Atomic Energy Act-1954

Westinghouse Electric Corporation
Astronuclear Laboratory

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SUBMITTED BY:

Westinghouse Electric Corporation
Astronuclear Laboratory
Pittsburgh 36, Pennsylvania

PREPARED BY:

H.C. Woodsum
H.C. Woodsum

APPROVED BY:

F.D. Retallick
F.D. Retallick

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**INTERRELATIONSHIP
OF FACTORS AFFECTING
SHIELD DESIGN CRITERIA**

(Title Unclassified)

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LIST OF FIGURES

<u>Figure No.</u>	<u>Description</u>
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2	Effect of Shield Diameter and Tank Cone Angle on Tank Heat Input
3	Effect of Shield Weight Vs. Tank Angle
4	Effect of Tank Cone Angle on Tank and Interstage Support Structure Weight
5	Effect of Separation Distance on System Weight
6	Effect of Tank Pressure on Tank Weight
7	Steel Attenuation Factors
8	Lithium Hydride Attenuation Factors
9	Shield Weight Vs. Volume Percent Steel
10	Volume Per Cent Steel as a Function of F_N and F_G for a Minimum Weight Steel Li-H Shield
11	Shield Thickness as a Function of F_N and F_G for a Minimum Weight Steel LiH Shield

I. INTRODUCTION

The design of the shield for NERVA is dependent on a large number of factors with the main design criterion for the nuclear stage being a high reliability. It could be argued with equal fervor that minimum nuclear stage weight (or equivalently, maximum payload) could as well be the main design criterion with reliability being a contributing factor or constraint. Actually, low weight and high reliability are both very strong requirements in the design of a nuclear rocket but we prefer to put reliability in top position because it seems that we might be willing to sacrifice a little weight to achieve a high reliability. Below reliability, then, are a number of factors which affect it and which determine the shield design. The WANL concept of the interrelationship of factors affecting the shield design criteria for a NERVA vehicle is summarized in schematic form in Figure 1. This figure is drawn to show all of the direct and indirect ties between the circles. These factors and their interrelationships will now be explained and commented on more fully in the body of this report.

II. CONCLUSIONS

Based on the discussion which follows, the two quantities which must be determined in order to set the shield requirements are:

1. The maximum allowable coolant temperature rise
2. The engine and payload radiation environment restrictions

For Item 1, we are in particular interested in the maximum temperature rise caused by nuclear heating only since the non-nuclear sources do not directly affect the shield design. An alternative to setting these two quantities is to specify the maximum allowable radiation limits at all points outside the reactor.

III. RECOMMENDATIONS

In order to arrive at a set of shield design criteria, it is recommended that WANL continue and strengthen its support to REON in the following areas:

1. Continue calculations of the radiation leakage and environment outside of the reactor.
2. Provide estimates of the radiation energy deposition rates and temperature rise in the coolant as a function of separation distance, shield configuration, tank configuration, and residual coolant requirements.
3. Provide shield weight estimates as a function of shield configuration and composition for the parameters listed in Item 2.

A list of documents pertaining to previous WANL shielding studies in these areas is given at the end of this report.

IV. DISCUSSION

The two parts of the overall nuclear vehicle which would seem to most affect the reliability are the reactor coolant system and the vehicle control system. In the space environment with the nuclear engine on, it is possible that these systems might cause the reactor to fail because the liquid hydrogen coolant is not pumped in sufficient quantity through the reactor or because of a malfunction of the control system caused by the nuclear environment. Hence, the allowable maximum coolant temperature rise and the engine and/or payload radiation environment restrictions are shown in Figure 1 to be the two most important parameters in determining a high overall system reliability.

Another parameter very important to the design of a nuclear rocket is the weight. It is necessary to achieve the minimum weight consistent with a high reliability in order to provide maximum payload. Since minimum weight and maximum reliability are only achieved through a trade-off of opposing factors, an optimization process is clearly indicated.

First, let us list and discuss these opposing factors which must be considered in the optimization process required to arrive at firm shield design criteria.

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Allowable Maximum Coolant Temperature Rise

If we allow an excessive rise in temperature of the coolant leaving the tank, the coolant pumps may cavitate and we will experience a loss of flow of coolant to the reactor. Also, with a large temperature rise, the coolant may be heated to near the critical point where accuracy requirements of the pressure control instrumentation are excessively stringent. In order to prevent this from happening and to assure a high reliability, we must maintain the coolant in a liquid state. This may be accomplished by (1) adding shield weight to decrease the temperature rise (2) increasing tank pressurization (3) venting (4) adding internal tank baffles to provide better mixing of the coolant in the tank or (5) altering other determining factors in an optimum fashion.

Three factors which directly affect the coolant temperature rise are the nuclear heat sources as determined by the shield, non-nuclear heat sources which are not affected by the shield design, and the mode of internal mixing of the coolant.

Non-nuclear heat sources which contribute directly to the temperature rise of the coolant are: solar heating, aerodynamic heating (in leaving the atmosphere), and reflection of solar heat by the earth and/or other planets. Together with these sources, another factor which affects the temperature rise

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in the coolant is the insulation material. Since the previous sources are external sources which deposit heat on the surface, the heat initially is absorbed in the tank walls and leaks through the internal insulation to eventually accumulate in the coolant (assuming insulation internal to the tank walls). The rate at which this heat leaks through the insulation is a function of the insulation material. Thus the amount of heat which accumulates in the coolant is a function of the insulation material and time. A long flight and/or a long coast with low or zero power conditions would produce relatively more non-nuclear heat vs. nuclear heat than would a short flight. Further, the nuclear and non-nuclear heat sources are directly additive. Hence, for missions where the ratio of full power to zero (or low) power conditions is large, the nuclear heat sources may be the predominant method for producing coolant temperature rise. For a low ratio, the non-nuclear heat sources may predominate.

Especially for the non-nuclear sources, a laminar flow of coolant can result in a higher maximum temperature than would a complete mixing since some of the coolant picks up heat from the region near the tank wall and circulates and recirculates like a heat exchanger, adding heat on each pass near the walls. The laminar flow can be broken up by internal baffles, but these baffles are costly in weight. Hence an optimization to provide better mixing by baffling vs. a decrease in the nuclear heat source input by providing more shielding is required.

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System Weight

A. Overall System

Factors which directly affect the weight of the system are: (1) tank pressurization (maximum design tank pressure) (2) interstage and tank support structure weight and (3) the shield design. Thus, the shield design effects both the vehicle weight and coolant temperature rise.

B. Shield

Factors which affect the shield design are engine and payload radiation environment restrictions, desired neutron-to-gamma ratio, maximum allowable shield diameter, mission, tank cone angle, reactor-tank separation distance, venting, and residual coolant requirements. Each of these factors should be considered in some detail since each may contribute in an important way to the shield design criteria.

1. Engine Environment Restrictions

The engine radiation environment restrictions, such as radiation damage limits and nuclear heating to engine components or payload, place certain minimum requirements on the shield. These requirements have to be met regardless of other requirements in order to achieve the main goal of high reliability.

2. Neutron-Gamma Ratio

The neutron-to-gamma ratio is a parameter which is determined by the shield design which can be altered by a change of shield materials, material

thicknesses, a placement of materials, or a combination of any or all of these.

In order to indicate how this factor affects shield weight, a set of parametric curves showing the shield weight/unit area vs. attenuation factor for various gamma-to-neutron ratios is included in Appendix 1. No secondary gamma sources have been included in this study. The interstage sleeve and pressure vessel weights have been included by adding a homogenized density of 0.653 g/cm^3 for these items. These curves show that for a given total energy attenuation, there is a minimum shield weight which corresponds to a certain gamma-to-neutron ratio. Thus for a different required gamma-to-neutron ratio, some weight penalty would be incurred. Requirements for a certain gamma-to-neutron ratio may be determined by radiation environment considerations or the coolant temperature rise at the tank exit which in turn depends on the mode of coolant mixing. For complete mixing, it should make no difference to the coolant temperature rise whether the nuclear heat is deposited by gammas, by neutrons or a combination of both. For a laminar flow, however, the steep gradients in heating density near the tank walls, as characteristically produced by neutrons, may cause a greater maximum temperature rise than would an equal quantity of heat deposited by gamma rays.

3. Maximum Shield Diameter

The maximum shield diameter limits the effective shielded area to a cone within the "shadow" of the shield. If the diameter is small, the shielded

cone area is also small and a considerable portion of the reactor radiation is not shielded at all. Depending on the coolant tank cone angle (for a conical bottom tank) and the reactor-tank separation distance, a major fraction of the nuclear tank heating could be caused by radiation by-passing the shield.

Another way of looking at this parameter is to consider total heat input to the tank vs. the shield thickness. For a given shield diameter, the heat input decreases with increasing shield thickness up to the point where essentially all of the direct radiation from the reactor within the shield cone is stopped by the shield. At this diameter, a lower limit is reached. This effect is illustrated graphically in Figure 2 where heat input to the tank is plotted vs. shield thickness for several different shield diameters and tank cone angles. Clearly then, there is some optimum configuration of shield diameter and shield thickness for a given tank cone angle and tank separation distance. Figure 2 and subsequent figures are included in order to show trends rather than absolute magnitude since most of these studies were made for an early concept of the nuclear vehicle.

4. Tank Angle

The coolant tank should also be optimized for a minimum weight configuration. It is fairly obvious that, assuming a conical bottom cylindrical tank, a small tank cone angle will intercept a small amount of radiation leaving the reactor and will thus absorb less nuclear heat than will a large cone angle. Also, the

maximum shield diameter can be decreased for this case while maintaining the same overall attenuation. However, this is only done at the expense of increasing the tank support structure and interstage structure weights. Again an optimization of these variables is required in order to obtain overall minimum weight and maximum stability and reliability. Characteristic curves showing trends that such an optimization might take are shown in Figure 3 and 4.

5. Reactor-Tank Separation Distance

An alternate method for reducing the solid angle of the coolant tank "seen" at the reactor, is to increase the reactor-tank separation distance. Again, this would decrease the shielding weight but increase the interstage structure weight. Thus, the separation distance represents another independent variable which must be optimized. A typical curve of system weight vs. reactor tank separation distance is shown in Figure 5.

6. Residual Coolant and Venting

The residual coolant requirements will directly affect the maximum coolant temperature rise and this will indirectly affect the shield design. Since the coolant remaining in the bottom of the coolant tank near the end of a NERVA firing has been in the tank longer than that which has already left, for any flow model except the no-mix model (which is probably not realistic), this coolant has acquired more heat per unit volume than the coolant which has already left

the tank. As long as this coolant is never used for further firing, it represents stored heat which reduces the average heat input to the coolant which was used. If it is required to use some of this remaining coolant, perhaps some of it could be vented to reduce the temperature of the remainder or it could be used for after heat removal from the reactor. Thus, by adding extra liquid hydrogen and tankage for storing heat, and after heat removal, and/or venting, we can maintain a lower maximum coolant temperature rise with the same amount of shielding or the same maximum temperature rise with less shielding. Once again, an optimization should be performed to decide whether extra shielding or extra residual coolant is the more efficient process.

7. Mission

The mission requirements will certainly affect the shield design criteria in several important ways. Important parameters regarding mission are:

1. Manned or Unmanned?
2. How long and at what power is the rocket fired?
3. Is venting possible between firings?
4. What are the residual coolant requirements?
5. What is the schedule of coolant usage?
6. What are the problems of atmospheric radiation scattering?

The shield design requirements at the reactor may be no more stringent for a manned than for an unmanned mission, depending on items 2 through 6, since the residual coolant can be used as personnel shielding and a certain

minimum amount of shielding will be required around the crew when in space in order to reduce the danger from space radiation. Thus, it may be more efficient to split the reactor shielding and place some with the crew.

8. Pressurization

Another alternative to allowing the coolant temperature to rise to the point where it becomes partially gaseous and hence produces cavitation in the pump, is to pressurize the coolant so that it is below its critical point. Pressurization can only be accomplished by a resultant increase in tank wall thickness and weight. Hence, we must again consider an optimization of this parameter. A typical curve of tank pressure vs. tank weight is shown in Figure 6.

Engine and Payload Radiation Environment Restrictions

Certain materials are more sensitive to heat and radiation than are other materials. Among the more sensitive materials are organics and transistors. In order to achieve the reliability goal set, controls and electronic service equipment must operate to its full rated design capacity. Thus components which would be damaged excessively by the radiation environment will require substitution by an equivalent non-sensitive component or shielding to reduce the radiation level below the damage point. It is not always possible to make substitutions and sometimes such substitutions would involve excessive weight penalties. Hence, substitution and removal of sensitive components must be balanced against the shield weight increase.

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear
		HCU 7/16/63	HCU 8/20/63

EFFECT OF SHIELD DIAMETER AND TANK CONE ANGLE ON TANK HEAT INPUT FOR VARIOUS TANK CONE ANGLES AND SHIELD DIAMETERS	CURVE NO.	INDEX NO.
	564429	

FIGURE 2

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear
		HCW 7/17/63	HCW 8/20/63

EFFECT OF SHIELD WEIGHT VS. TANK ANGLE FOR TWO SHIELD DIAMETERS - FIGURE 3	CURVE NO.	INDEX NO.
	564430	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

EFFECT OF TANK CONE ANGLE ON TANK AND INTERSTAGE SUPPORT STRUCTURE WEIGHT -	CURVE NO.	INDEX NO.
	564427	

FIGURE 4

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear
		Hcw 7/17/63	Hcw 8/20/67	

TOTAL WEIGHT CHANGE, LBS. (SHIELD + TANK + INTERSTAGE)

SEPARATION DISTANCE, FT.

EFFECTS OF SEPARATION DISTANCE ON SYSTEM WEIGHT FOR VARIOUS TANK ANGLES - FIGURE 5	CURVE NO.	INDEX NO.
	564426	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear
		HCU 7/17/63	HCU 8/20/63	

TANK WEIGHT - LBS/FT² OF TANK SURFACE

6
5
4
3
2
1
0

TANK PRESSURE - PSIA

EFFECT OF TANK PRESSURE ON TANK WEIGHT - FIGURE 6	CURVE NO.	INDEX NO.
	564428	

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LIST OF DOCUMENTS PERTAINING TO PREVIOUS WANL SHIELDING STUDIES

1. WANL-TNR-083, "Tank Heating Codes TIC-TOC and TOE for IBM 7090 Computer", H. C. Woodsum, P. C. Heiser, Jan. 1963, Unc.
2. WANL-TNR-002, "Shielding and Radiation Analysis - NERVA Phase I Activity", March 1962
3. WANL-TNR-058, "Radiation Environment Around the NERVA Engine with NRX-A Reactor", June 1, 1962, CRD
4. WANL-TNR-078, "KIWI-B5 Shield, Vol. II, Radiation Design and Analysis", M. A. Capo, R. N. Nassano, Dec. 28, 1962, CRD
5. WANL-TNR-001, "Shield Requirements for a KIWI-B1 Reactor Core for Use in the NERVA System", D. W. Call, M. A. Capo, P. A. Nelson, L. O. Ricks, Nov. 17, 1961, CRD
6. WANL-TME-224, "Status Report of Tank Heating Calculations for NERVA", H. C. Woodsum, Jan. 1963, CRD
7. WANL-TME-330, "Status Report of Analysis of the KIWI-B5 Shield Measurements at Los Alamos", H. C. Woodsum, April 1963, CRD
8. WANL-TME-226, "Radiation Environment Inside and Outside of the NRX-A1", L. D. Stephenson, R. N. Nassano, Dec. 1962, CRD

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APPENDIX I

INTRODUCTION

A parameter survey has been performed to facilitate the selection of a minimum weight steel - LiH shield containing 10% void by volume. Weight as used in this report includes the weight of the pressure vessel and interstage sleeve added to accommodate the shield and is expressed as thickness x density. The survey covered center line attenuation factors of 0.2, 0.1, 0.06 and 0.04. The fraction of the total energy incident on the hydrogen tank attributed to either neutrons or gamma rays ranged from 0.3 to 0.7 in increments of 0.1. Attenuation factors for neutrons and gamma rays in steel and lithium hydride were obtained by use of the computer program 14-0. The KIWI-B4 core provided this source.

This minimum weight study is based on the attenuation of primary radiations only. Secondary gamma production, which is a function of both the composition of the shield and the location of the materials within the shield, was not included.

In order to use the curves presented in this appendix, the fraction of the energy incident on the unshielded hydrogen tank associated with both neutron and gamma ray leakage must be first determined. The curves may then

be used to find the per cent steel, and thickness of a minimum weight shield which provides the required center line attenuation.

NOMENCLATURE

F_N = fraction of total energy incident on hydrogen tank associated with the unshielded core neutron leakage

F_G = fraction of total energy incident on hydrogen tank associated with the unshielded core gamma leakage

P = radiation attenuation factor for neutron plus gamma radiation along core - shield axis

$G(t_l)$ = attenuation factor for gamma rays in lithium hydride (Fig. 8)

$G(t_s)$ = attenuation factor for gamma rays in steel (Fig. 7)

$N(t_l)$ = attenuation factor for neutrons in lithium hydride (Fig. 8)

$N(t_s)$ = attenuation factor for neutrons in steel (Fig. 7)

t_l = lithium hydride thickness - cm

t_s = steel thickness - cm

τ = thickness of pressure vessel and interstage sleeve added to accommodate shield = $\left[\frac{t_s + t_l}{.9} - 12.7 \right] \text{ cm}^*$

T = total shield thickness, including 10% void by volume - cm

*Thickness 12.7 cm (5 inches) is required whether or not a shield is present due to the elliptical shaped head on the current pressure vessel designs.

$$\begin{aligned}\rho_l &= \text{density of lithium hydride} = 0.73 \text{ gm/cm}^3 \\ \rho_s &= \text{density of steel} = 7.94 \text{ gm/cm}^3 \\ \rho_T &= \text{density of aluminum pressure vessel and interstage sleeve} \\ &\quad \text{added to accommodate shield} = 0.653 \text{ gm/cm}^3 \\ V_s &= \text{volume per cent steel in shield containing 10\% void}\end{aligned}$$

EQUATIONS

Thicknesses of lithium hydride and steel required to achieve a specified center line attenuation factor for radiation incident on the hydrogen tank were obtained from the equation;

$$P = F_N N(t_l) N(t_s) + F_G G(t_l) G(t_s) \quad (1)$$

Solution of this equation for a specified value of P yields a family of curves, $t_s = f(t_l)$, which depend on the values of F_N and F_G .

The volume per cent steel in a steel - Li H shield providing the radiation attenuation defined by equation 1 was obtained from the following equation:

$$V_s = t_s \left[\frac{.9}{t_s + t_l} \right] \quad (2)$$

where t_s and t_l must satisfy equation 1.

The weight of a shield providing the required attenuation was obtained from equation 3. Included is the weight of the pressure vessel and interstage sleeve added to accommodate the shield. A weight in grams cannot be obtained from equation 3 because the shield, pressure vessel and interstage sleeve do not have the same area. However, the equation provides an adequate basis for comparing shield plus structure weights for various shield compositions.

$$W = \rho_s t_s + \rho_l t_l + \rho_T T \quad (3)$$

where t_s and t_l must satisfy equation 1.

Weight as a function of volume per cent steel for several values of P and the factors F_N and F_G are plotted in Figure 9.

The thickness of a steel - Li H shield containing 10% void which provides the required reduction factor for radiation incident on the hydrogen tank was obtained from the equation;

$$T = \frac{t_s + t_l}{.9} \quad (4)$$

where t_s and t_l must satisfy equation 1

Variations of volume per cent steel and thickness as functions of the factors F_N and F_G subject to the conditions that equation 1 and the equation

$$dW/dV_s = 0 \quad (5)$$

are satisfied are plotted in Figure 10 and Figure 11.

RESULTS

In the actual shield design for the KIWI B-4 the volume per cent steel is 27% for $P = 0.04$, $F_N = 0.48$ and $F_G = 0.52$.¹ The value of $P = 0.04$ is the center line attenuation required to achieve a 90% heat input reduction factor for the hydrogen tank. Figure 10 of this report shows that for $P = 0.04$, $F_N = 0.48$ and $F_G = 0.52$, the volume per cent steel for a minimum weight shield is 24.6%. It may be seen in Figure 9 that dW/dV is a slowly varying function near the minimum point. Therefore, the value of 27% steel¹ is felt to be in a reasonable agreement with the

¹ WANL-TNR-002

value obtained in this study; i. e. , the actual shield design for the KIWI-B4 is of minimum weight. A preliminary analysis of recently published⁽¹⁾ Monte Carlo results indicates that $F_N = 0.37$ and $F_G = 0.63$ for the unshielded B-4 core. Figure 10 of this report shows that for these values of F_N and F_G , 28.8% steel is required in a minimum weight 96% center line reduction shield.

- (1) WANL-TME-224, "Status Report of Tank Heating Calculations for NERVA",
H. C. Woodsum, January, 1963

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

STEEL ATTENUATION FACTORS - FIGURE 7	CURVE NO.	INDEX NO
	562287	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

FIGURE 8 LITHIUM HYDRIDE ATTENUATION FACTORS	CURVE NO	INDEX NO
	562286	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

SHIELD WEIGHT VS VOLUME PERCENT STEEL FOR A STEEL-LiH SHIELD WITH 10% VOID - FIGURE 9-A	CURVE NO.	INDEX NO.
	598033	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

SHIELD WEIGHT VS VOLUME PERCENT STEEL FOR A STEEL-LIH SHIELD WITH 10% VOID - FIGURE 9-B	CURVE NO.	INDEX NO.
	598034	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

SHIELD WEIGHT VS VOLUME PERCENT STEEL FOR A STEEL-LIH SHIELD WITH 10% VOID - FIGURE 9-C	CURVE NO.	INDEX NO.
	598035	

REFERENCE		PREPARED BY	APPROVED BY	Astronuclear

SHIELD WEIGHT VS VOLUME PERCENT STEEL FOR A STEEL-LIH SHIELD WITH 10% VOID - FIGURE 9-D	CURVE NO.	INDEX NO.
	598036

VOLUME PERCENT STEEL AS A FUNCTION OF F_N AND F_G FOR A MINIMUM WEIGHT STEEL-LIH SHIELD - FIGURE 10	CURVE NO.	INDEX NO.
	598037

SHIELD THICKNESS AS A FUNCTION OF F_N AND F_G FOR A MINIMUM WEIGHT STEEL-LiH SHIELD FIGURE 11	CURVE NO	INDEX NO.
	598038	