft has been designed. Secondly, the optimum parameters of the shielding system have been determined, that is distance between the reactor and shielding, distance between the payload and antenna, shadow angel, thickness of the shielding layers. All this allowed decrease summary mass of the radiation shielding and communications of the spacecraft more than 2 tone.
The size of this report doesn't allow us to describe the process of the optimum search in details. Therefore we have shown on fig.2 only the result of the optimum choice for distance between reactor and payload.

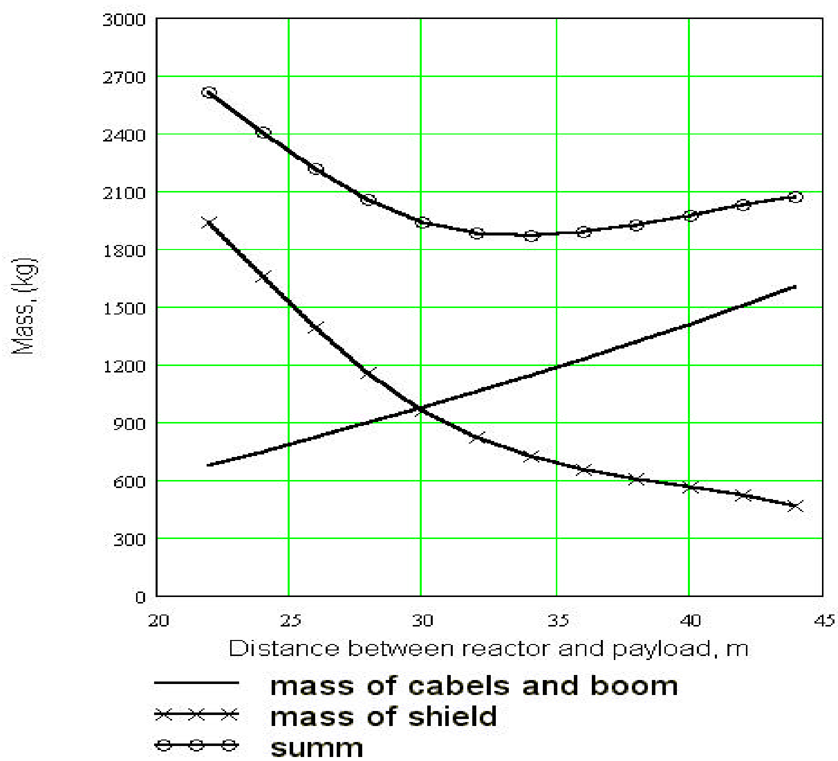

Figure 2. A mass of the radiation shielding as a function of the distance between reactor and payload.

At the second stage of the designing we have used the code solving the transport equation in two-dimensional geometry (KASKAD, RAPID) and tree-dimensional geometry (MCNP).
Mainly the code RAPID has been used because of it is solving the task of radiation shield SNPS. Very strong angel anisotropy is one of the characteristic peculiarly of the solving the transport equation in such calculation area. The techiques such as: direct integrating the transport equation on the direction mesh and the method of the last collision have generated the individual angel mesh for every space knot, that is to distinguish the main direction of radiation transport. The same techiques are been using for solving the adjoint transport equation and calculating spatial distribution of contributton current on the arbitrary surfaces. It should be noted that the integral from contributton current on the surface gives the value of radiation functional (on the shielded object) which are needed to find.
The methods realized in code RAPID allow to solve the radiation transport task in part for such extend system as SNPS itself. To solve the direct transport equation in trend from radiation source (reactor) to shielded object (payload), but adjoint transport equation – from payload to radiation source (fig. 3) enables us: firstly, simplify the task, secondly it is possible to vary second part of the task.
For example, the situation plane S_1 (fig.3) between the reactor and shield allows:
To vary the reactor structure , if the adjoint solution $\boldsymbol{F}^{+}\left(\vec{\boldsymbol{r}},\vec{\Omega},\boldsymbol{E}\right)$ was calculated on plane S_1;
To vary the structure and profile of the shield, if the particle flux $\boldsymbol{F}\left(\vec{\boldsymbol{r}},\vec{\Omega},\boldsymbol{E}\right)$ was calculated only one;
To vary payload structure, if the plane S_2 was combined with doze plane and if we calculated angel contribution of the direct radiation.
At last, the shielding can be shaped with a help of the contributton. The results of the model task solution for optimal profile of the shadow radiation shield of SNPS BUK-TEM for spacecraft with antenna is shown on fig 4. The choice of the optimal configuration of the radiation shield (fig.6) allows to decrease its mass from 4700 kg to 860 kg, that is more than 5 times. The mass of the shield the shadow from which covers it fully is equals 4700 kg. During the execution of the optimization calculations the aspiration of the maximum approaching more close to reactor of the shielding surface has appeared. Therefore the limited surface was introduced. On fig.4 it was called a “designing”. The outer reactor construction is disposed more to the left and below. The radiation shield is placed more to the right and above.
Thus, inner radiation shield as though “is stretched” on the “designing” surface, but the profile of the outer surface is determined when the mass will be minimized and the neutron fluence on the equipment compartment will be limited.

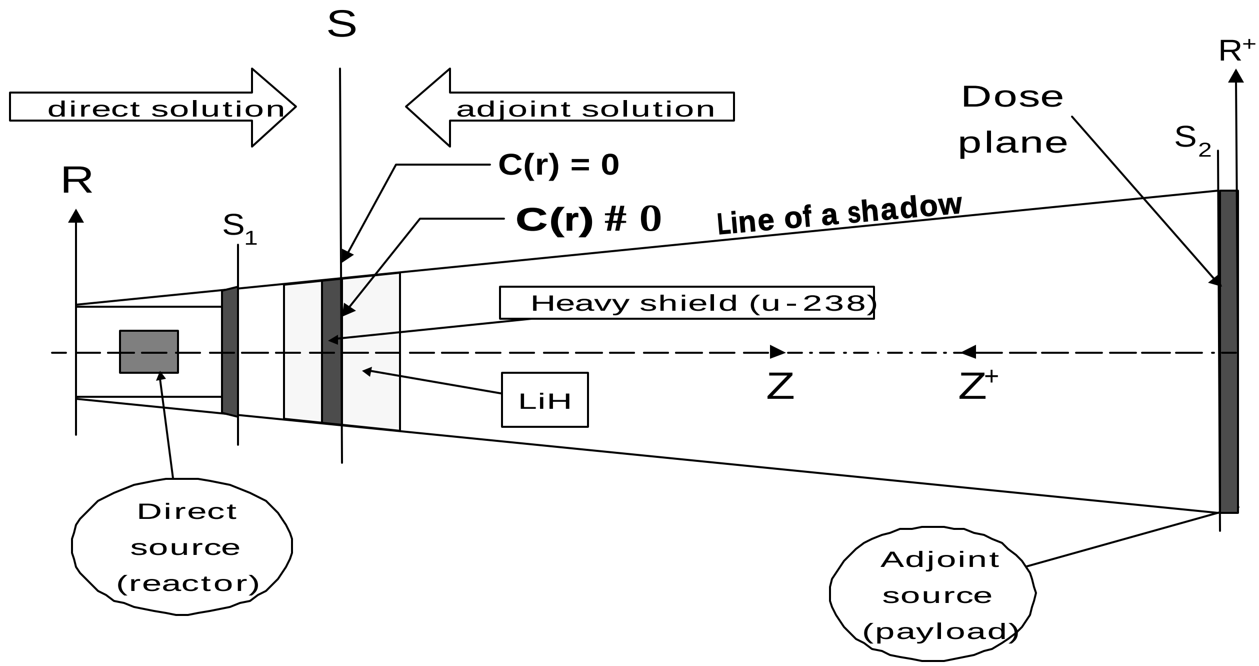

Figure 3. The geometry of the direct and adjoint solution of a transport equations

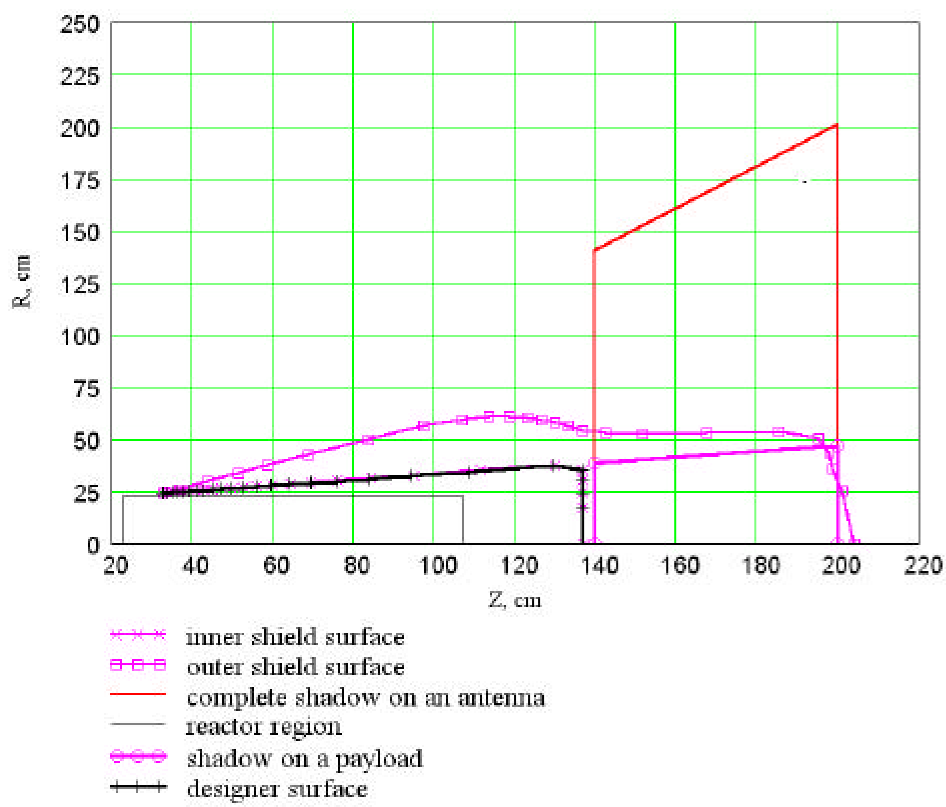

Figure 4. The optimum profile of the radiation shield.

A contributons currents and the optimization algorithms which is based on the theory of optimum control were been using when the optimum profile of the radiation shield was been searching.

The task for the determination of the optimum shield profile in terms of the theory of optimum control is formulated as follows:

“Movement” of the object is described by the system of equations (1).

$$\frac{dx_0}{dt} = \frac{2 \cdot p \cdot g}{3} * \{ [r_0^1(t) + u_1(t)]^3 - [r_0^2(t) + u_2(t)]^3 \}$$

$$\frac{dx_1}{dt} = 2 \cdot p \cdot C_0^1(t) \times exp\{ \Sigma_1(t) \cdot u_1(t) \} \times [r_0^1(t) + u_1(t)]^2 \qquad (1)$$

$$\frac{dx_1}{dt} = 2 \cdot p \cdot C_0^2(t) \times exp\{ \Sigma_2(t) \cdot u_2(t) \} \times [r_0^2(t) + u_2(t)]^2$$

To move the object from point with coordinates $\vec{\mathbf{x}}(\mathbf{t}0)$ to point with coordinates $\vec{\mathbf{x}}(\mathbf{T})$, so that

$$x_0(T,\vec{u}) = \int_{t0}^{T} \frac{dx_0(t,\overline{u})}{dt} dt \qquad (2)$$

have the minimum value.

Boundary data:

$$x_1(T) + x_2(T) = 2 \times F_d \qquad (3)$$

Here F_d – permissible neutron fluence on the payload.

$$x_1(T) = \int_{t0}^{T} \frac{dx_1(t,\vec{u}(t))}{dt} dt \ , \ x_2(T) = \int_{t0}^{T} \frac{dx_2(t,\vec{u}(t))}{dt} dt \qquad (4)$$

All functional are been calculating in the spherical system of coordinate with a center on the cone top oriented on antenna.

t0 – cosine of the maximum opening angel of cone, T = 1.

$\boldsymbol{C_0^i(t)}$ - contributton flux, $\boldsymbol{r_0^i}$ - surface radius, $\boldsymbol{u_i}$ -(control) the variation of the radius of surfacei. i – index of the shield surface.

X_1 and X_2 – neutron fluence, which is resulted from the integration of the contributons currents on the inner and outer shield surface, accordingly. X_0 – the shield mass.

The well-known code MCNP is used for veryfying of the optimization results and for estimation tree-dimensional effects of radiation transport.

In reduced above example the profiling of the light component of the shield is carried out at limitation of the neutron fluence on payload. The similar results are obtained for the heavy component of the shield [5]. It should be noted that results of the decision of an adjoint transport equation obtained code RAPID are used by us for acceleration of the calculation on MCNP. This effect is reached by a simple manner. The solution of an adjoint transport equation obtained by code RAPID ($F^{+}(\vec{r})$) is set as a value of the cell (imp:n=…). At this moment this effect is arrived at 20 times. In so much times the quantity of the history during calculating neutron fluence behind the shield from LiH is reduced. The thickness of radiation shield is equals more than 60 cm.

4. CONCLUSION

The examples presented above illustrate the efficiency of the complex approach and developed methods of the radiation shield optimization as a subsystem of the nuclear power installation and spacecraft. This approach gives a possibility to decrease a shield mass and makes the space nuclear power system more competitive in comparison with other source of energy.

REFERENCES

1. S.P. Zatcerkovniy, A.I. Kuzin, K.A. Pavlov, G.A. Shevtcov, "Transport-energy modules", Proceedings of the international workshop "Space energy XXI century (Nuclear aspect)", Obninsk, Russia, p. 15, (1998).

2. Dubinin A.A., Eremin A.G., Levchenko V.M, Pyshko A.P. "Calculating, optimization and designing of the radiation shield NPI as a spacecraft subsystem", Topic thesis of VII Russian scientific conference on radiation shielding of nuclear installation, Obninsk, SSC of Russian Federation Institute of Physics and Power Engineering, p.p. 235-237, (1998).

3. A.P. Pyshko, A.A. Dubinin, V.M. Levchnko, A.Yu. Plotnikov, “New Capabilities of RAPID-Code for Calculation of Reactor Radiation Functional on the Spacecraft Subsystems ”, Proc. RP&S Topical Meeting, Nashville, Tennesee, Vol. 1, p.241-248, (1998).

4. Briesmeister, Ed., “MCNP4A - A General Monte Carlo N - Particle Transport code”, Los Alamos National Laboratory report, LA-12625-M (1993).

5. A.A. Dubinin, V.M. Levchenko, A.P. Pyshko, "Using the contributons for calculating and profiling radiation shield for SNPS", Topic thesis of VII Russian scientific conference on radiation shielding of nuclear installation, Obninsk, SSC of Russian Federation Institute of Physics and Power Engineering, p.p. 78-80, (1998).