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Weight of X-Ray Shields for Interceptor Missiles

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A decision to shield interceptor propulsion systems from x-rays emitted by a nuclear weapon during a nuclear engagement results in significant increases in system weight. Shielding is one alternative available to the designer to reduce the x-ray dose in the solid-propellant grain component of the propulsion system. Exposure to x-ray emissions can result in system failure by inducing unacceptable changes in the solid-propellant ballistic and mechanical properties, or premature ignition, or both. The magnitude of the shield weight required to protect the solid-propellant grain from x-rays has been determined for various motor case materials, nuclear weapon spectra, and nuclear fluence levels. The study was conducted by determining the shield thickness required to reduce the x-ray dose in the propellant to 2 cal/g. An empirical design equation suggested by Watcher was investigated and found to yield incorrect results when compared with results obtained using an energy deposition computer code. Graphite, fiberglass, and Kevlar motor case materials were studied in typical interceptor designs. Both equal-thickness and equal-strength designs were considered. Weapon spectra with blackbody temperatures ranging from 2 to 15 keV and fluence levels up to 100 cal/cm^2 were studied. The x-ray shield material was tantalum carbide. For a motor case thickness of 1.27 cm, shield weights of approximately 1.6 g/cm^2 are required to protect the solid propellant. For a typical interceptor design, this translates into a total weight penalty of approximately 129 kg (285 lb).

I. Introduction

THE vulnerability of interceptor missile propulsion systems to x-rays emitted from a nuclear weapon is of interest in assessing the overall vulnerability of interceptor missile systems. Figure 1 contains a schematic diagram of a typical propulsion system subjected to x-ray radiation. It is well known[1] that damage to the structure of the propulsion system can be caused by in-depth heating and subsequent stress-wave propagation. Also, if the fluence is sufficiently high, the structure can be loaded impulsively by sublimation of the surface material exposed to the x-ray emission. This impulsive load can also damage the system.[2] In addition to these mechanical modes of damaging the system, x-rays may produce unacceptable chemical change in the rocket motor propellant or cause premature ignition of the propellant; both of these effects are unacceptable. The absorptive characteristics of the propellant itself greatly influences possible failure by chemical change or premature ignition. Propellants containing high-atomic-number materials (high Z materials) are particularly vulnerable.

To protect the interceptor missile propulsion sytem from x-ray damage, one solution is to shield the vulnerable components by placing a layer of highly x-ray-absorbent (high-atomic-number) material over the vulnerable components. Considering the geometry of conventional solid rocket motors, as illustrated in Fig. 1, the entire outer surface of the motor case would have to be covered with the x-ray shield. This obviously produces an added weight component to the structure. The magnitude of this weight penalty is the subject of this study. The objective of the work described here is to assess the magnitude of the x-ray shield weight as a function of the nuclear weapon spectrum and fluence and the influence of several typical motor case materials. The only failure mode of interest in this study is that of excessive energy deposition in the solid propellant itself, which can result in unacceptable chemical change in the propellant or premature propellant ignition.

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II. X-Ray Shield Technology

One possible method for shielding the rocket motor case and consequently the solid propellant is to spray a thin layer of high-atomic-number material over a layer of porous epoxy, which is attached directly to the outer surface of the motor case. The purpose of the porous epoxy layer is to protect the structure from impulsive loads caused by sublimation of the high-atomic-number outer material.This type of shield was assumed in the study described here.[3]

Another shielding technique involves mixing particles of high-atomic-number materials directly into an epoxy matrix and applying the mixture as a single layer on the outer surface of the motor case. It also appears possible to mix the high-Z particles directly into the epoxy used in fiberglass motor cases. These latter two techniques are not considered to be state-of-the art technology.[4,5]

The shield structure to be studied here is illustrated in Fig. 2. It consists of an outer layer x-ray shield, an intermediate stress-wave attenuator epoxy layer, the motor case layer, and finally the propellant. Both equal thickness and equal strength motor case configurations were studied. The propellant is assumed to be infinitely thick, and the critical region is assumed to be in the propellant immediately adjacent to the motor case. Failure is assumed to occur when the energy dose in the propellant exceeds 2 cal/g.

A procedure for the design of x-ray shields has been suggested by Watcher et al.[3,6] This procedure involves the solution of some relatively simple algebraic equations that take into account the energy absorption characteristics of the layered structure. Since the validity of this technique is uncertain, a photon energy deposition code was used to check the design and modify it if appropriate.

The fluence threshold ϕ_t for a specified dose D_c may be expressed as[6]

$$\phi_t = \left[D_c\left(\sum_s\right)^b \Big/ a\right]\left(\frac{Z_{es}^n}{Z_{ea}^n}\right) \tag{1}$$

where a,b,n are parameters given in Ref. 6, Table 2, pp. 2-14, and where

$$\sum_s = \sum_s \rho_i X_i = \rho_1 X_1 + \rho_2 X_2 + \rho_3 X_3 \tag{2}$$

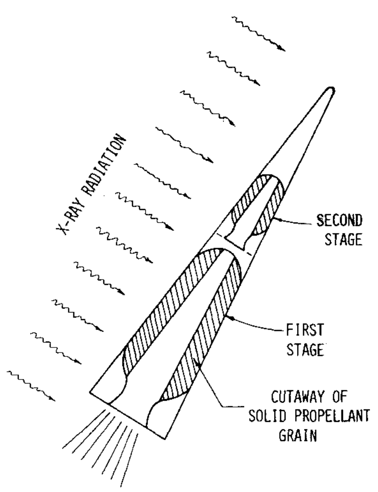

Fig. 1 Interceptor missile exposed to x-rays.

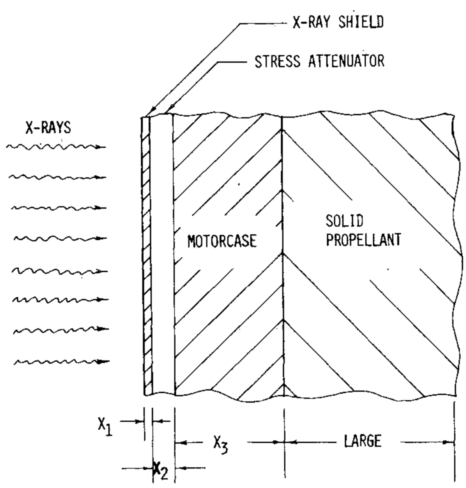

Fig. 2 Shield configuration.

and

$$Z_{ea}^n = \frac{\rho_1 X_1 (Z_e)_1^n + \rho_2 X_2 (Z_e)_2^n + \rho_3 X_3 (Z_e)_3^n}{\rho_1 X_1 + \rho_2 X_2 + \rho_3 X_3} \tag{3}$$

In the above equations, ρ_i is the mass density in the ith layer, which has an effective atomic number $(Z_e)_i$ and a thickness X_i. Z_{ea} is the effective atomic number for the absorbing material (propellant). The effective atomic number of a material can be calculated from the material elemental composition using the relation[6]

$$Z_e = \left(\sum w_i Z_i^3\right)^{1/3} \tag{4}$$

where w_i is the weight fraction corresponding to element i with an atomic number Z_i.

Values of $a,b,$ and n obtained from Ref. 6 are $a=0.24$, $b=1.0$, and $n=3.3$. For these values of $a,b,$ and n, Eq. (1) can be solved for the thickness of the shielding material X_1, i.e.,

$$X_1 = \frac{a\phi_t}{\rho_1 D_c} \frac{(Z_{ea})^n}{(Z_{e1})^n} - \frac{\rho_2}{\rho_1} X_2 \frac{(Z_{e2})^n}{(Z_{e1})^n} - \frac{\rho_3}{\rho_1} X_3 \frac{(Z_{e3})^n}{(Z_{e1})^n} \tag{5}$$

The thickness of the attenuating material X_2 can be computed from Ref. 6, Eq. 105, by specifying the peak stress allowed in the motor case. This calculation gives

$$X_2 = \frac{0.144\phi_t}{(E_m \sigma_a \rho \{1 + [(\rho c)_s / (\rho c)_a]\})^{1/2}} \tag{6}$$

where

E_m = sublimation energy of x-ray shield
$(\rho c)_s$ = acoustic impedance of shield
$(\rho c)_a$ = acoustic impedance of motor case
σ_a = allowable impulsive stress in motor case
ρ = density of undistended attenuator

To summarize the design procedure, first specify the shield, motor case, and propellant materials and compute the appropriate material properties. Calculate the stress-wave attenuator thickness X_2 using Eq. (6) and specify the motor case thickness X_3. Finally use Eq. (5) to calculate the x-ray shield thickness X_1 for a specified fluence ϕ_t and allowable dose D_c.

For routine shield design, the above procedure could be automated such that deposition profiles are computed automatically for different shield thicknesses until a satisfactory thickness is obtained. In fact, such a procedure has been developed and is operational at the Air Force Weapons Laboratory. However, the results obtained here were obtained by manually changing the input data and executing KNISH in separate runs.

III. Actual Shield Design Procedure

The procedure described in Sec. II can be used to design the shield. Since the equations represent a simple mathematical description of a very complex phenomenon, the theoretical design was checked using a photon energy deposition code KNISH.[7] If the theoretical shield thickness proved to permit too great or too small an x-ray dose in the solid propellant, the x-ray shield thickness was changed to permit an allowable dose of 2 cal/g in the propellant. Determination of the shield thickness using the KNISH code involved a trial-and-error procedure with repeated evaluations of the propellant dose for different shield thicknesses.

The KNISH photon deposition computer code used to compute the energy deposition profiles and the dose in the propellant treats Compton single scattering and photoelectric energy deposition in a one-dimensionl slab geometry. The accuracy of KNISH was investigated by comparing the profiles computed with KNISH with profiles computed using the Air Force Weapons Laboratory code PUFF 66.[7] Good accuracy was obtained using KNISH for all blackbody temperatures investigated.

The specific materials considered in the study are 1) x-ray shield—tantalum carbide (TaC); 2) stress attenuator layer —Epon Epoxy 934; 3) motor case—fiberglass, Kevlar, and graphite. The specific material properties used in the study are presented in Table 1.

Blackbody spectra were assumed for the x-ray source and temperatures of 5, 9, and 15 keV were studied. Fluence values were studied from 10 to 100 cal/cm^2. Photoelectric cross sections were computed for each composite material using the element photoelectric cross section data of McMaster[8] and the elemental composition of each composite. The procedure was checked by comparison with standard composite cross section data available in the literature.[3]

IV. Motor Case Design

The motor case was assumed constructed of continuous fibers wrapped in a combination of helical and circumferential windings around a circular mandrel. Fiber materials studied included glass, graphite, and Kevlar. The following numerical values were assumed for parameters needed to define the case thickness:

R_{mean} = mean radius = 50 cm (19.68 in.)
P = internal pressure = 22.41 MN/m^2 (3250 psi)
α = wrap angle = 40 deg
v_f = volume fraction of fiber = 60%

Table 1 Material properties for shield design

Material	Z_e	ρ, g/cm^3	E_m, cal/g	$(\rho c)_s$	$(\rho c)_a$	σ_a, kbar
TaC	71.4	14.5	360	...	...	...
Epon 934	6.1	1.38	...	0.241	...	...
Fiberglass	8.8	1.88	...	...	0.57	0.5
Kevlar	6.4	1.36	...	...	0.64	0.5
Graphite	6.2	1.34	...	...	0.62	0.5
CMBD/ZR	16.7	1.78	...	...	...	...

Table 2 X-ray shield thickness required for two different fiberglass case thicknesses[a]

Temperature (keV)/ fluence, cal/cm^2	X_1, cm	X_1^*, cm	X_2, cm	X_2^*, cm	w, g/cm^2	w^*, g/cm^2
5/10	0.0023	0.0032	0.0862	0.0862	0.142	0.157
5/50	0.0072	0.0082	0.4309	0.4309	0.639	0.656
5/100	0.0093	0.0105	0.8619	0.8619	1.191	1.211
9/10	0.0082	0.0091	0.0862	0.0862	0.242	0.257
9/50	0.0230	0.0240	0.4309	0.4309	0.906	0.923
9/100	0.0300	0.0310	0.8619	0.8619	1.540	1.558
15/10	0.0110	0.0119	0.0862	0.0862	0.289	0.304
15/50	0.0300	0.0310	0.4309	0.4309	1.024	1.041
15/100	0.0400	0.0406	0.8619	0.8619	1.710	1.720

[a] Quantities with asterisk refer to $t_c = 0.376$ cm case; others to $t_c = 0.5$ cm case.

The composite fiber strength, in MN/m^2 (ksi), in helical wraps σ_ϕ and in circumferential wraps σ_θ for the different materials studied are defined as follows.

Graphite and Kevlar: $\sigma_\phi = 2069\ (300)$ $\quad \sigma_\theta = 2413\ (350)$

Glass: $\sigma_\phi = 2826\ (410)$ $\quad \sigma_\theta = 3103\ (450)$

Using standard netting analysis design procedures,[9] the thickness of the helical wraps t_ϕ and circumferential wraps t_θ can be computed by the relation

$$t_{\text{total}} = t_\phi + t_\theta = \frac{PR}{v_f}\left[\frac{1}{2\sigma_\phi \cos^2\alpha} + \frac{1-(\tan^2\alpha/2)}{\sigma_\theta}\right] \tag{7}$$

Using the numerical values defined above, the motor case thicknesses in cm (in.) for the different materials may be computed as follows.

Graphite and Kevlar: $t_\phi = 0.77\ (0.303)$ $\quad t_\theta = 0.50\ (0.197)$

$t_{\text{total}} = 1.27\ (0.500)$

Glass: $t_\phi = 0.56\ (0.222)$ $\quad t_\theta = 0.39\ (0.154)$

$t_{\text{total}} = 0.95\ (0.376)$

The values of t_{total} above correspond to equal-strength motor cases. In addition to a study based on the equal-strength motor cases, a study was also conducted assuming the motor case to be of equal thickness for all materials. The case thickness was assumed to be 1.27 cm (0.500 in.) for this facet of the study.

V. Results and Discussions

Utilizing the theoretical design procedure described in Sec. II, thicknesses of the x-ray shield and stress attenuator layer were calculated for various fluence levels. Results of these calculations are illustrated in Fig. 3 by the dashed line. Examination of Eqs. (5) and (6) indicates that the x-ray shield thickness equation does not account for changes in blackbody temperatures and depends linearly on the fluence. This is reflected in Fig. 3.

Utilizing KNISH and the trial-and-error procedure described in Sec. III, the x-ray shield thickness was determined for various levels and blackbody temperatures. The results are indicated by the solid lines in Fig. 3. The design equation results and the KNISH results do not agree for the conditions studied. It appears that the design equation results might be applicable for blackbody temperatures of approximately 3 keV for the materials and configurations studied but are not applicable for higher source temperatures. The KNISH code results are believed to be the most accurate of the two methods studied. On the basis of these results, the trial-and-error procedure employing the KNISH code was utilized in all subsequent studies.

Because of differences in strength of glass, Kevlar, and graphite reinforcing materials, the required motor case thickness to support the internal pressure varies depending on which material is employed. The fiberglass is stronger than both Kevlar and graphite and would require a smaller motor case thickness. To determine if the reduction in thickness would require a significant increase in x-ray shield weight, a study of fiberglass was conducted to determine the shielding sizes assuming first a thickness of 1.27 cm (0.5 in.) and then a thickness of 0.95 cm (0.376 in.), as discussed in Sec. IV.

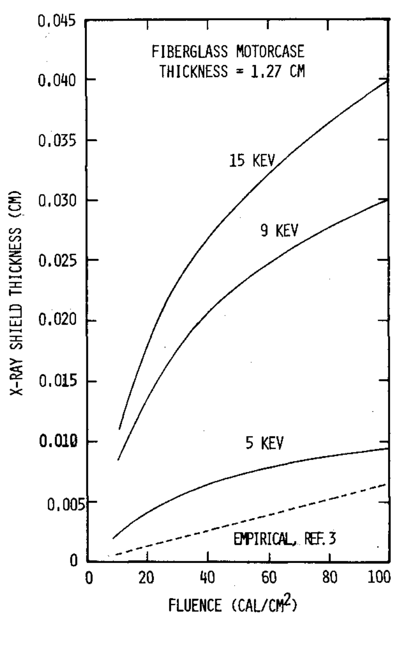

Fig. 3 X-ray shield thickness dependence on fluence and weapon temperature.

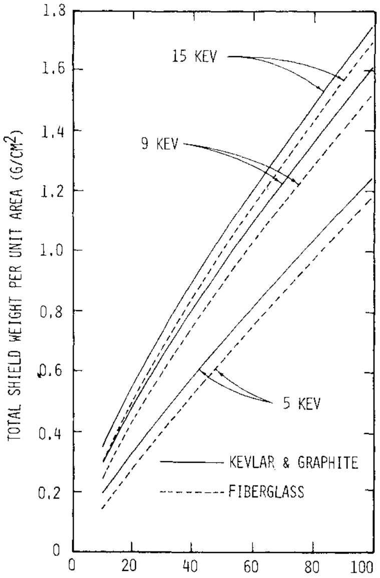

Fig. 4 Total shield weight dependence on fluence and weapon temperature.

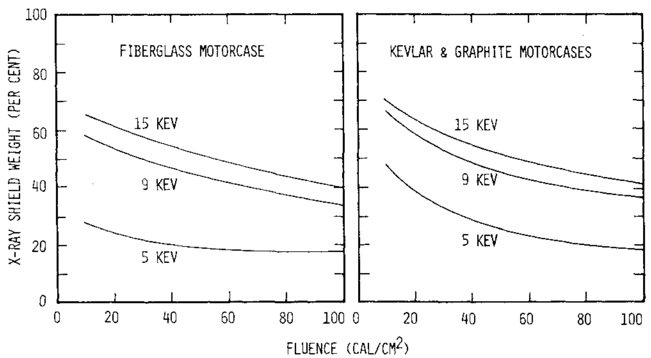

Fig. 5 Fraction of total shield weight required for x-ray shield only.

Typical results are presented in Table 2 where it can be seen that changes in case thickness of the magnitude discussed here do not significantly alter the required shield weight. This result is due to the relative transparency of fiberglass to x-rays.

The effect of fluence level and blackbody temperature on the total shield weight is illustrated in Fig. 4. Results are presented for the fiberglass, Kevlar, and graphite motor cases. As might be expected, a slightly thicker, heavier shield is needed for the Kevlar case (assuming equal motor case thicknesses), since the effective atomic number of Kevlar is less than that of fiberglass. The shielding characteristics of the Kevlar and graphite materials were the same, as illustrated in Fig. 4.

To translate these weight figures into more meaningful quantities, assume that a circular cylindrical motor case 100 cm (39.37 in.) in diameter and 300 cm (118.11 in.) long must be shielded from a nuclear weapon radiating with a characteristic temperture of 5 keV. The fluence is assumed to be 80 cal/cm^2. The surface area of the motor case is 94,248 cm^2. From Fig. 5 we see the Kevlar motor case shield would weigh 1.04 g/cm^2 or 98.017 kg (216 lb). The fiberglass motor case shield would weigh 0.98 g/cm^2 or 92.363 kg (204 lb). If the weapon temperature is 9 keV, the total shield weights are 129 kg (285 lb) and 122 kg (270 lb), respectively, for the Kevlar and fiberglass motor case conditions.

The results in Fig. 4 include the weights of both the x-ray shield and stress attenuator layer. Figure 5 indicates the percentage of total shield weight attributable to the x-ray shield. As can be seen from Fig. 5, the stress-wave attenuator layer occupies an increasing percentage of the total shield weight as the fluence increases. The design of this layer should receive considerable attention in the shield design process. It is not clear that Eq. (6) is adequate to predict the thickness of this layer.

In conclusion, it can be fairly stated that applying x-ray shields to interceptor solid rocket motors will add significant weight to the interceptor missile. For equal motor case thickness the use of Kevlar or fiberglass materials does not significantly affect the required shield weight. The added strength of fiberglass, which permits a smaller motor case thickness, does not appear to influence the required shield weight.

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