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SUBJECT: Shielding of Demineralizers and Filters in the HFIR Primary Coolant System

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Summary

Thicknesses of ordinary concrete required to shield the demineralizers and filters in the HFIR primary water system have been computed for normal operating conditions and for abnormal conditions such as a meltdown of the fuel within the reactor. About $4\frac{1}{2}$ ft, $3\frac{1}{2}$ ft, and $4\frac{1}{2}$ ft of concrete are required to shield the cation exchange unit, the anion exchange unit, and the filter unit, respectively, to the most stringent of the following radiation levels: a) 0.75 mr/hr for normal reactor operation or reactor operation with one defective fuel plate; b) 1 r/hr immediately following the meltdown of 1% of the fuel; and c) 1 r/hr 24 hours following a total fuel meltdown. Shielding thicknesses may be estimated for other tolerances from the graphs presented in the report.

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Introduction

Shielding is being provided for the HFIR primary coolant system to provide protection against the gamma photons released in this system during normal and abnormal conditions within the reactor. It has been stated^{1,7} that the primary water system shielding must meet all of the following requirements:

- a. The dose rate at the shield surface must be less than 0.75 mr/hr during the normal operation of the reactor or the operation of the reactor with one defective fuel plate.
- b. The dose rate at the shield surface must be less than 1 r/hr immediately after a meltdown of 1% of the fuel within the reactor.
- c. The dose rate at the shield surface must be less than 1 r/hr 24 hrs after a total meltdown of the fuel within the reactor.

The shielding of the pipes in the primary coolant system has been considered previously,¹ and this study considers the shielding needed for the demineralizers and filters in this system. Ordinary concrete with a density of 2.3 g/cc is assumed to be the shield material.

Shielding of the Cation Exchange Unit

During the usual operation of the HFIR, the main active constituent in the cation resin is Na^{24} . The concentration of this isotope in the primary coolant during normal conditions is 1.82×10^8 atoms/ml if the water pH is 5 and 7.3×10^8 atoms/ml if the water pH is 7.² Assuming that the flow rate to the demineralizer is 200 gpm, all the Na^{24} is removed from the water passing through the cation unit, and the volume of the resin is 50 ft³,³ the Na^{24} activity in the resin is 9.7×10^7 dis/ml-min for a water pH of 5 and 3.9×10^8 dis/ml-min for a water pH of 7. A 1.38 Mev gamma photon and a 2.76 Mev gamma photon is released for each disintegration of Na^{24} .

The dose rate at the surface of a shield located at the midplane of the cylindrical surface of the cation exchange unit is calculated from the source by the following relation:⁴

$$\phi = \frac{BS_v R_o^2 F(\theta, b_2)}{2(a+z)} \quad (1)$$

Symbols used in these equations are defined in the nomenclature section on page 11. Using the buildup factor of the form,⁴

$$B(E_o, \mu x) = A_1 e^{-\alpha_1 \mu x} + A_2 e^{-\alpha_2 \mu x} = \sum_{n=1}^2 A_n e^{-\alpha_n \mu x} \quad (2)$$

for concrete only, Equation 1 becomes,

$$\phi = \frac{S_v R_o^2}{2(a+z)} \sum_{n=1}^2 A_n F(\theta, b_{2n}) \quad (3)$$

A typical size ion exchange unit for this application is a cylinder of a 5 ft diameter and a 6 ft length which contains 50 ft³ of ion exchange resin.³ Assuming that the resin is in the center portion of the ion exchanger, the source is regarded as a cylinder of a 5 ft diameter and a 2.6 ft length. The wall of this unit is assumed to be $\frac{1}{2}$ in. 304 stainless steel and the inner surface of the concrete shield is assumed to be 1 ft from the vessel. The attenuation properties of the ion exchange resin are assumed to be the same as those of water, and the stainless steel wall is regarded as iron with a density of 8 g/cc.

Results using these equations and assumptions for shielding the cylindrical surface of the cation exchange unit during the ordinary operation of the HFIR are shown in Fig. 1. Assuming that the permissible dose rate at the shield surface is 0.75 mr/hr, 3.8 ft of concrete is required for a water pH of 5.0 and 4.3 ft of concrete is required for a water pH of 7.0. Hence, a concrete shield thickness of $4\frac{1}{2}$ ft should be satisfactory.

At the end of the cation exchange unit, the upper limit of the dose rate at the shield surface is calculated by the following relation (assuming the length of the ion exchange bed is greater than 3 relaxation lengths):⁴

$$\phi = \frac{BS_v}{2\mu_s} \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta_1)}{\sec \theta} \right] \quad (4)$$

Again using the buildup factor of the form shown in Equation 2 for concrete only, Equation 4 becomes:

$$\phi = \frac{S_n \sum_{n=1}^2 A_n}{2\mu_s} \left[E_2(b_{1n}) - \frac{E_2(b_{1n} \sec \theta_1)}{\sec \theta_1} \right] \quad (5)$$

Since it is assumed that the resin is in the center portion of the ion exchange unit, it is further assumed that the space between the resin and end of the unit is filled with water.

Results using this equation and the above assumptions for shielding the end of the cation exchange unit during the ordinary operation of the HFIR are shown in Fig. 2. Assuming again that the permissible dose rate at the shield surface is 0.75 mr/hr, 3.2 ft of concrete is required for a water pH of 5.0 and 3.7 ft of concrete is required for a water pH of 7.0. Hence, the $4\frac{1}{2}$ ft concrete thickness required to shield the cylindrical surface of the ion exchange unit is more than adequate to shield the end of the same unit.

Figure 1

Dose Rate at the Surface of a Concrete Shield
Located at the Side of the Cation Exchange Unit

In case of a total meltdown of the fuel within the reactor, it is assumed that the entire fuel is evenly distributed in both cation exchange beds in the HFIR primary coolant system, which is a very conservative assumption. Both units are included in this particular calculation since both of them would be put into operation following any possible meltdown of the fuel within the reactor.

The source strength in the cation exchange beds 24 hours after the melting of the fuel is estimated by the "effective energy" method described by Ashley.⁵ This method is suitable if the concrete shield thickness is greater than 3 ft. Using this source with Equation 3, the dose rates at the shield surface were calculated and are shown in Fig. 3. It can be seen from this graph that the dose rate at the surface of a $4\frac{1}{2}$ ft concrete shield is 65 mr/hr which is much less than 1 r/hr, the desired limit for the radiation level 24 hours after a fuel meltdown. Also, it can be seen by extrapolation that 5.9 ft of concrete reduces the radiation level to 0.75 mr/hr.

Shielding of the Anion Exchange Unit

Most shielding is assumed to be needed for the anion resin after a meltdown of the fuel within the reactor. The geometry of the anion unit is the same as that of the cation unit,³ and it is assumed that all of the anions (bromine and iodine) released during the meltdown of the fuel are completely adsorbed by the two anion exchange units in the HFIR primary coolant system. Using the values previously reported for the amount of anions released from the fuel during a meltdown,⁶ the gamma source strengths in the anion resin are:

Energy Range	Immediately after a 1% Meltdown	24 hrs after a Total Meltdown
≤ 0.25 Mev	5.2×10^6 $\frac{\text{photons}}{\text{sec cc}}$	5.4×10^5 $\frac{\text{photons}}{\text{sec cc}}$
$0.26 \leq 1.00$ "	2.1×10^8 "	9.2×10^9 "
$1.01 \leq 1.70$ "	7.2×10^7 "	4.2×10^8 "
≥ 1.71 "	5.9×10^7 "	2.8×10^8 "

Using Equation 3 and these source strengths, the dose rates at the concrete shield surface were calculated and are shown in Fig. 4 (The average energy assumed for each energy range has been previously reported.¹) Assuming that the permissible dose rate at the shield surface is 1 r/hr immediately after the meltdown of 1% of the fuel or 24 hrs after the total meltdown of the fuel, the required thickness of concrete shielding for the anion exchange unit is $3\frac{1}{4}$ ft. To reduce the dose rate to 0.75 mr/hr, 5.6 ft of concrete shielding is required.

Shielding of the Filter Unit

For the filter, it is assumed that the fuel element has melted in the reactor and has become evenly distributed in the filter unit. Use is again made of the "effective energy" method described by Ashley⁵ to estimate the source strength

Figure 3
Dose Rate at the Surface of a Concrete Shield
Located at the Side of the Cation Exchange Unit
24 hrs after a Fuel Meltdown

and of Equation 3 to estimate the dose rate at the shield surface. The filter unit is assumed to be a cylinder of 2 ft diameter and 1 5/8 ft length, and the inside concrete surface is assumed to be 1 ft from the vessel. The thickness of the unit wall is assumed to be 1/4 in., which is the same as that assumed for the ion exchange units. Results of the calculations using these assumptions and methods are shown in Fig. 5. Assuming a permissible dose rate of 1 r/hr at the shield surface 24 hrs after the fuel meltdown, about 4 1/2 ft of ordinary concrete is required to shield the filter unit. To reduce the radiation level to 0.75 mr/hr, about 6.6 ft of ordinary concrete is required.

Conclusions

The thicknesses of ordinary concrete required to shield the cation exchange unit, the anion exchange unit, and the filter unit to the radiation levels stated in the introduction are 4 1/2 ft, 3 1/2 ft, and 4 1/2 ft, respectively. Shielding thicknesses may be estimated for other tolerances from the graphs presented.

Nomenclature

ϕ = Scalar flux, $\frac{\text{photons}}{\text{cm}^2 \text{ sec}}$

B = Symbolic buildup factor

S_v = Volume source strength, $\frac{\text{photons}}{\text{cm}^3 \text{ sec}}$

R_o = Inside radius of cylindrical vessel, cm

a = Distance between source and point of measurement, cm

z = Self-attenuation distance, cm

$$F(\theta, b_1) = \int_0^\theta e^{-b_1 \sec \theta'} d\theta'$$

$$E_2(x) = x \int_x^\infty \frac{e^{-t}}{t^2} dt$$

$$b_1 = \sum_j^n \mu_j t_j$$

$$b_2 = b_1 + \mu_s z$$

$$\theta = \tan^{-1} (h/2)/(a + z)$$

h = Height of cylindrical source

$$\theta_1 = \tan^{-1} R_o/a$$

μ_j = Attenuation coefficient of material j, cm^{-1}

t_j = Thickness of material j, cm

μ_s = Attenuation coefficient of source material, cm^{-1}

A_1 = Constant in the buildup factor

α_1 = Constant in the buildup factor

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