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Shield Nuclear Design for the 5-kwe TE System

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ABSTRACT

The nuclear analysis of the 5-kwe reactor shield is presented. Calculation methods and optimization techniques used are presented. Borated stainless steel was selected for the gamma ray shield with tungsten alloy as an alternate. The total shield weight was calculated to be 355 lb.

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I. INTRODUCTION

With a reactor heat source, shielding is required to reduce the radiation levels at the payload. The reactor emits two types of radiation that must be attenuated by the shield, neutrons, and gamma rays. Neutrons are most effectively attenuated by light hydrogenous materials. For gamma ray attenuation, metals with high density are the most efficient materials. The reactor shield is thus comprised of a combination of a high density material and a hydrogenous material.

Since the shielding of a reactor power system represents a significant fraction of the total power system weight, careful system design is required to minimize shield weight. The shield weight is a function of many variables, some of which are influenced by the system design. The primary variables of importance are the separation distance between the reactor and the dose plane, and the shield cone half-angle that must be shielded. The shield weight can be minimized by increasing the separation distance, and by reducing the shield cone half-angle. The allowable radiation level at the dose plane is also a key variable and will be discussed in the next section.

II. DOSE CRITERIA

The dose criteria set for the 5-kwe system is based on acceptable levels for conventional aerospace electronic components. The 5-yr dose limits at the dose plane were set at the following:

Neutrons   - 10^{12} nvt ($E_n > 0.1$ Mev)
Gamma rays - 10^6 rads.

The above integrated doses are averaged over the dose plane area.

III. SHIELD MATERIAL SELECTION

Shielding materials of different types must be used to attenuate gamma rays and neutrons in order to obtain a minimum weight shield. Such materials must be picked to minimize system weight, while being consistent with other system design requirements. Selection of a shield material cannot be made solely on the basis of its primary function, that of radiation

attenuation; such factors as structural characteristics, physical, and chemical properties, fabricability, availability, etc., must be considered.

A. Neutron Shield

Lithium hydride (LiH) was selected for the neutron shield, since it has proved to be a very effective neutron shield material. It has a low density - 0.72 gm/cc - and a very high effective neutron attenuation coefficient which has been confirmed experimentally. It also has a high melting point (1270°F) and a very low dissociation pressure.

B. Gamma Ray Shield

The weight of the gamma ray shield represents a significant fraction of the total shield weight. Thus, a careful selection of a gamma ray shield material may result in large weight savings. Since the gamma ray shield is placed immediately below the reactor core, the secondary gamma ray generation in the shield due to neutrons is a very important factor.

Various high density shield materials were considered: U - 8 Mo, Ta - 10W, Tungsten alloy (95% W), lead, and borated stainless steel. Ta- 10W was rejected due to excessive weight. Lead was rejected due to its very low melting point (620°F). U - 8 Mo shield resulted in a low shield weight; however, it was rejected due to its higher internal heating (due to fast fission), and due to its instability at high temperatures.

1D transport calculations were performed to compare tungsten alloy, stainless steel, borated steel (with natural and B^{10} enriched B_4C) and tungsten alloy with a thin sheet of borated steel between it and the LiH shield. The relative shield weights are presented in Table I. Further 2D perturbation theory using DOT code calculations were performed to shape the gamma ray shield by varying the thickness and radius. Relative weights are presented in Table I for tungsten alloy and borated steel (natural boron). Since the shield weight using borated steel is less than that of tungsten

alloy, it has been selected as the reference shield material with tungsten alloy as an alternate.

IV. CALCULATIONAL METHODS

The calculational methods used can be divided into two categories: scoping and detailed* calculations. The purpose of the scoping calculations was to obtain parametric data and to get an estimate of the shield weight. One dimensional ANISN (Transport Theory Code) was used extensively. A quadrature of 16 (S_{16}) was used for fluxes and P_3 approximation was used for cross sections. Twenty-one energy groups were used for neutrons, which were coupled to 18 energy groups for gamma rays. In addition to the ANISN code, QAD code which is a 3-dimensional code using ray-tracing was used for gamma rays. In this case, 18 energy groups were used.

For detailed calculations, the DOT/SPACETRAN code was used. The DOT code is also a 2-dimensional transport code, and was used in the R-Z geometry. Coupled 21 neutron and 18 gamma ray cross section groups were used. The angular currents leaking from DOT surfaces are fed into the SPACETRAN code which then calculates both the neutron flux and gamma ray dose rates at a particular dose point.

One final code used for detail analysis has been the MORSE Monte Carlo code that was used to determine the neutron streaming through the NaK ducts in the LiH shield. This will be discussed in greater detail in the next section.

V. EFFECT OF SYSTEM ON SHIELD DESIGN

The effect of reactor system components on the shield design is extremely important. This section discusses the effect of radiator scattered dose rate (if radiator is outside shield cone), the attenuation provided by the PCS equipment, the radiation level from the radioactive primary NaK pump, and neutron shield penetrations.

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* The detailed calculations described here were conducted primarily at ORNL.

A. Neutron Scattering From Radiator Outside Shielded Cone

At the beginning of this study, the radiator was designed such that part of it was outside the shielded cone. Figure 1 presents the radiator geometry that was considered. It may be noted that the outermost point on the radiator is 2° outside the shielded cone. The neutron flux leaking from the side of a shielded SNAP reactor for manned application is proportional to sine cubed function. Where the angle in consideration is the one with the side shield surface, see Figure 2. Using this relationship, the neutron flux at the outermost point on the radiator (i. e., 2° out) coming from the reactor side shield is much less than the neutron flux coming out of the LiH shield (i. e., the direct neutron flux).

For unmanned systems (with no side shielding), however, the side leakage is proportional to the sine of the angle (see Figure 2) raised to only ~ 1.5 power. Thus, for a 2° angle, the neutron flux coming from the reactor side is about 65 times greater than the direct flux. Furthermore, the neutron scattered flux with the radiator is now greater than the direct flux. Thus, it was decided to have a radiator which does not extend beyond the shielded cone.

B. Attenuation Provided by PCS

The attenuation provided by the PCS which includes: TE modules, TE pumps, piping, and NaK accumulators is a very important consideration. Figure 3 presents the shield weight saving as a function of PCS gamma ray dose rate attenuation factor. The weight saving is normalized to a PCS attenuation factor of 3.0. It may be noted that if no credit is taken for the PCS attenuation, i. e., PCS attenuation factor = 1.0, the additional shield weight required is ~ 200 lb. This shows the importance of including the attenuation provided by the PCS equipment.

The PCS gamma ray dose rate attenuation factor was calculated using hand calculations, the QAD code, and finally the DOT/SPACETRAN code. The hand calculations were based on a view factor, and each section of the PCS provided a small amount of attenuation. The QAD code was used in 3 dimensions where each TE module was homogenized, and treated separately. Ray tracing technique was used throughout without buildup factor. In the case of the DOT/SPACETRAN calculations, the PCS equipment was mocked up in R-Z geometry. This means that all the PCS equipment was broken down into a series of rings. The leakage from the DOT bottom surface is fed into the SPACETRAN code which then integrates over this bottom surface for the dose rate at a point on the dose plane.

For a system with 8° shield cone half-angle, the PCS gamma attenuation factor was calculated to be 3.0 using hand calculations, 3.2 using the QAD code, and 2.5 using the DOT/SPACETRAN code.

C. Radioactive NaK Activity

An additional gamma ray source to consider is that from the radioactive NaK below the shield. As NaK circulates through the core, both sodium and potassium absorb neutrons, and thus become radioactive, namely, Na^{24} and K^{42} with half lives of 15.0 and 12.4 hr, respectively. After a few days of reactor operation, the activities will saturate and remain constant the rest of the reactor operation time.

Based on previous studies, ~ 0.68 Ci of Na^{24} is present in the primary loop per kilowatt of reactor power. Thus, for the present design, there will be 64 Ci of Na^{24} in the primary loop, of which 72% is below the shield, or 46 Ci of Na^{24} . Based on the present design, the dose rate from the NaK was calculated to be 5.41 rem/hr at the dose plane, assuming no shielding from the PCS equipment. The attenuation provided by the PCS equipment was calculated to be 1.5 for the NaK primary loop. Thus, the radiation level from the radioactive NaK loop below the shield is 3.6 rem/hr at the dose plane.

D. Neutron Shield Penetrations

Detailed neutron streaming calculations through the NaK pipe penetrations in the LiH shield were performed. The DOT-DOMINO-MORSE (DDM) code was used. The DDM code uses the DOT 2D transport code to generate angular fluxes above the LiH shield. The DOMINO code then couples these results to the MORSE code (a multigroup Monte Carlo code) which then calculates the streaming through the NaK pipes. The MORSE output is then fed to the SPACETRAN code which finally calculates the neutron flux at the dose plane. Table II presents relative neutron fluxes for various duct diameters and duct slant angles. For the no duct case (i.e., zero inch duct) a DOT/SPACETRAN was also run, and the agreement is fairly good with the DDM/SPACETRAN case. In the present conceptual design, the duct diameter is 1.87 in. and relative neutron flux at the dose plane is expected to be about 1.5. Since these calculations are preliminary, the effect neutron shield penetrations has not been included in the conceptual design.

VI. SHIELD DESIGN

As was mentioned in the previous section, the dose rate from radioactive NaK is 3.6 rem/hr. The dose criteria for gamma rays are 10^6 rads/5 yr or 22.8 rem/hr. Thus, the dose rate from the reactor should be the difference or 19.2 rem/hr. Since the NaK dose rate is less than the gamma ray dose criteria, a gallery to house a NaK-to-NaK heat exchanger is not necessary. It should be noted that if the gamma ray dose criteria were reduced by a factor of 10, or if the reactor power level is increased by a factor of about 4, then a NaK-to-NaK heat exchanger will be required.

The present shield has a gamma ray shield below the reactor followed by LiH, see Figure 4. This design was calculated using two dimensional perturbation theory techniques with the DOT code. The gamma ray shield was shaped by varying the thickness as a function of shield radius to yield

a minimum weight. The shaped shield is thickest below the reactor vessel, and thinner in the annular ring section below the reflector.

The effect of the neutron shield shaping was also analyzed with the DOT/SPACETRAN code and the resultant neutron flux was calculated to be flat across the dose plane.

The total shield weight was calculated to be 355 lb. The borated stainless steel shield weighs 98 lbs, and the LiH shield weighs 257 lb. The LiH shield includes 195 lb of LiH and stainless honeycomb, and 62 lb for the casing.

VII. CONCLUSIONS

The previous sections have shown that the shield shown in Figure 4 will meet the dose criteria of 10^6 rads/5 yrs and 10^{12} nvt/5 yrs at the dose plane. Furthermore, this dose criteria is met all over the dose plane. Both the gamma ray shield and neutron shield have been shaped to yield a minimum weight.

The calculational methods: DOT/SPACETRAN, DOT/DOMINO/MORSE/SPACETRAN, and 2D perturbation theory techniques have been used in the analysis of this shield. These methods have shown to be effective in the analysis of shields for unmanned space nuclear systems. These same techniques will be used in the analysis of the shield design using the latest system design geometry.

VIII. ADDITIONAL TASKS

The following are additional shielding tasks that are required.

A. Gamma Ray Shield Material Selection

The present reference design uses borated stainless steel. Both tungsten alloy, and tungsten alloy with borated steel on LiH shield side, will be considered. The selection of the gamma ray shield material will be

based on minimum weight in addition to other considerations such as cost, engineering properties, etc.

B. Attenuation Provided by PCS Equipment

The attenuation provided by the PCS equipment will be recalculated with the best available calculational methods. The refined value will be used in the final design.

C. Neutron Streaming Along NaK Pipes in LiH Shield

The estimates of the neutron flux at the dose plane due to streaming along the NaK pipes in the LiH shield will be refined. Better methods will be used to determine this important value. Results of this task may influence the location of the NaK lines in LiH shield.

D. Gamma Ray and Neutron Shield Dimensions

The shield dimensions will be recalculated with the best tools available. The shield surfaces will be contoured to yield a minimum weight, yet consistent with engineering requirements.

E. NaK Activity

The Na²⁴ and K⁴² activities will be calculated in detail using the DOT code. The activities will be used to calculate the dose rate from the primary loop.

TABLE I
GAMMA SHIELD MATERIALS COMPARISON

Material(s)	Relative Weight	
	1-D Analysis	2-D Analysis with Shaping
W	1.00	1.00
SS	1.02	
SS + 2% B ₄ C	0.72	0.88
SS + 2% B ₄ ¹⁰ C	0.70	
W + SS + 2% B ₄ ¹⁰ C	0.75	

TABLE II
EFFECT OF NEUTRON SHIELD PENETRATIONS ON NEUTRON
FLUX AT DOSE PLANE

Duct Diameter (in.)	Duct Slant Angle (deg.)	Relative Flux	
		DOT/SPACETRAN	DDM/SPACETRAN
0	-	~0.9	1.0
2.37	0	60	
2.37	23		2.2
2.0	23		1.6
1.75	45		1.2

FIGURE 1.
DESIGN WITH RADIATOR OUTSIDE SHIELDED CONE

FIGURE 2.
DESIGN OF MANNED SHIELD

Figure 3. Shield Weight Penalty vs. PCS Gamma Attenuation Factor

FIGURE 4.
REFERENCE SHIELD DESIGN