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DATE: July 28, 1958

SUBJECT: Deposition of Gamma-Ray Heating in Stratified Lead and Water Slabs

TO: Distribution

FROM: L. A. Bowman,* D. K. Trubey

ABSTRACT

This memorandum presents typical results from a calculation of the deposition of heat in stratified lead and water slabs caused by a monodirectional, monoenergetic beam of gamma rays incident on the slabs. A total of 512 cases were calculated for infinite slabs with finite thicknesses of 1, 2, 4, and 6 mean free paths; source energies of 1, 3, 6, and 10 Mev, and source angles of incidence which were chosen to give slant slab thicknesses of 1, 2, 3, and 4 times the normal thickness. The results were fitted to an empirical formula, which can be simplified for special cases. While for the cases examined, the fit was usually good to within 5%, it is to be emphasized that the formula has been compared only with the results from a very limited number of parameters.

*On assignment from WADC.

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DISCLAIMER

Deposition of Gamma-Ray Heating in Stratified Lead and Water Slabs

The Oracle Monte Carlo code[1] for the calculation of the penetration of gamma rays through stratified slabs has been used to calculate a total of 512 problems for eight different lead and water configurations as shown in Fig. 1. The energy of the incident radiation, the angle of incidence, the thickness of the shield, and the percentage of lead preceding or following water were varied. The source was assumed to be a monodirectional beam with energies of 1, 3, 6, and 10 Mev. The incident angles chosen were those which would give slant thicknesses of 1, 2, 3, and 4 times the normal thickness, and the infinite slabs had finite thicknesses of 1, 2, 4, and 6 mean free paths. The results obtained include the dose rate and energy flux throughout the slab and at the rear; the heat deposited throughout the slab; and the energy and angular distribution reflected from and transmitted through the slab. The derived dose-rate buildup factors for normal incidence have been reported previously,[2] and this report considers the heat deposited throughout the slabs and presents a formula that fits the results. The information on the energy and angular distribution will be presented later.

The heating results are given as the percent of the total energy incident upon the slab absorbed in a specified region in the slab. Some typical plots of these results are shown in Figs. 2 to 21, which compare the Monte Carlo results averaged over a region of four intervals to the values obtained by using the following empirical formula:

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1. S. Auslender, "Compilations of Monte Carlo Calculations of Gamma-Ray Penetration in Multiregion Shields with Slab Geometry," ORNL-2310 (to be published).

2. L. A. Bowman and D. K. Trubey, "Stratified Slab Gamma-Ray Dose-Rate Buildup Factors in Lead and Water Shields," ORNL-CF-58-1-41 (1958); see also ORNL-2387, p. 320.

$$J_x(E_o,\Theta,X,Mat) = \left[\sec\Theta \frac{\mu_a(E_o,Mat_x)}{\mu_t(E_o,Mat_x)} e^{-\left(\frac{x_1 + x_2}{\cos\Theta}\right)}\right]\left[B_{a_1}\left(\frac{x_1}{\cos\Theta},E_o\right) B_{a_2}\left(\frac{x_2}{\cos\Theta},E_o\right)e^{-\left(\frac{x_2}{\cos\Theta}\right)}\right.$$

$$\left. + B_{a_2}\left(\frac{x_1 + x_2}{\cos\Theta},E_o\right)\left\{1 - e^{-\left(\frac{x_2}{\cos\Theta}\right)}\right\}\right]$$

$$\times \left[e^{-\left\{4\cos\Theta(1-\cos\Theta)\left(1 - \frac{\mu_a(E_o,Mat_1)}{\mu_t(E_o,Mat_1)}\right)\left(\frac{x_1 + x_2}{(x_1 + x_2)^4 + 1}\right)\frac{2}{\sqrt{E_o}}\right\}}\right]$$

where

$J_x(E_o,\Theta,X,Mat)$ = percent of total energy incident upon the slab absorbed in the slab at point x per mean free path,

x_1 = number of mean free paths of the first material,

x_2 = number of mean free paths of the second material,

E_o = energy of the incident gamma ray,

Θ = angle between the direction of the incident gamma ray and the normal to the slab,

$\frac{\mu_a(E_o,Mat_x)}{\mu_t(E_o,Mat_x)} = \frac{\text{energy absorption coefficient}}{\text{total absorption coefficient}}$,

$B_{a_1}\left(\frac{x_1}{\cos\Theta},E_o\right)$ = NDA point isotropic energy absorption buildup factor for the first material,[3]

$B_{a_2}\left(\frac{x_2}{\cos\Theta},E_o\right)$ = NDA point isotropic energy absorption buildup factor for the second material,

$e^{-\left(\frac{x_1 + x_2}{\cos\Theta}\right)}$ = exponential attenuation to point heating is calculated,

and

$$e^{-\left[4\cos\Theta(1 - \cos\Theta)\left(1 - \frac{\mu_a(E_o,Mat_1)}{\mu_t(E_o,Mat_1)}\right)\left(\frac{x_1 + x_2}{(x_1 + x_2)^4 + 1}\right)\frac{2}{\sqrt{E_o}}\right]}$$

is the empirical short-circuiting correction.

The first bracketed factor represents the expected fraction of incident energy to be deposited per mean free path if the scattered gamma rays are neglected.

The next bracketed term is the buildup factor. Near the boundary (x_2 small), where the spectrum is largely determined by the first material, the buildup is given by the first term. This term damps out as x_2 gets large and the buildup factor is characteristic of the second material. The buildup factors used in the formula were the results of the well-known NDA moments method calculation.[3] The energy absorption buildup factors used were for a point isotropic source since these were the only buildup factors presented in ref. 3.

The last bracketed factor is the "short-circuiting" factor. An attempt was made to separate the effects of the various parameters in the exponent. The factors which depend on the angle peak at 60 deg. It seems reasonable that a peak might occur about there owing to the combination of a decreasing path length and a decreasing cross section and final energy of a scattered gamma ray as the angle of scattering increases. The effect of distance from the initial boundary also shows a peak (near 1 mfp). There is little short circuiting at short distances since the heating is due largely to first collisions. The short-circuiting damps out at large distances since the buildup factor adequately accounts for the scattered gamma rays far from boundaries. The factor $1 - \frac{\mu_a(E_o, Mat_1)}{\mu_t(E_o, Mat_1)}$ is generally taken to be that of the first material since, in general, the short-circuiting effect is due to scattering near the initial boundary. This procedure seems adequate if the first material is 0.25 mean free path thick but probably is not adequate if the thickness of the first material is less than this. The variation with energy seems to break down with low energy and as a result the formula can be low by as much as 20% for the 1-Mev case.

For special cases the formula can be simplified. For example, for $\theta = 0$ deg:

3. H. Goldstein and J. E. Wilkins, Jr., "Calculations of the Penetration of Gamma Rays," NYO-3075, (1954).

$$J_x(E_o,X,Mat) = \frac{\mu_a(E_o,Mat_1)}{\mu_t(E_o,Mat_1)}\left[B_{a_1}(x_1,E_o)B_{a_2}(x_2,E_o)e^{-x_2} + B_{a_2}(x_1+x_2,E_o)\left\{1-e^{-x_2}\right\}\right]e^{-(x_1+x_2)}$$

For only one material:

$$J_x(E_o,\theta,X) = \sec\theta\,\frac{\mu_a(E_o)}{\mu_t(E_o)}\,B_a(x,E_o)e^{-\frac{x}{\cos\theta}-\left[4\cos\theta(1-\cos\theta)\left(1-\frac{\mu_a(E_o)}{\mu_t(E_o)}\right)\left(\frac{x}{x^4+1}\right)\frac{2}{\sqrt{E_o}}\right]}$$

and for x = 0:

$$J_x(E_o,\Theta,Mat) = \sec\Theta\,\frac{\mu_a(E_o,Mat_x)}{\mu_t(E_o,Mat_x)}$$

It should be emphasized that this formula has only been compared with data from this calculation which had a very limited number of parameters (as listed in the first paragraph) and therefore it is possible that the fit is not as good for other parameters, particularly outside the parameters examined. The worst fits were obtained for low energies, especially with lead following water, but even in these cases the error was less than 20%. In nearly all of the cases examined, the error was less than 5%.

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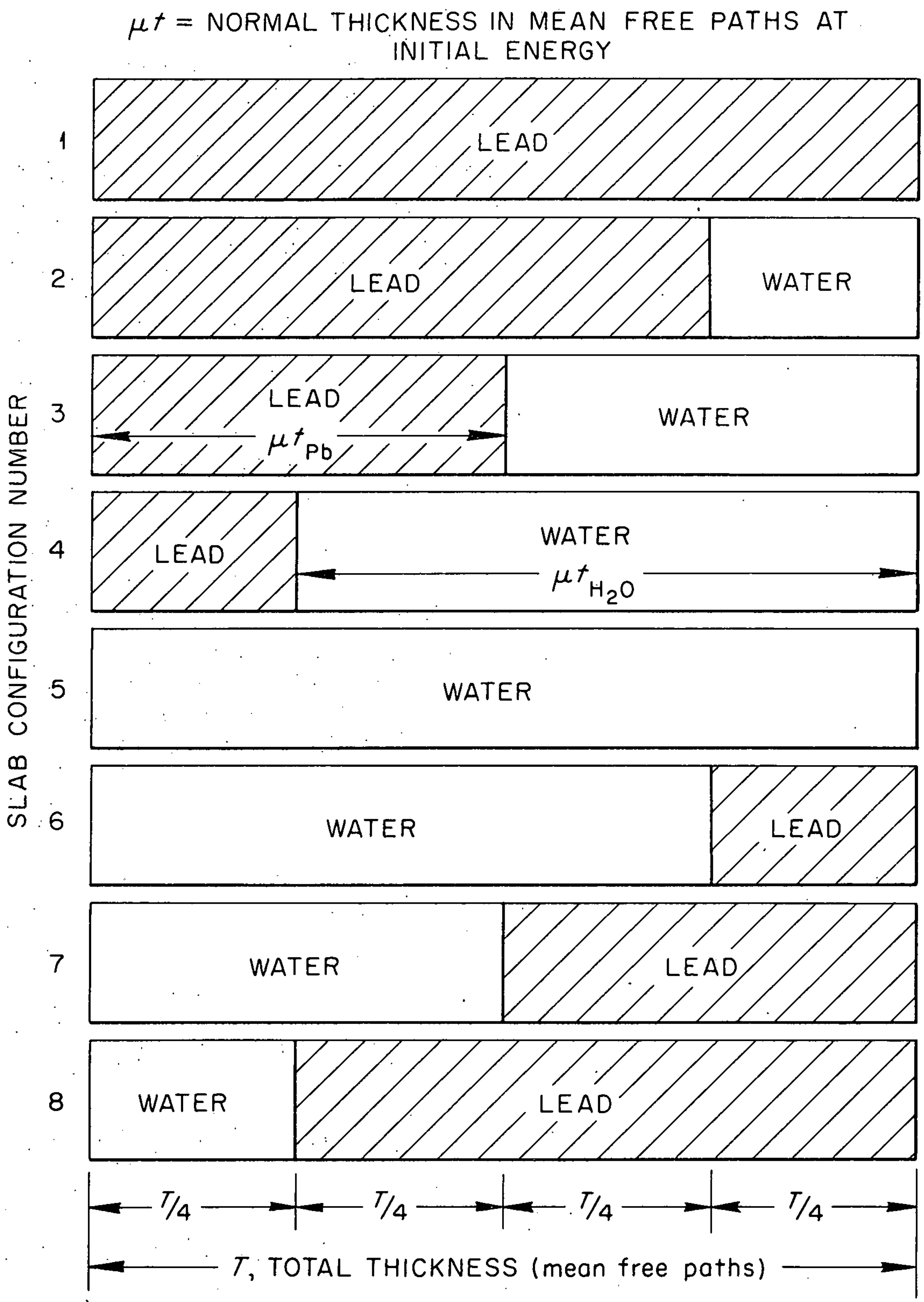

Fig. 1. Lead and Water Slab Configurations Used in Monte Carlo Calculations.

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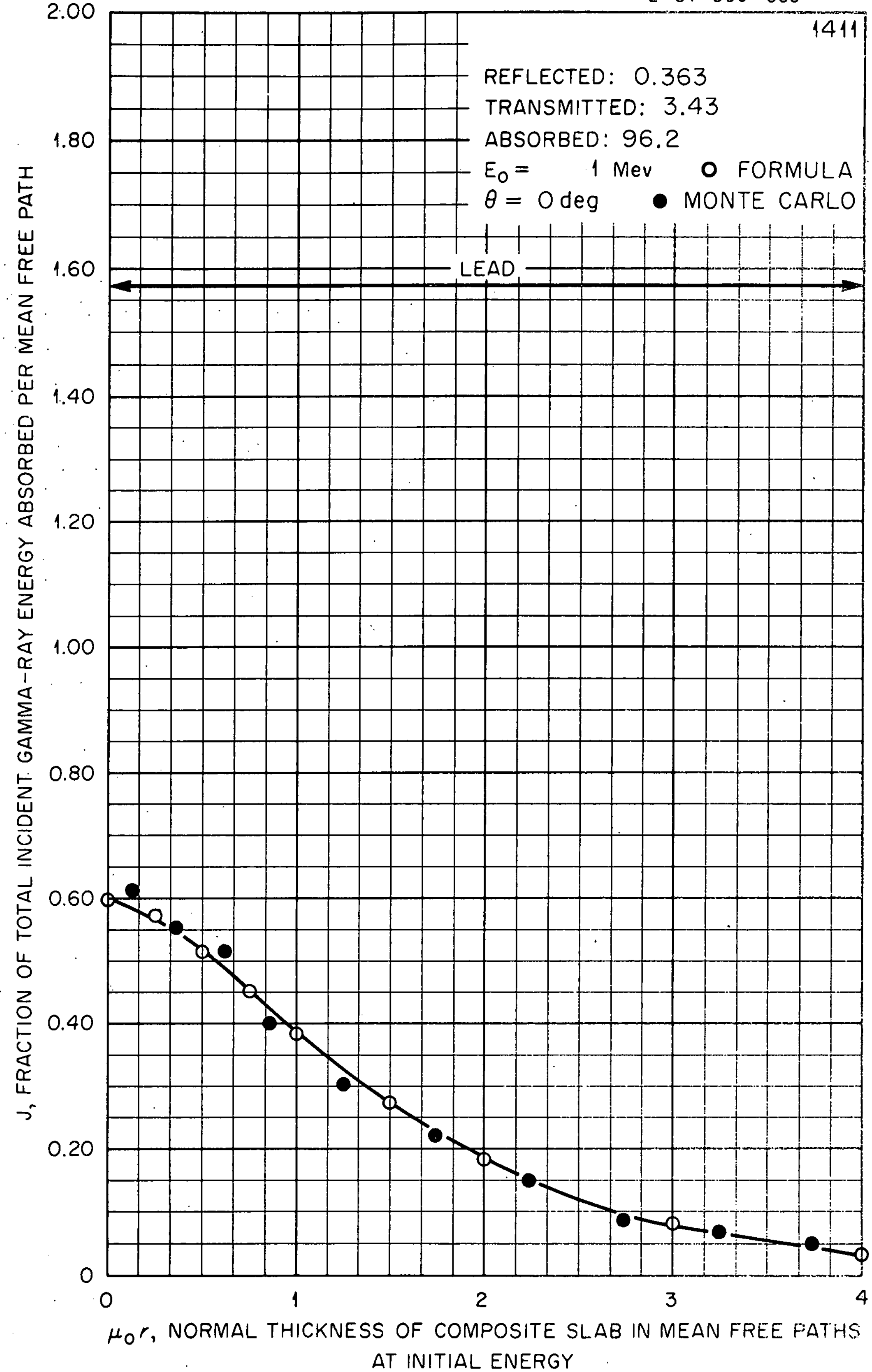

Fig. 2. Gamma-Ray Energy Absorption in a Lead Shield as a Function of the Shield Thickness.

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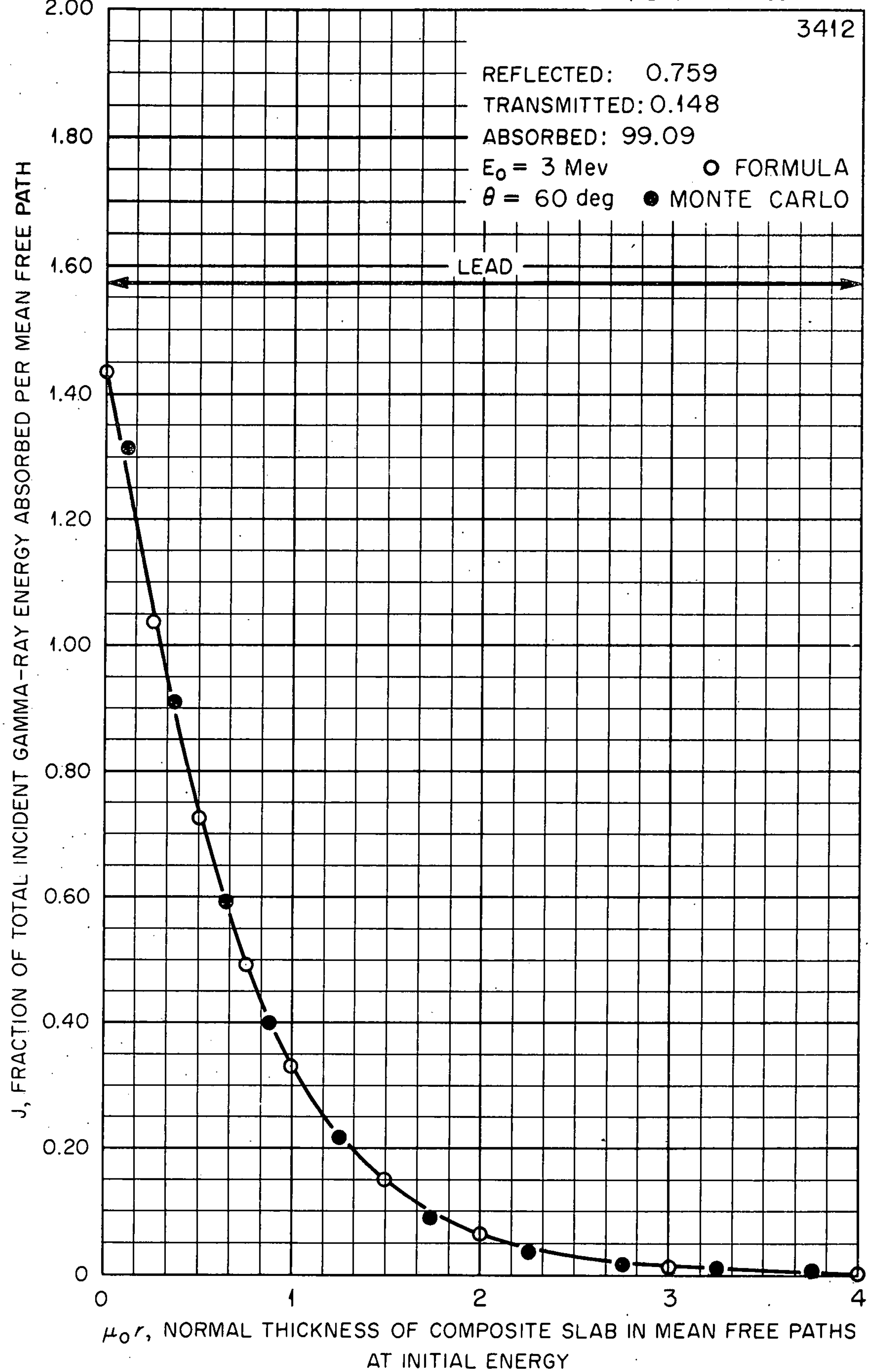

Fig. 3. Gamma-Ray Energy Absorption in a Lead Shield as a Function of the Shield Thickness.

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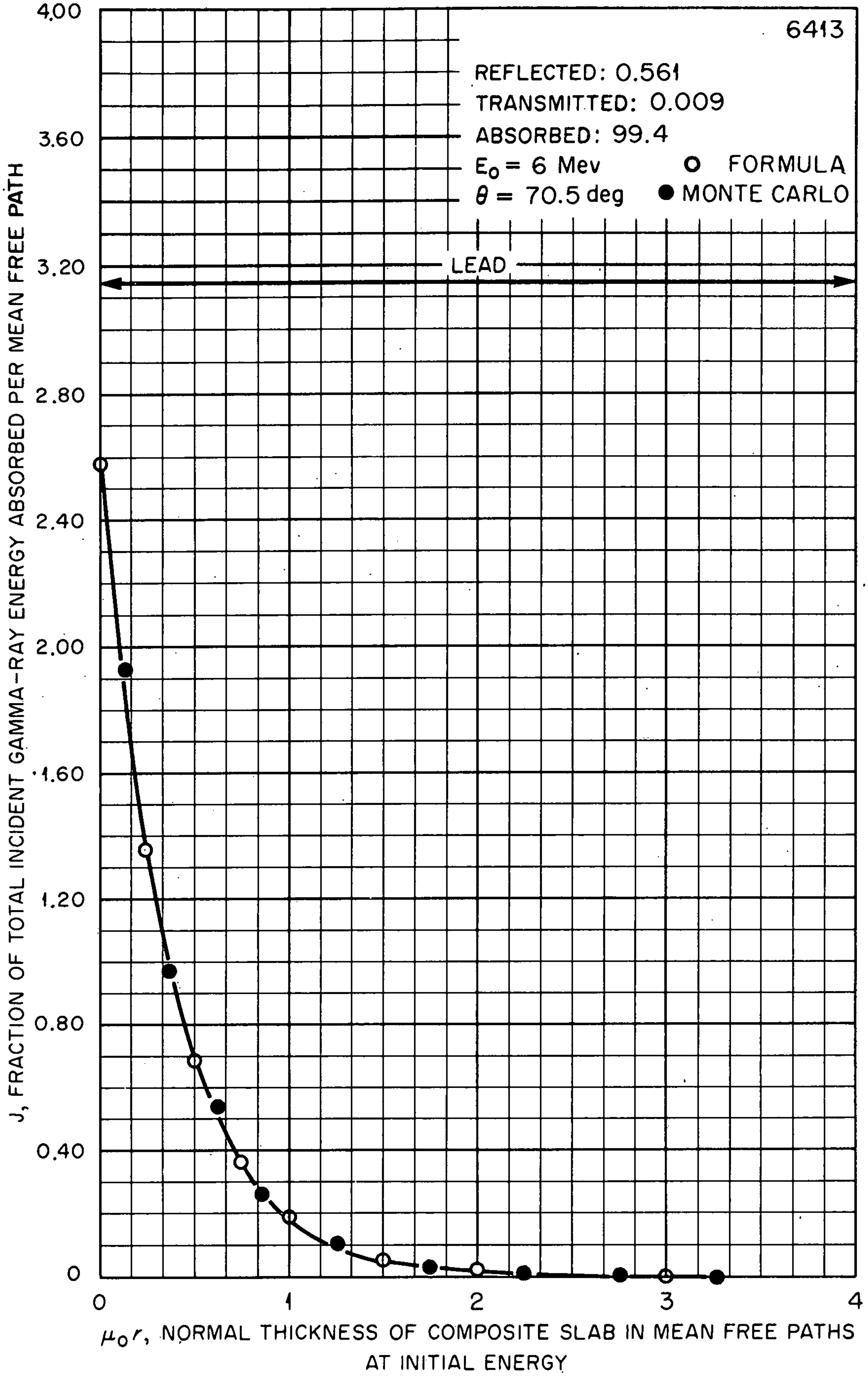

Fig. 4. Gamma-Ray Energy Absorption in a Lead Shield as a Function of the Shield Thickness.

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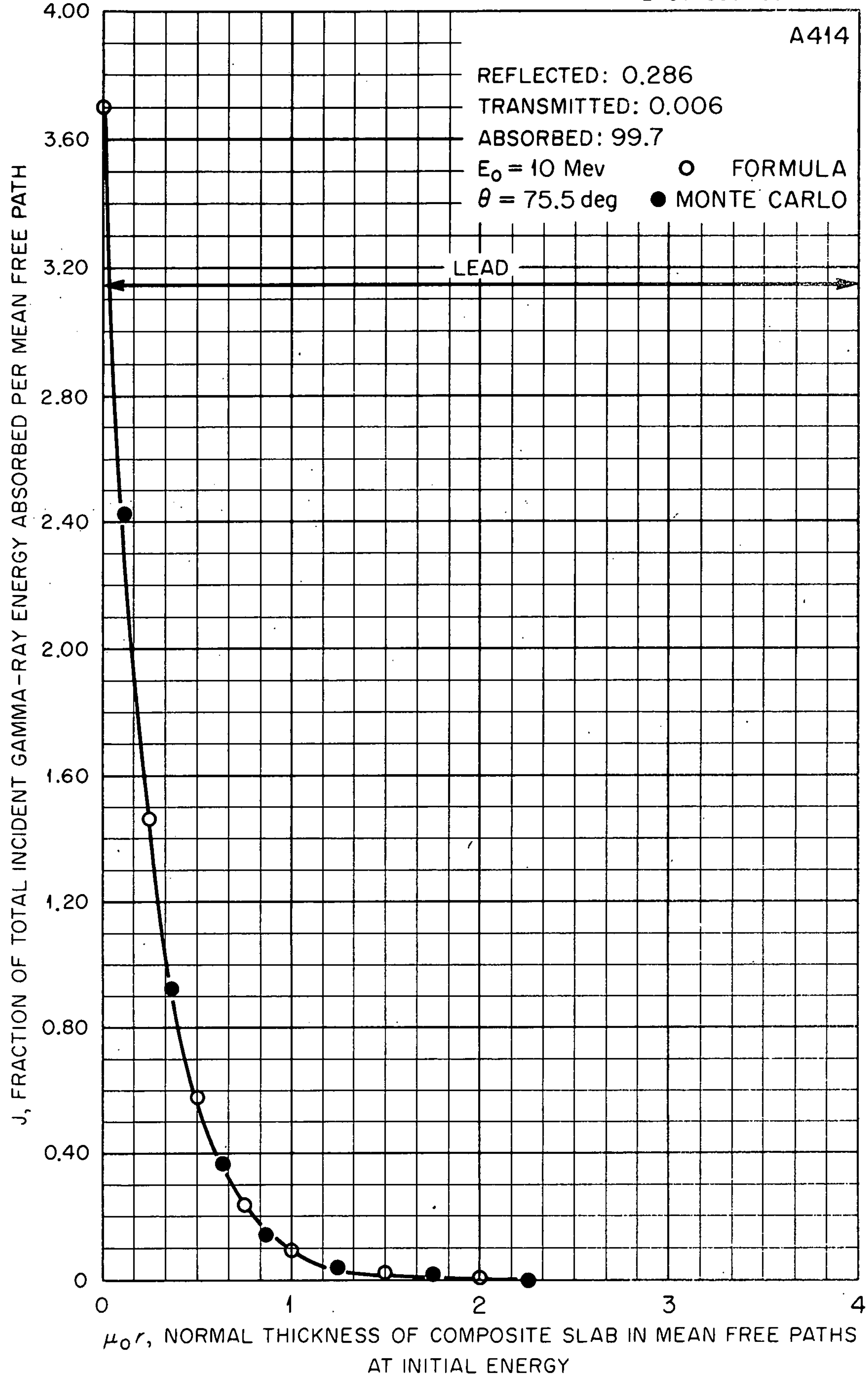

Fig. 5. Gamma-Ray Energy Absorption in a Lead Shield as a Function of the Shield Thickness.

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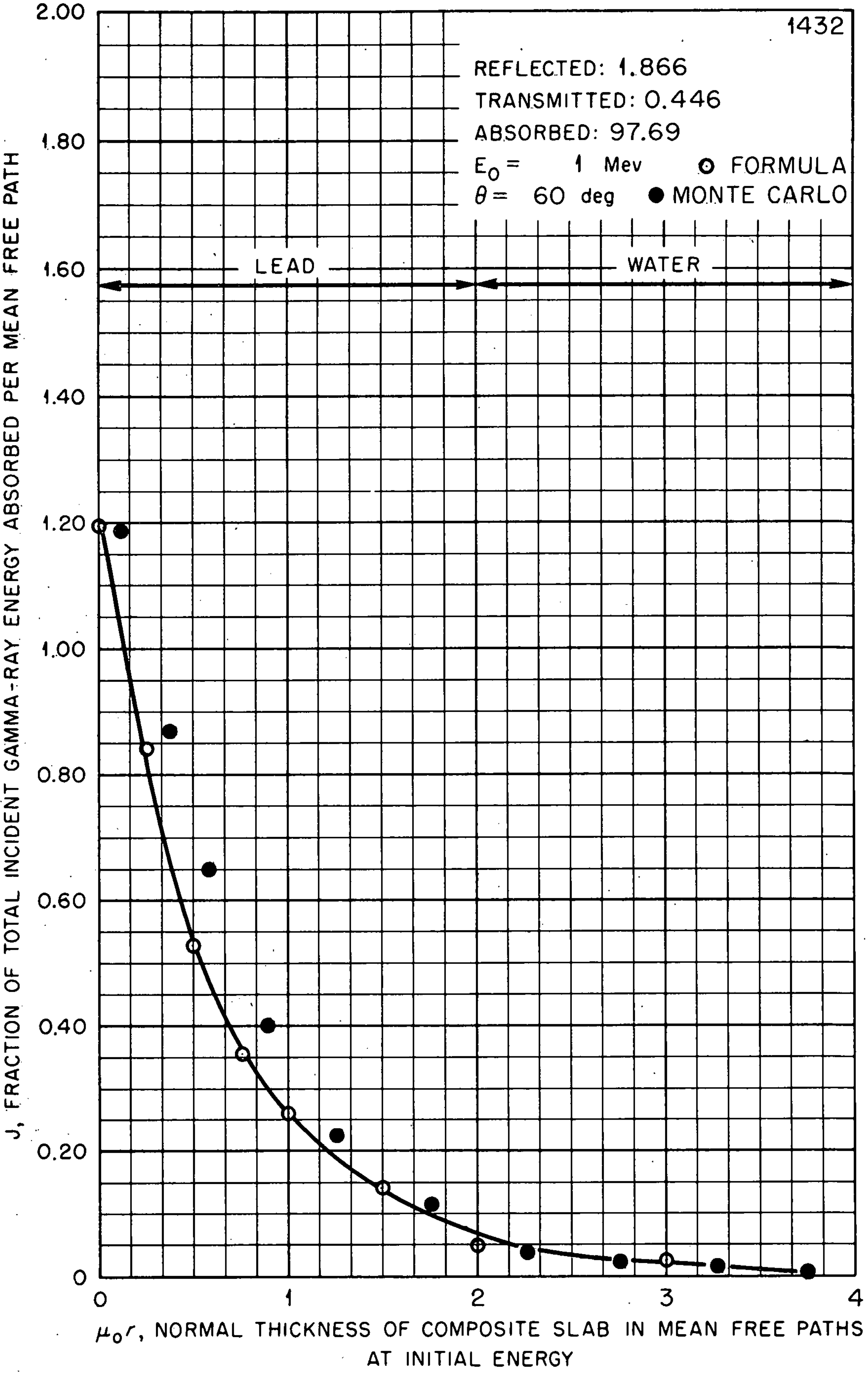

Fig. 6. Gamma-Ray Energy Absorption in a Lead-Water Shield as a Function of the Shield Thickness.

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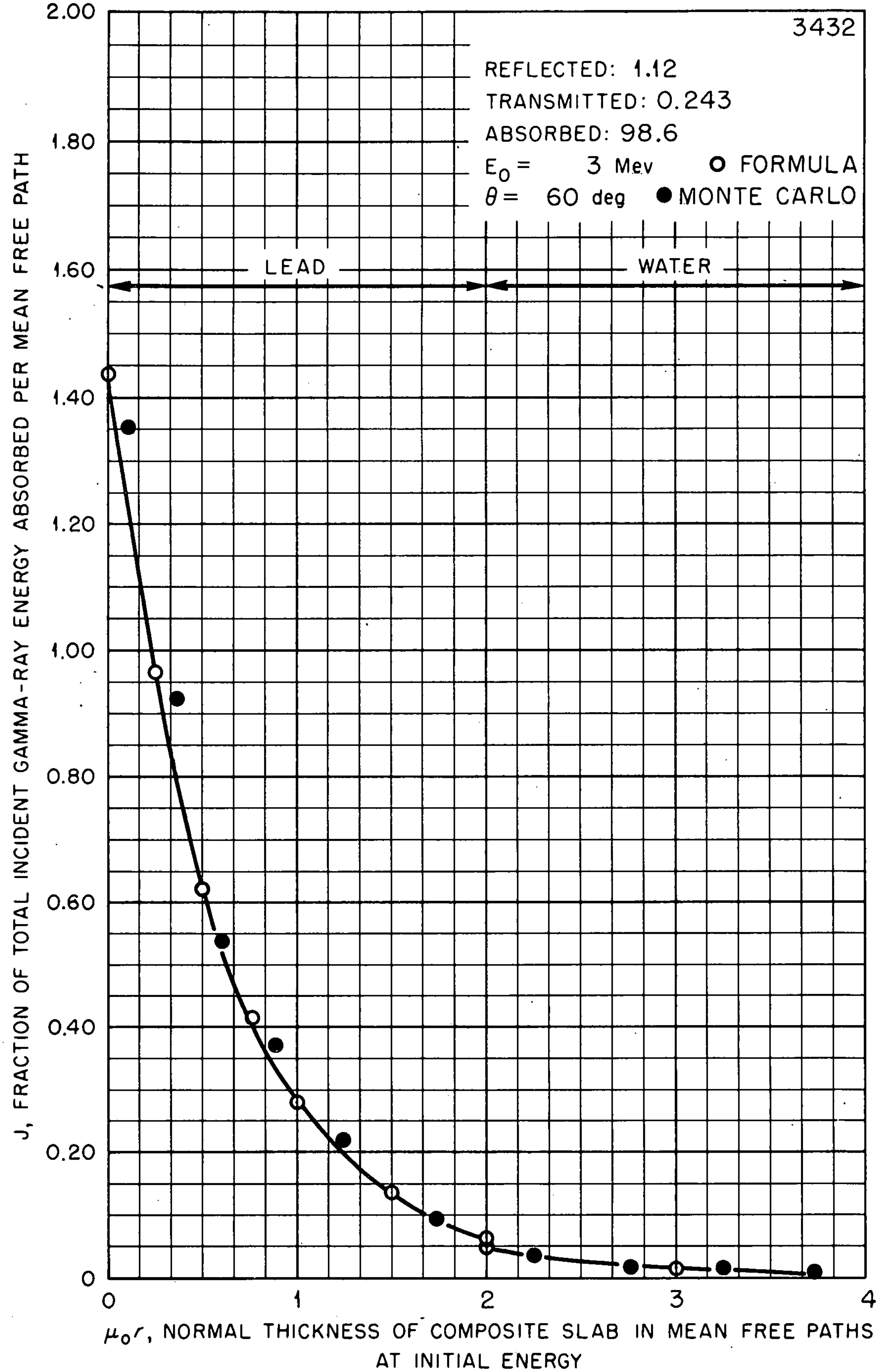

Fig. 7. Gamma-Ray Energy Absorption in a Lead–Water Shield as a Function of the Shield Thickness.

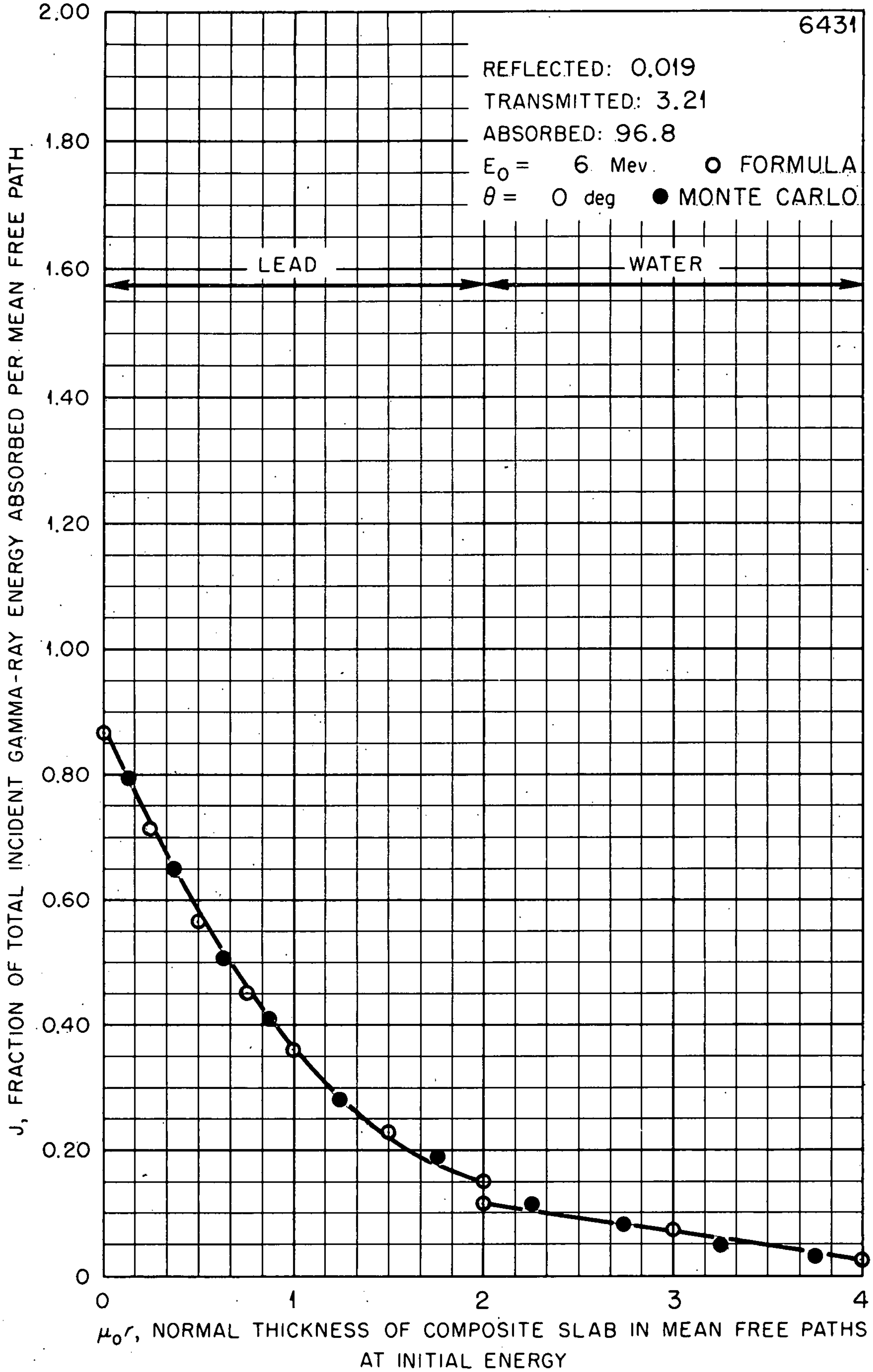

Fig. 8. Gamma-Ray Energy Absorption in a Lead—Water Shield as a Function of the Shield Thickness.

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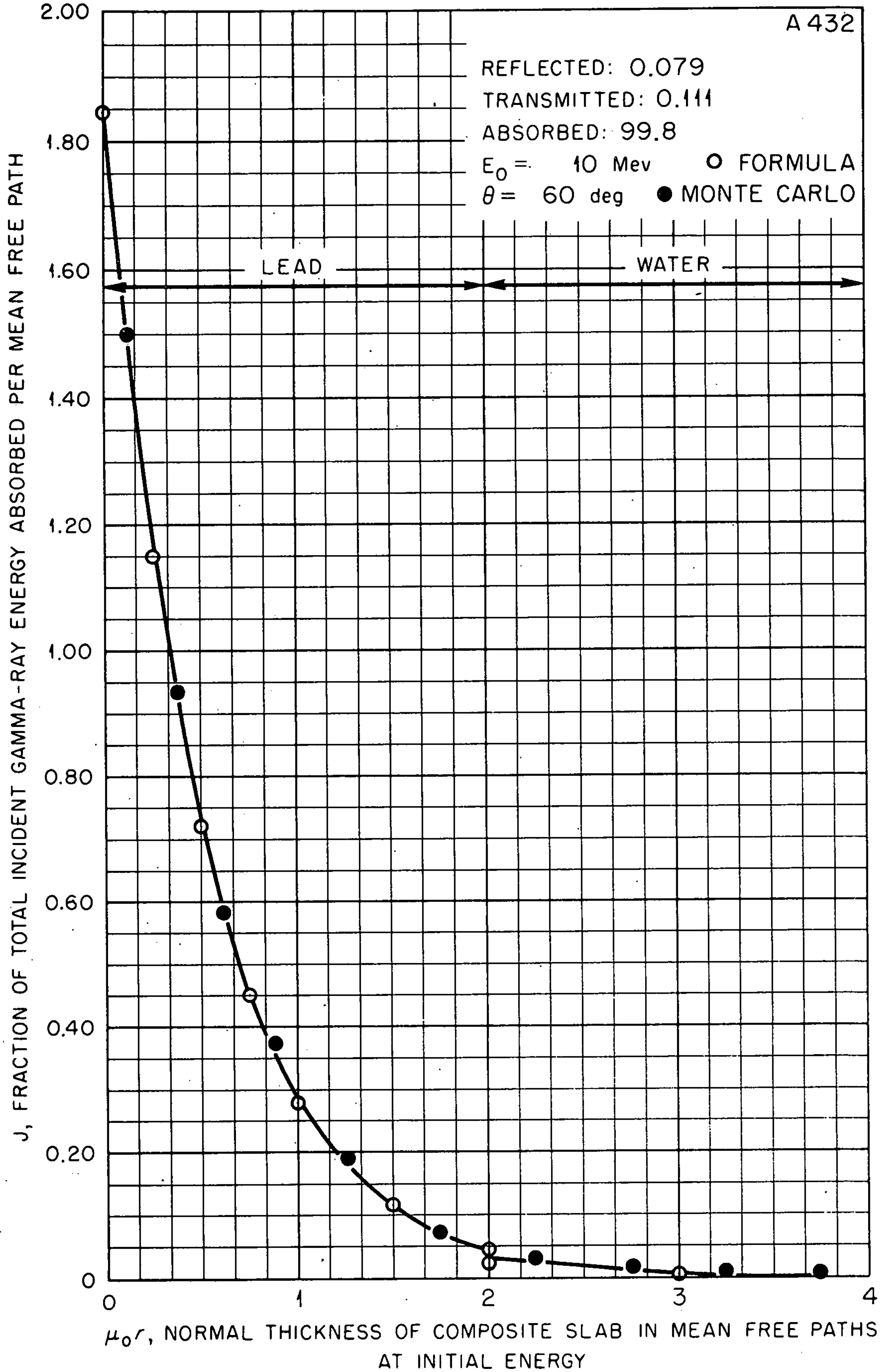

Fig. 9. Gamma-Ray Energy Absorption in a Lead-Water Shield as a Function of the Shield Thickness.

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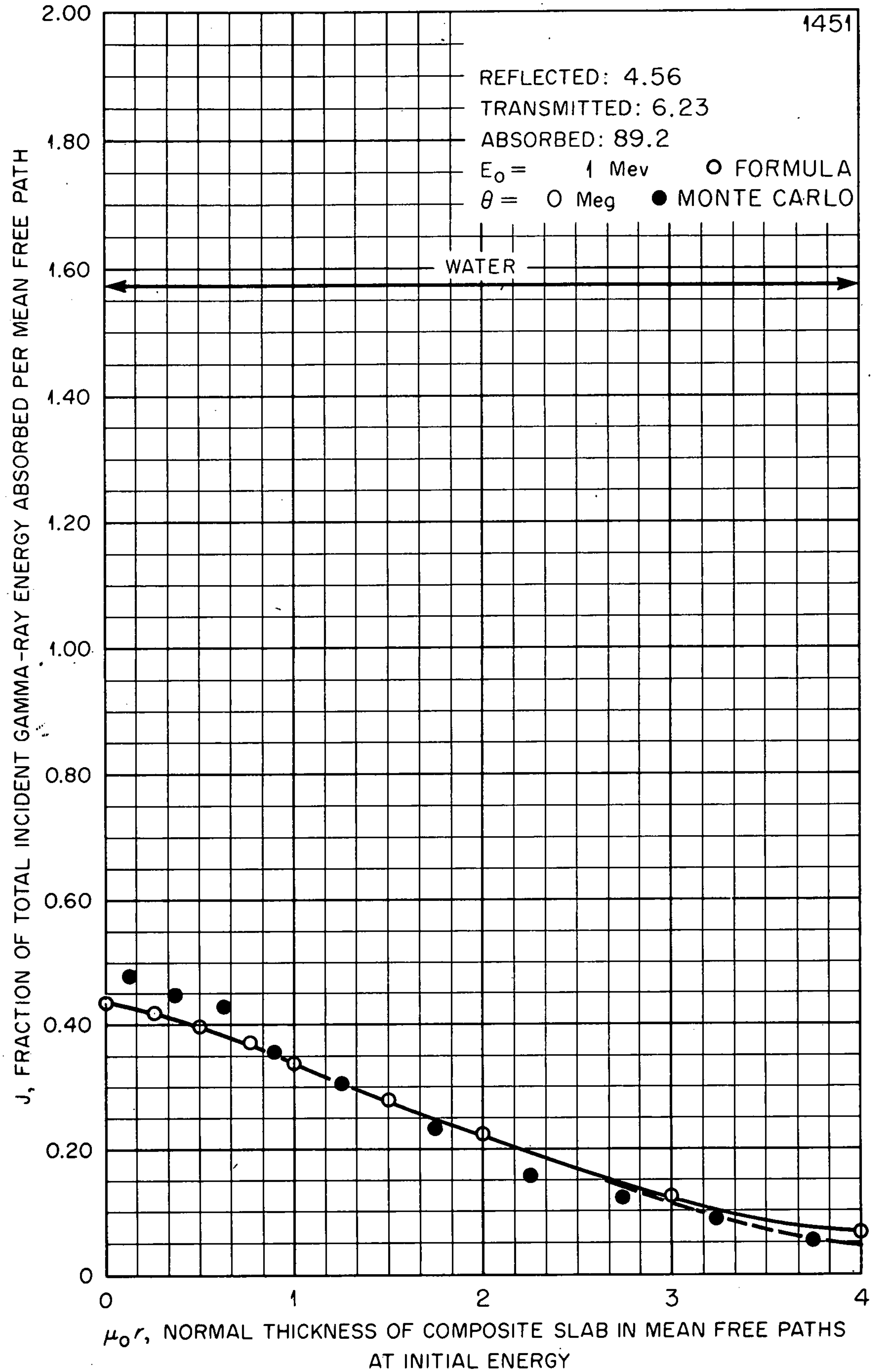

Fig. 10. Gamma-Ray Energy Absorption in a Water Shield as a Function of the Shield Thickness.

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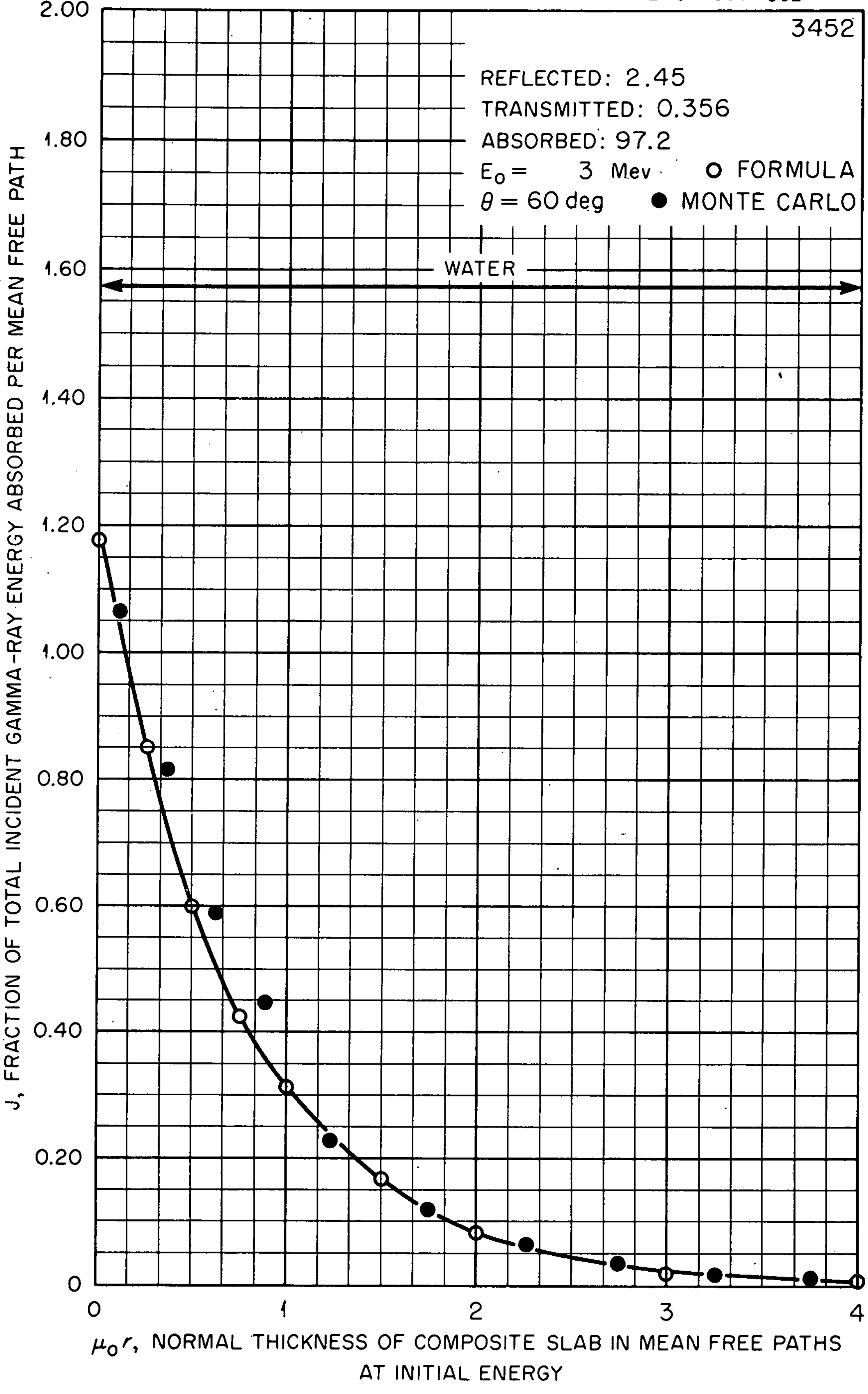

Fig. 11. Gamma-Ray Energy Absorption in a Water Shield as a Function of the Shield Thickness.

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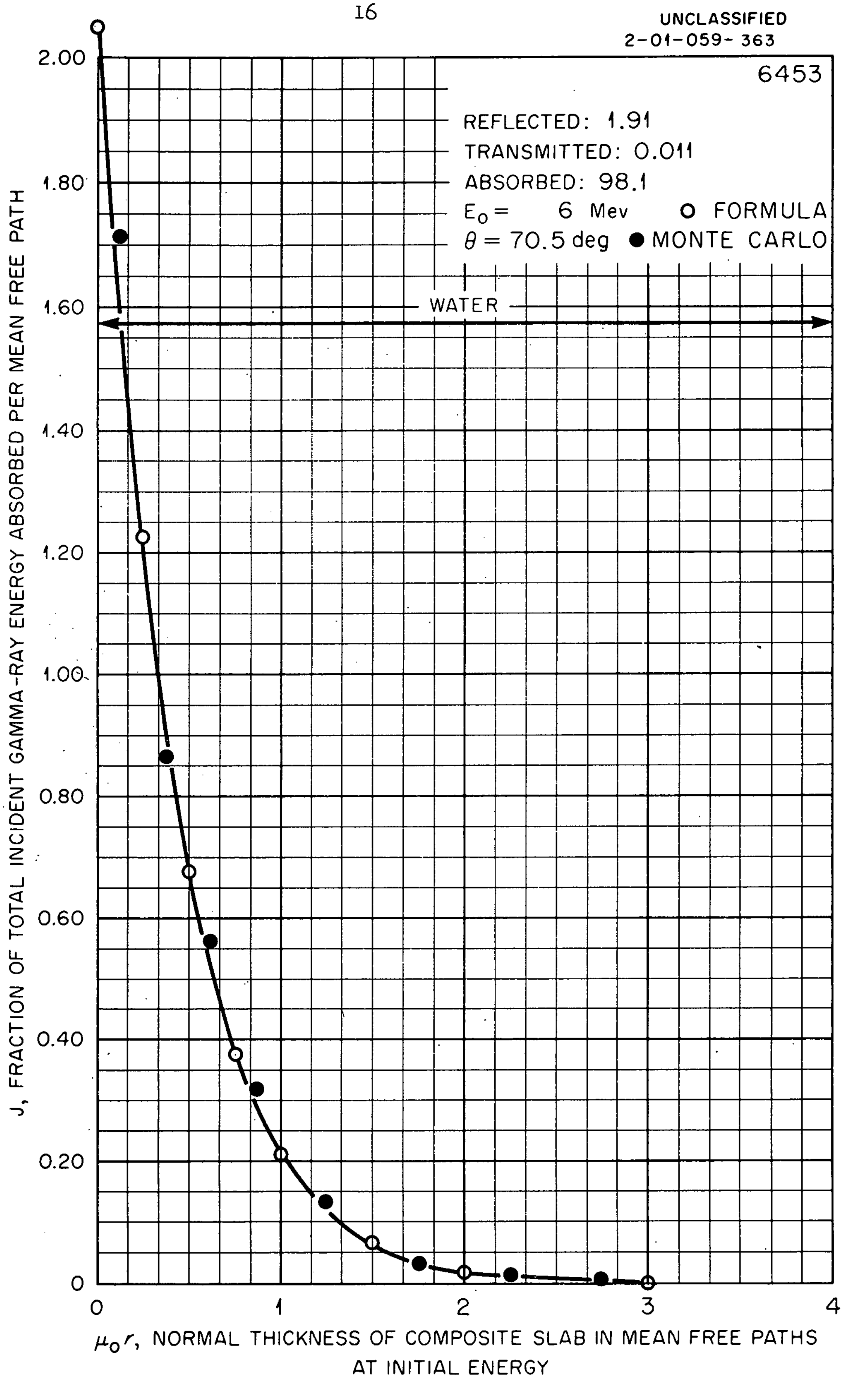

Fig. 12. Gamma-Ray Energy Absorption in a Water Shield as a Function of the Shield Thickness.

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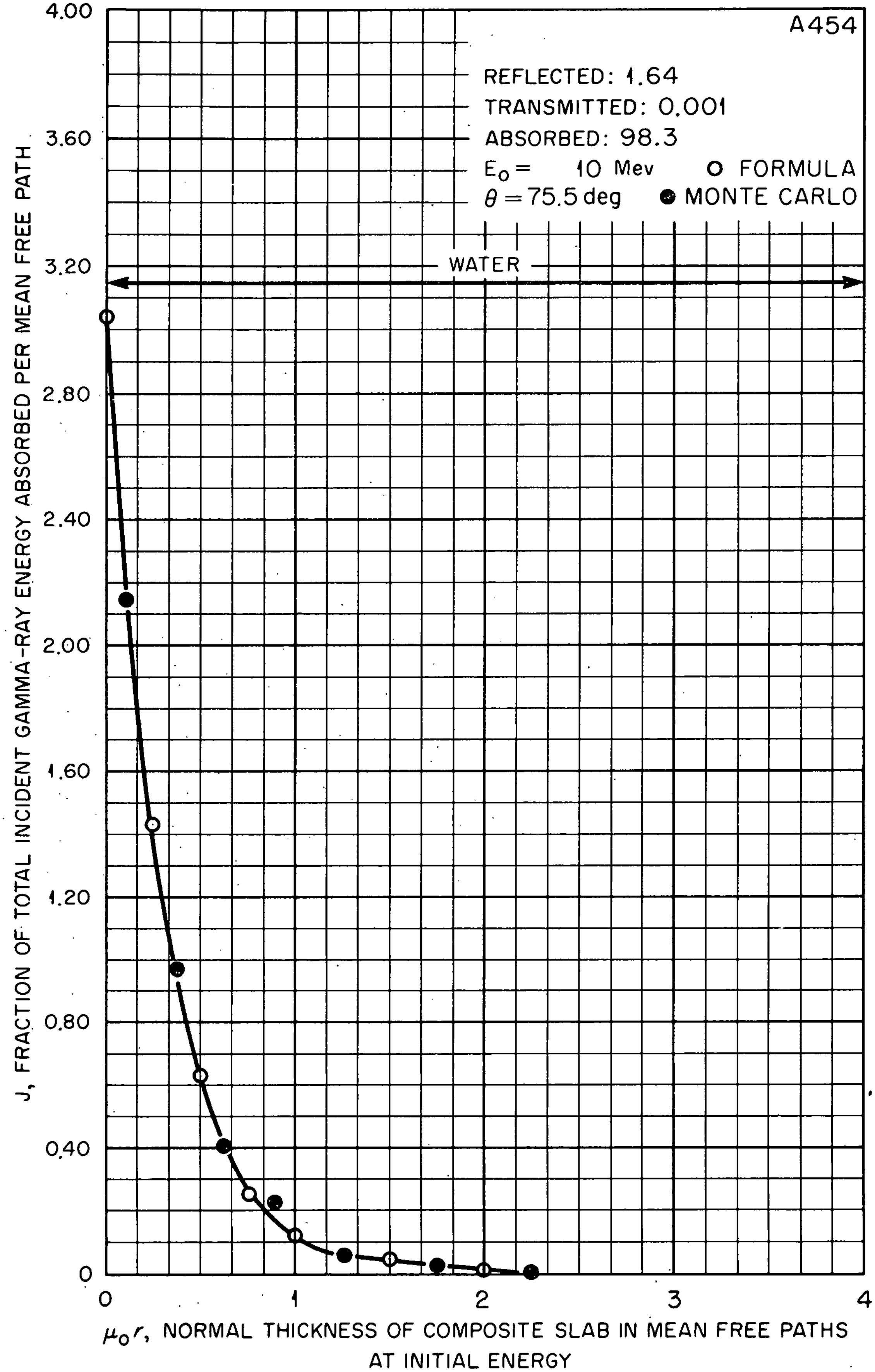

Fig. 13. Gamma-Ray Energy Absorption in a Water Shield as a Function of the Shield Thickness.

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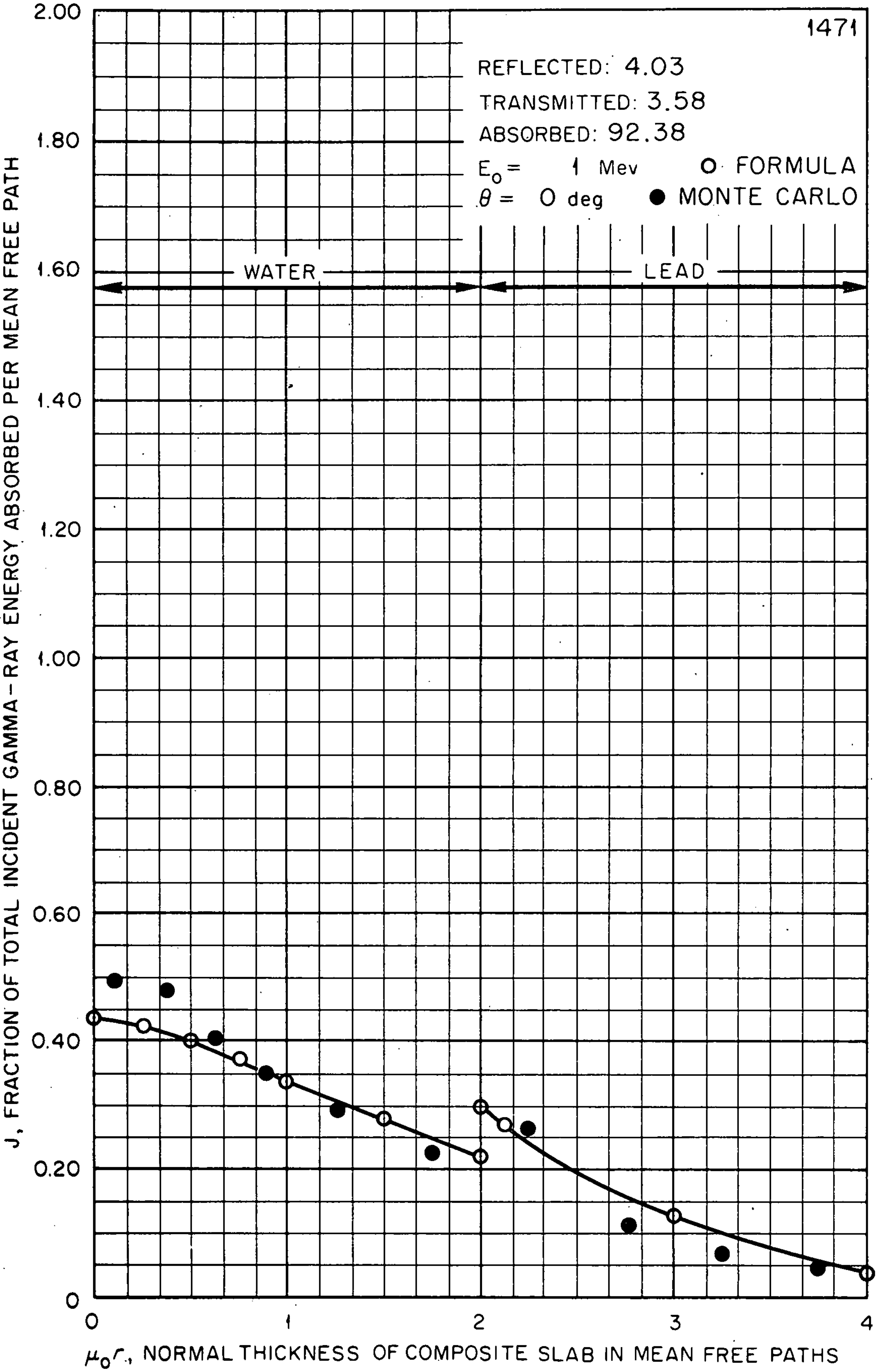

Fig. 14. Gamma-Ray Energy Absorption in a Water-Lead Shield as a Function of the Shield Thickness.

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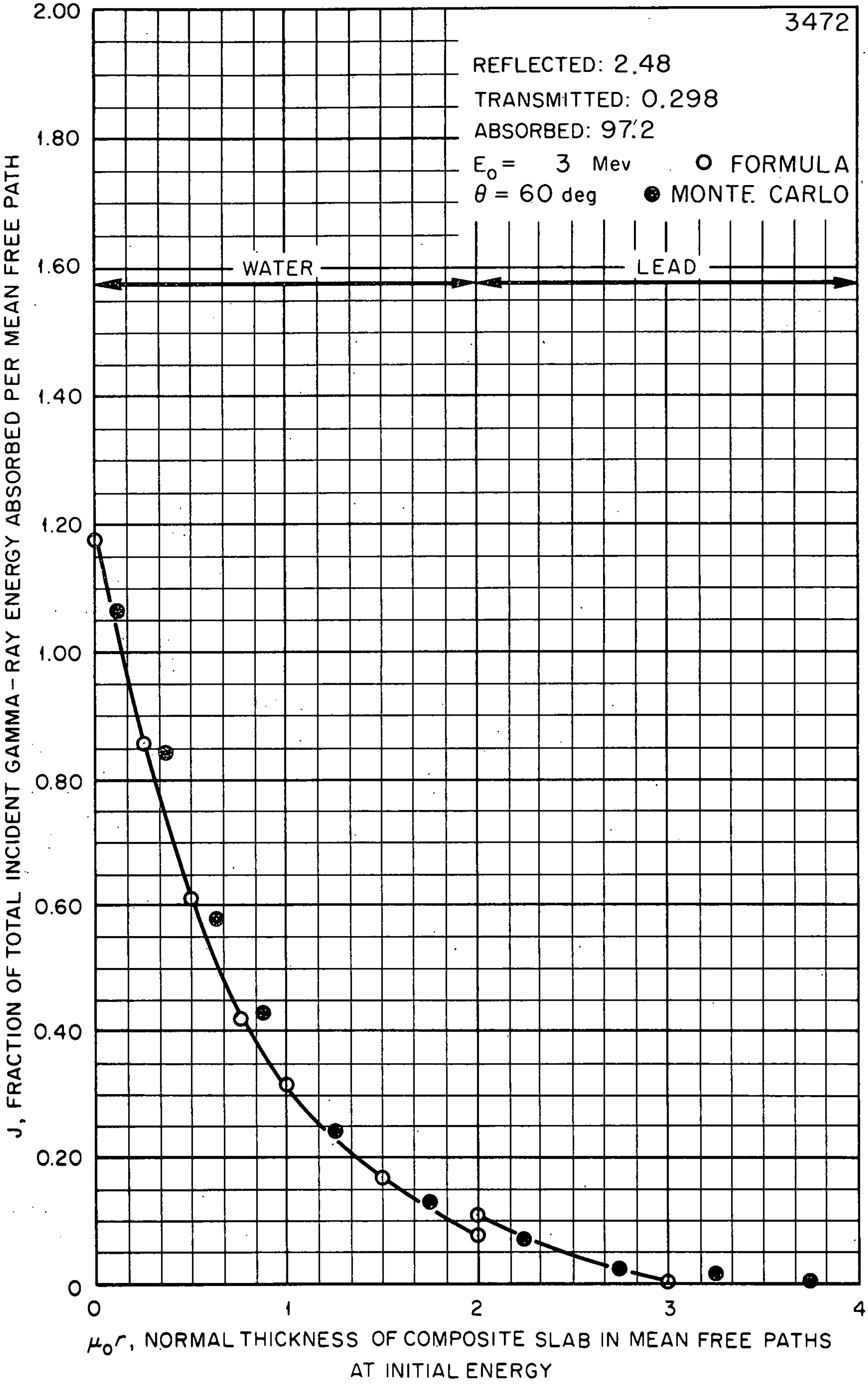

Fig. 15. Gamma-Ray Energy Absorption in a Water-Lead Shield as a Function of the Shield Thickness.

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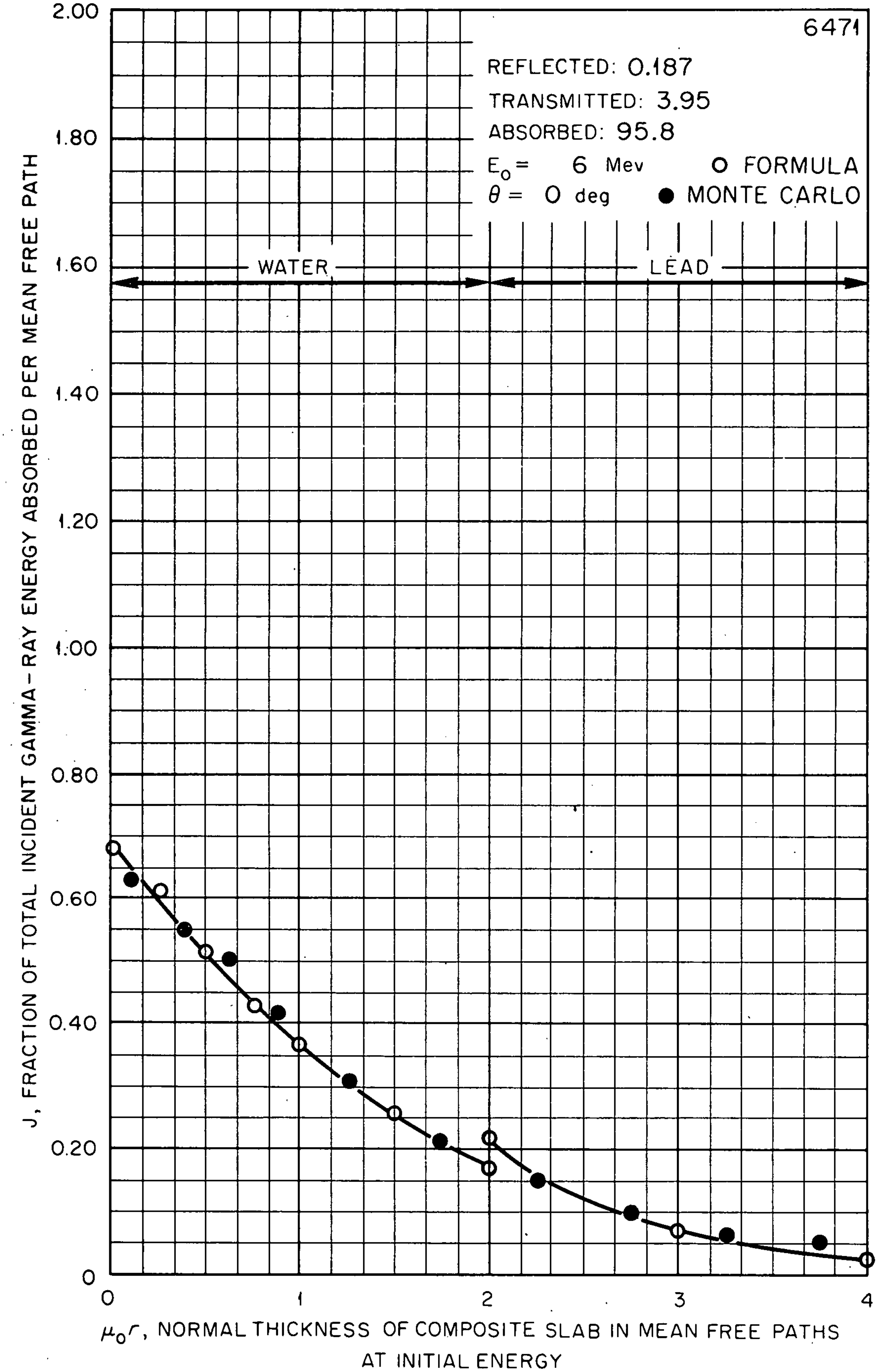

Fig. 16. Gamma-Ray Energy Absorption in a Water-Lead Shield as a Function of the Shield Thickness.

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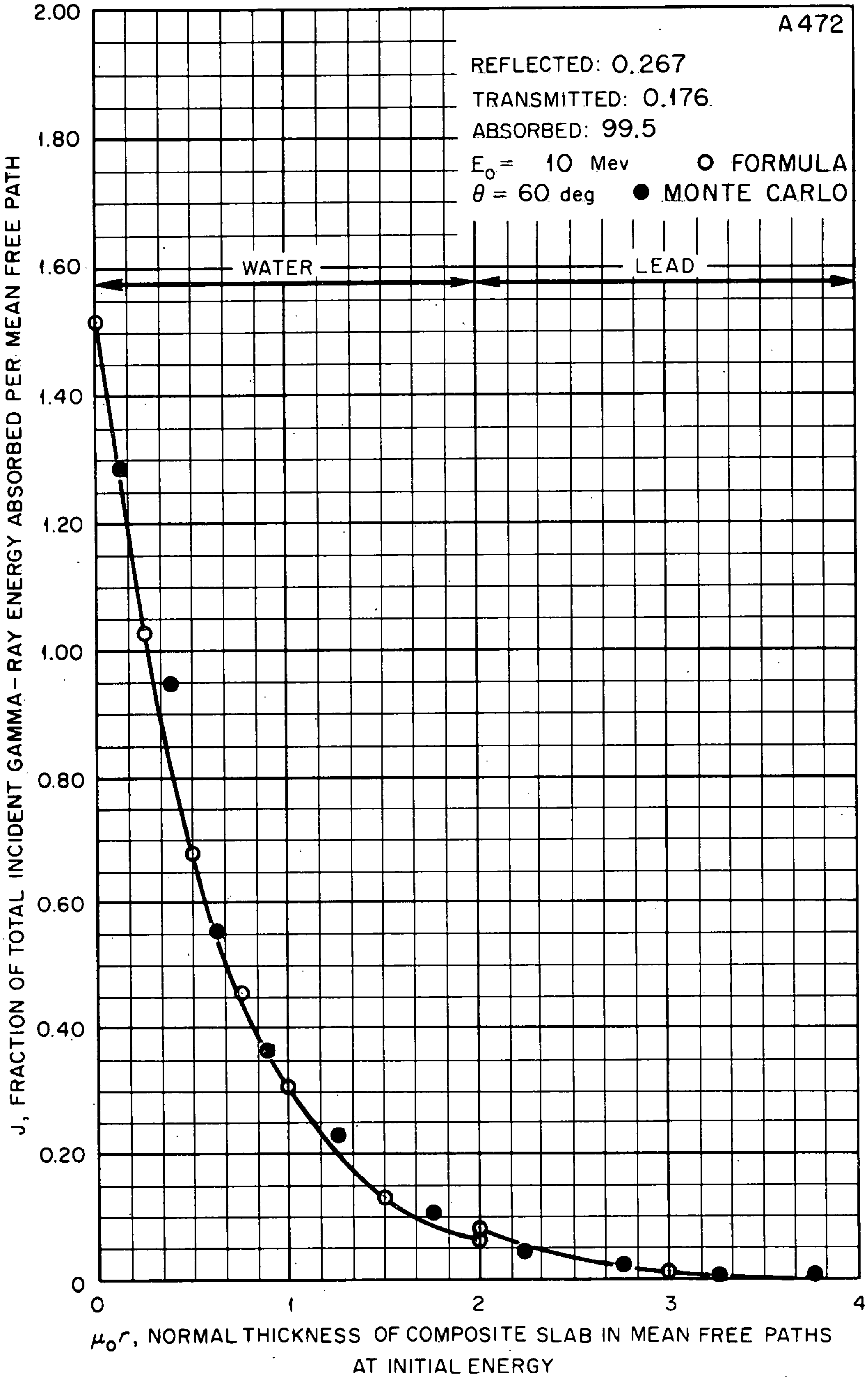

Fig. 17. Gamma-Ray Energy Absorption in a Water-Lead Shield as a Function of the Shield Thickness.

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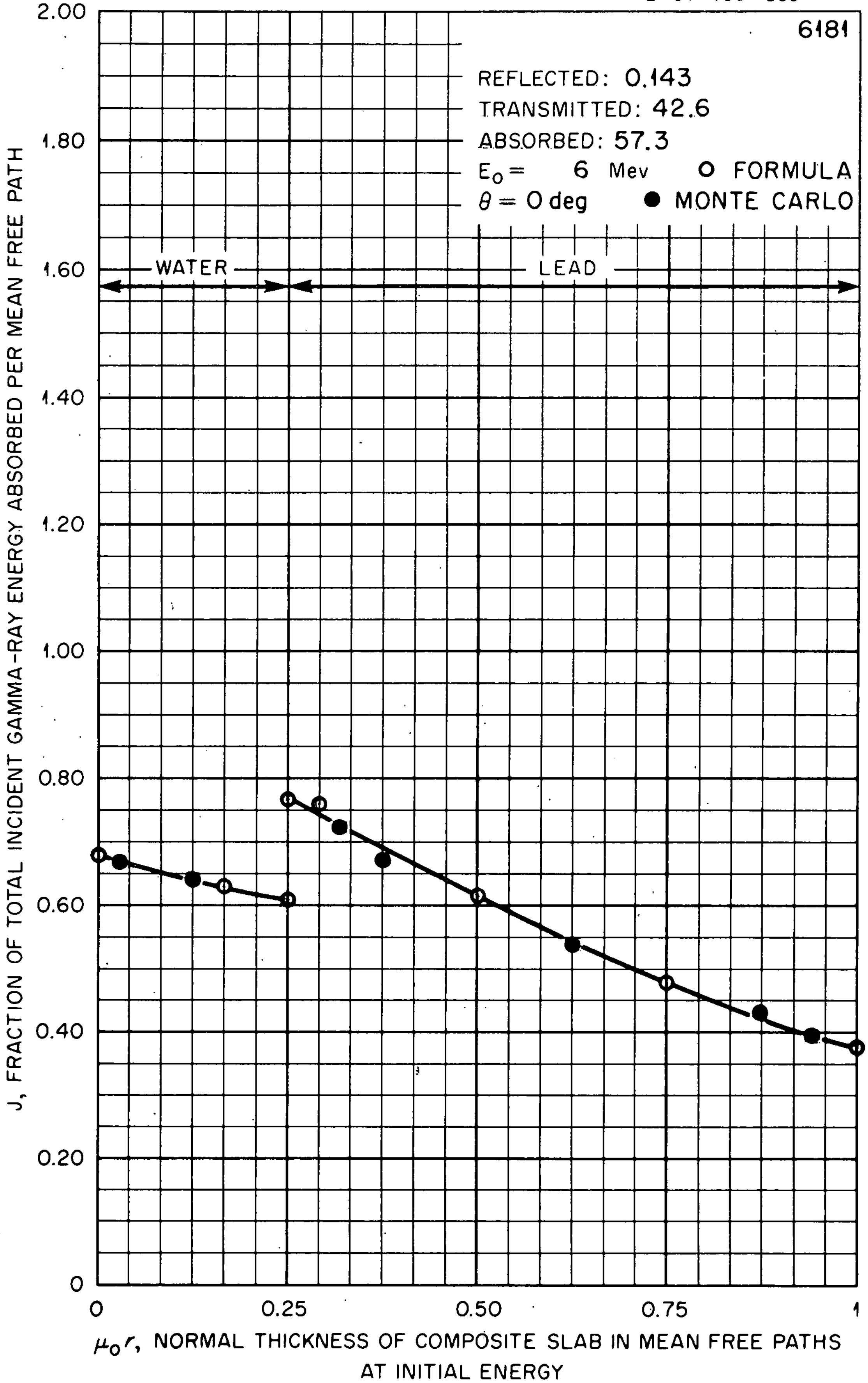

Fig. 18. Gamma-Ray Energy Absorption in a Water–Lead Shield as a Function of the Shield Thickness.

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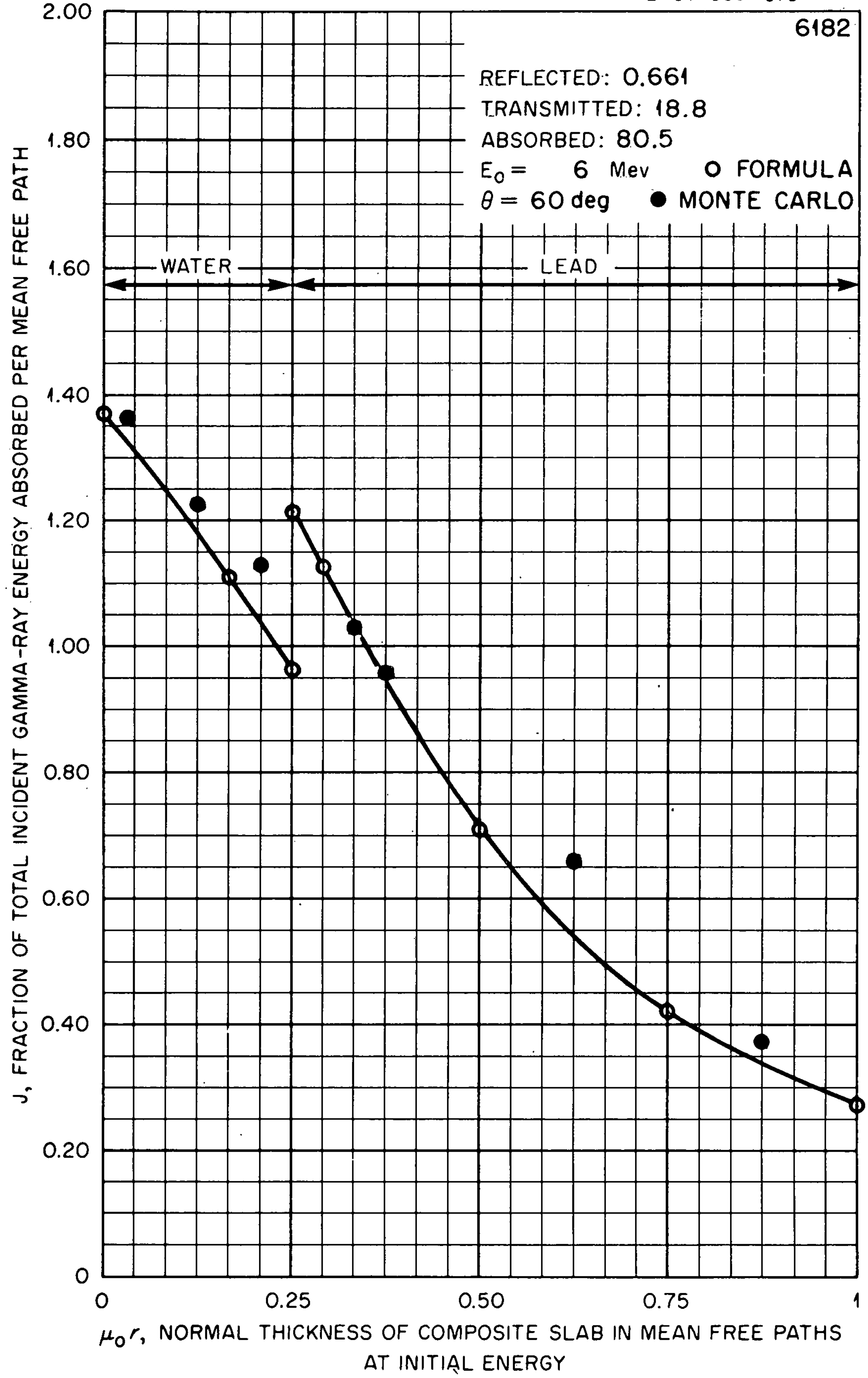

Fig. 19. Gamma-Ray Energy Absorption in a Water–Lead Shield as a Function of the Shield Thickness.

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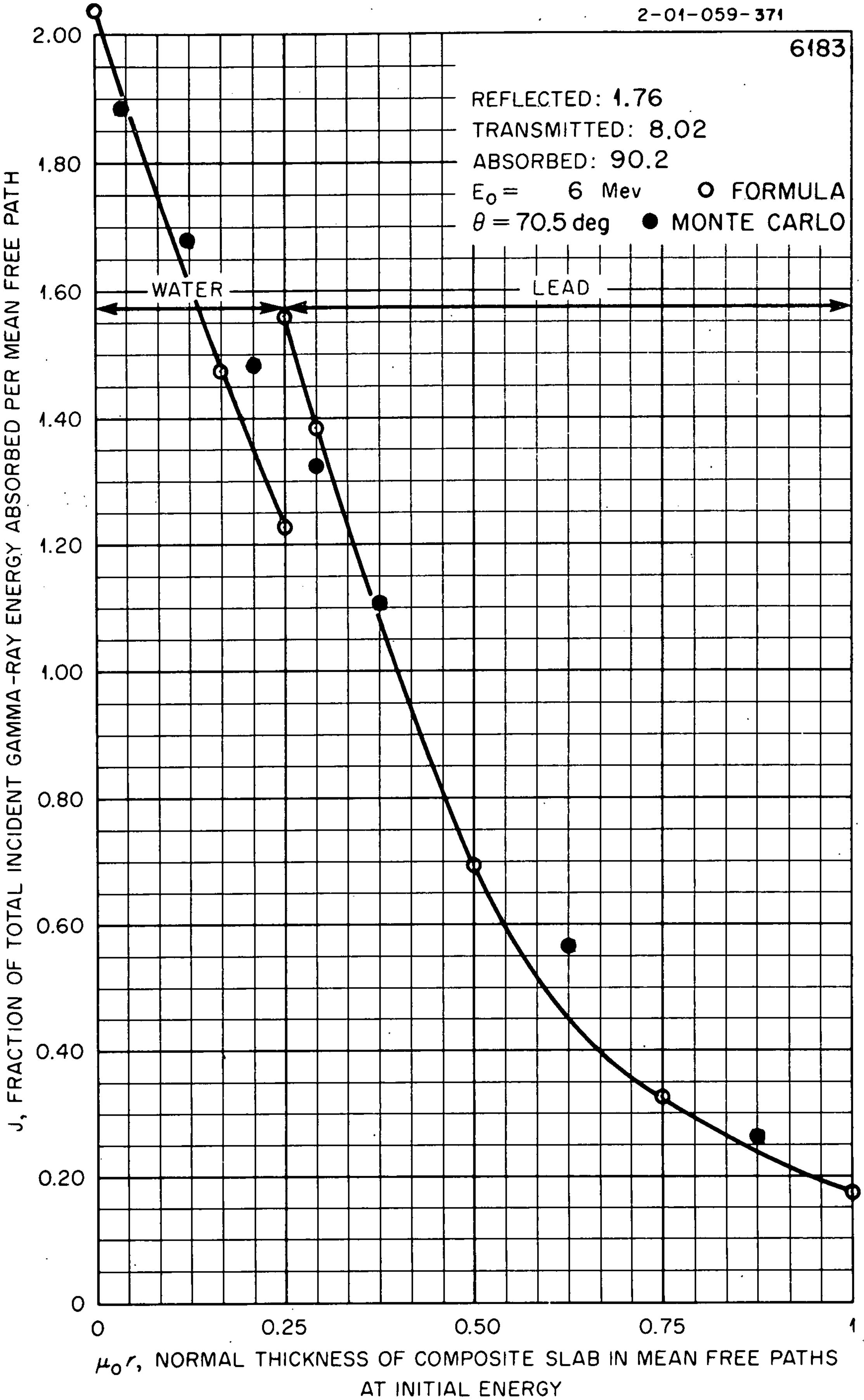

Fig. 20. Gamma-Ray Energy Absorption in a Water–Lead Shield as a Function of the Shield Thickness.

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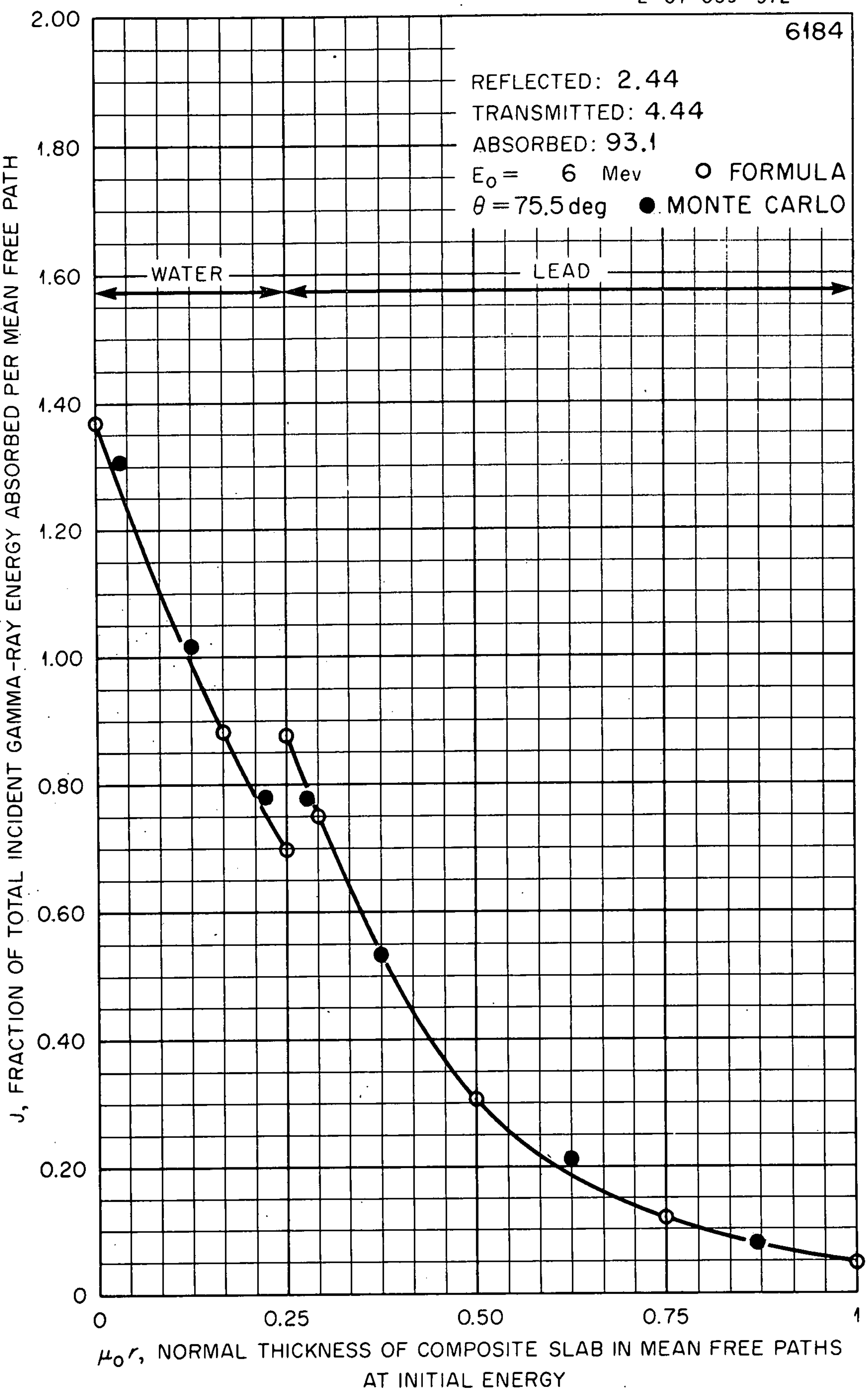

Fig. 21. Gamma-Ray Energy Absorption in a Water–Lead Shield as a Function of the Shield Thickness.

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