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A MONTE CARLO STUDY OF THE GAMMA-RAY ENERGY FLUX, DOSE RATE, AND BUILDUP FACTORS IN A LEAD-WATER SLAB SHIELD OF FINITE THICKNESS

S. Auslender

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A MONTE CARLO STUDY OF THE GAMMA-RAY ENERGY FLUX, DOSE RATE, AND BUILDUP FACTORS IN A LEAD-WATER SLAB SHIELD OF FINITE THICKNESS

S. Auslender

The gamma-ray energy flux, dose rate, and buildup factors in a lead-water shield of finite thickness have been calculated by a Monte Carlo method. The calculation included 1-, 3-, and 6-Mev photons incident on the slab both along a normal and at an angle of 60 deg. (Calculations for an angle of 75-1/2 deg were also performed, but they are not included here since the attenuation was quite large in spite of the large buildup factor. For the same reason the results of 1-Mev photons incident at an angle of 60 deg were also omitted.) The buildup factors for energy and dose obtained in this calculation were compared with those obtained by use of the moments method[1] for monoenergetic, plane monodirectional sources normally incident upon a semi-infinite, homogeneous medium.

Table 1. Normal Thicknesses of a Lead-Water Slab Shield

	Thickness			
		mfp		
Region	cm	1 Mev	3 Mev	6 Mev
Pb	11.58	9.089	5.654	5.878
H_2O	35.81	2.542	1.382	0.996
Total	47.40	11.630	7.035	6.874

1. H. Goldstein and J. E. Wilkins, Jr., Calculations of the Penetration of Gamma Rays, NYO-3075 (June 30, 1954).

Table 2. Dose Equivalent for Incident Flux

E(Mev)	$D_o/\phi_I \left(\frac{mr/hr}{\gamma/cm^2 sec}\right)$
1	0.001923
3	0.004368
6	0.007206

The thicknesses of the lead-water shield in centimeters and in mean free paths for the various incident gamma-ray energies are given in Table 1. Table 2 gives the tissue dose equivalent for the incident flux (no shield present).

The results of the calculations for 1-Mev photons are presented in Figs. 1 through 4, those for 3-Mev photons in Figs. 5 through 10, and those for 6-Mev photons in Figs. 11 through 16. An index to the figures is shown in Table 3.

The normalized energy flux for the 1-, 3-, and 6-Mev energy groups is plotted in Figs. 1, 5, and 11, respectively,as a function of the normal thickness of the shield in centimeter units. The uncollided energy flux, normalized to unity at the initial boundary, is also plotted. The third curve in each figure is the energy buildup factor, B_E, which is the ratio of the two energy flux curves:

$$B_E \equiv \frac{\phi_E/E_o\phi_I}{e^{-t/\lambda}} \equiv \frac{\phi_E}{E_o\phi_I e^{-t/\lambda}}$$

where

ϕ_E(Mev/cm^2 sec) = energy flux at the point of interest in the shield,

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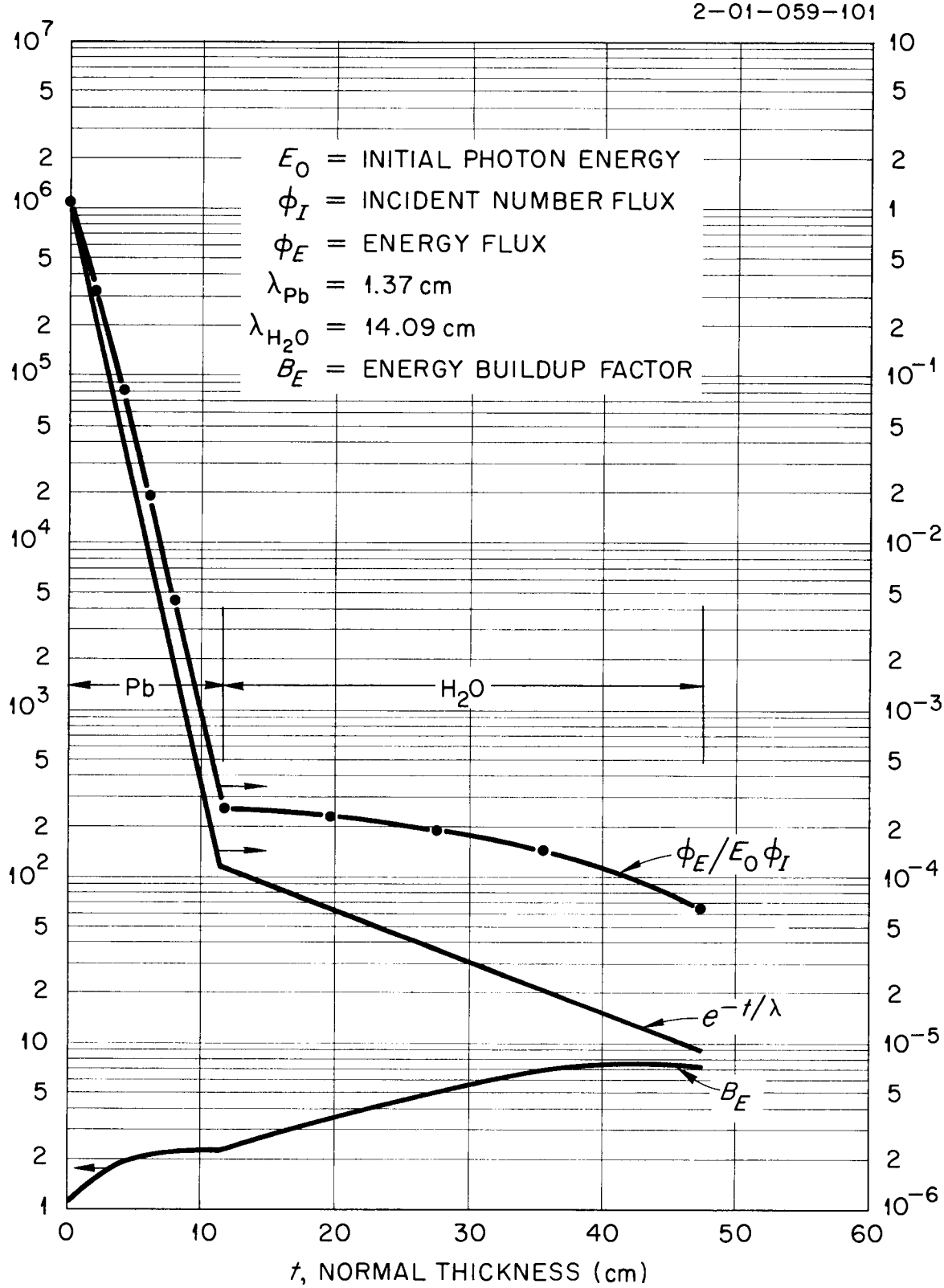

Fig. 1. Gamma-Ray Energy Flux and Energy Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 1-Mev Normally Incident Photons.

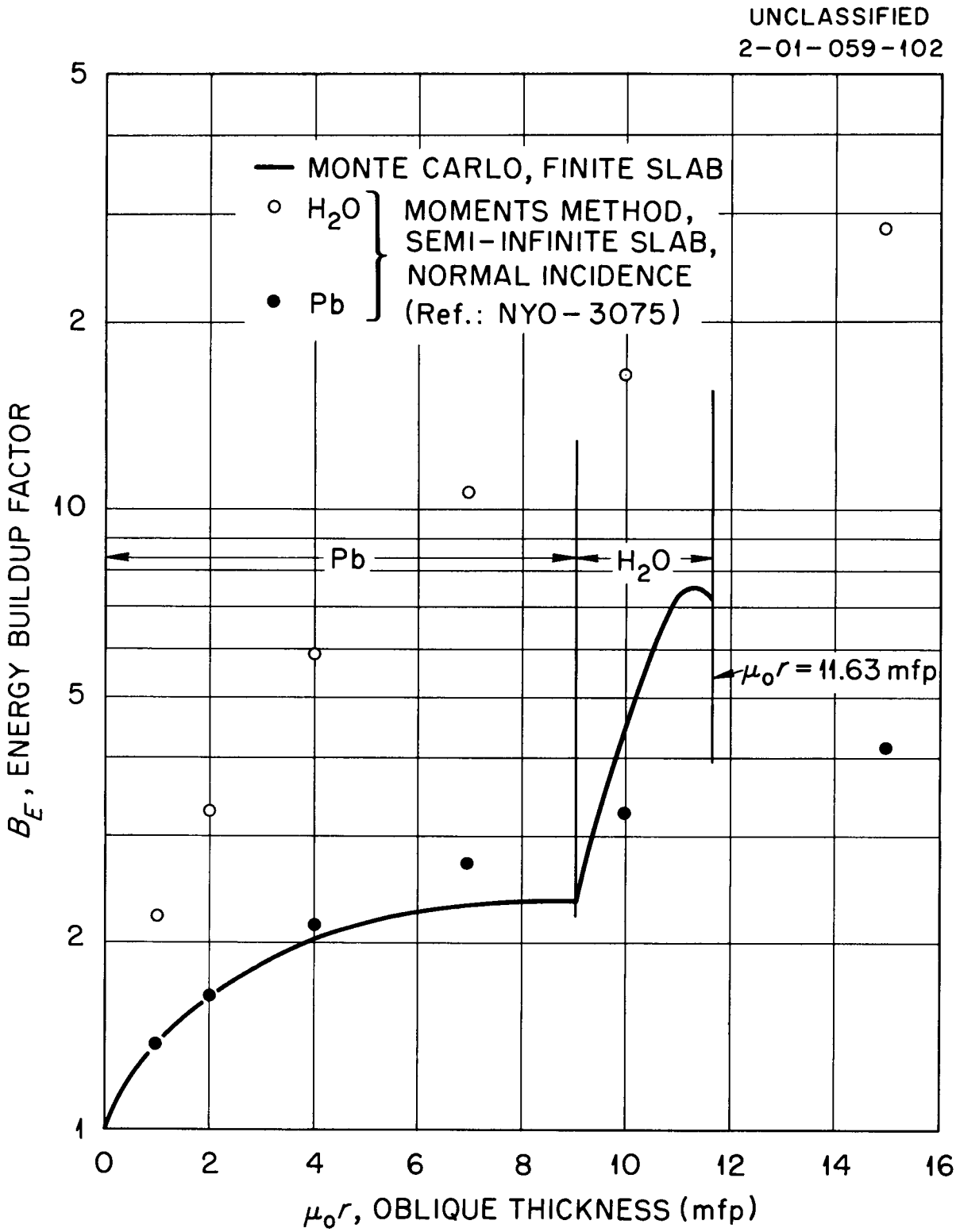

Fig. 2. Gamma-Ray Energy Buildup Factor as a Function of the Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield. 1-Mev Normally Incident Photons.

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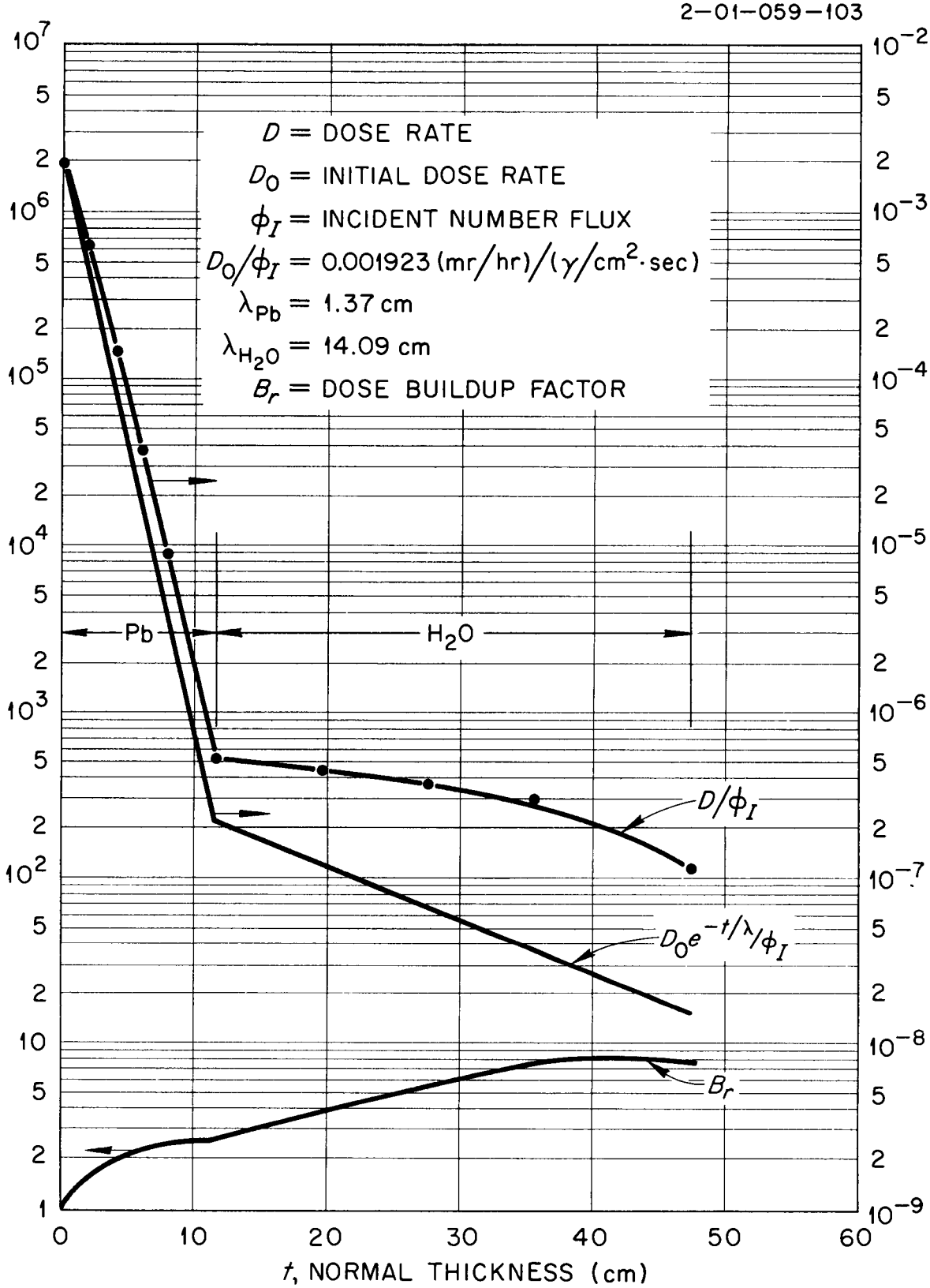

Fig. 3. Gamma-Ray Dose Rate and Dose Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 1-Mev Normally Incident Photons.

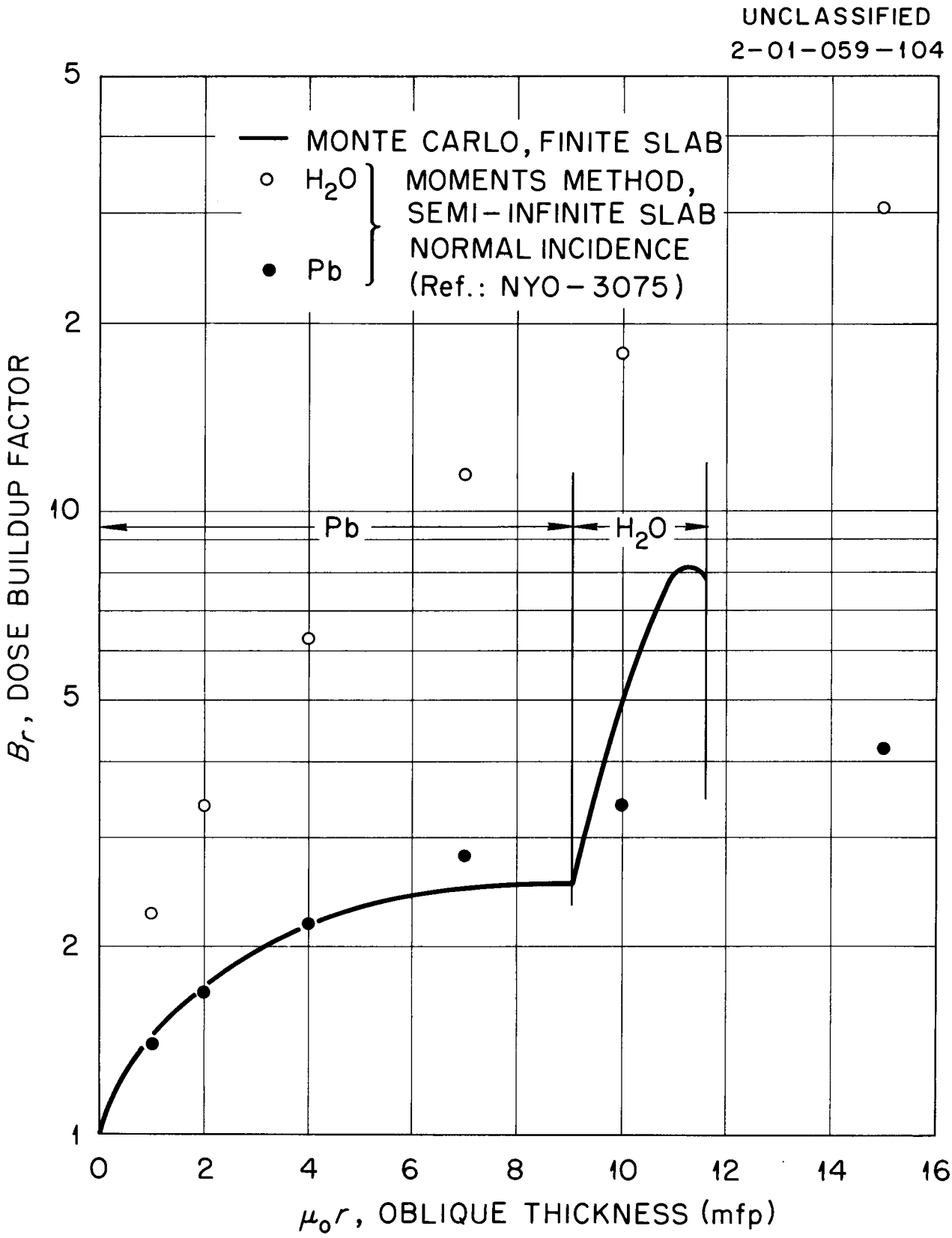

Fig. 4. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Lead-Water Slab Shield. 1-Mev Normally Incident Photons.

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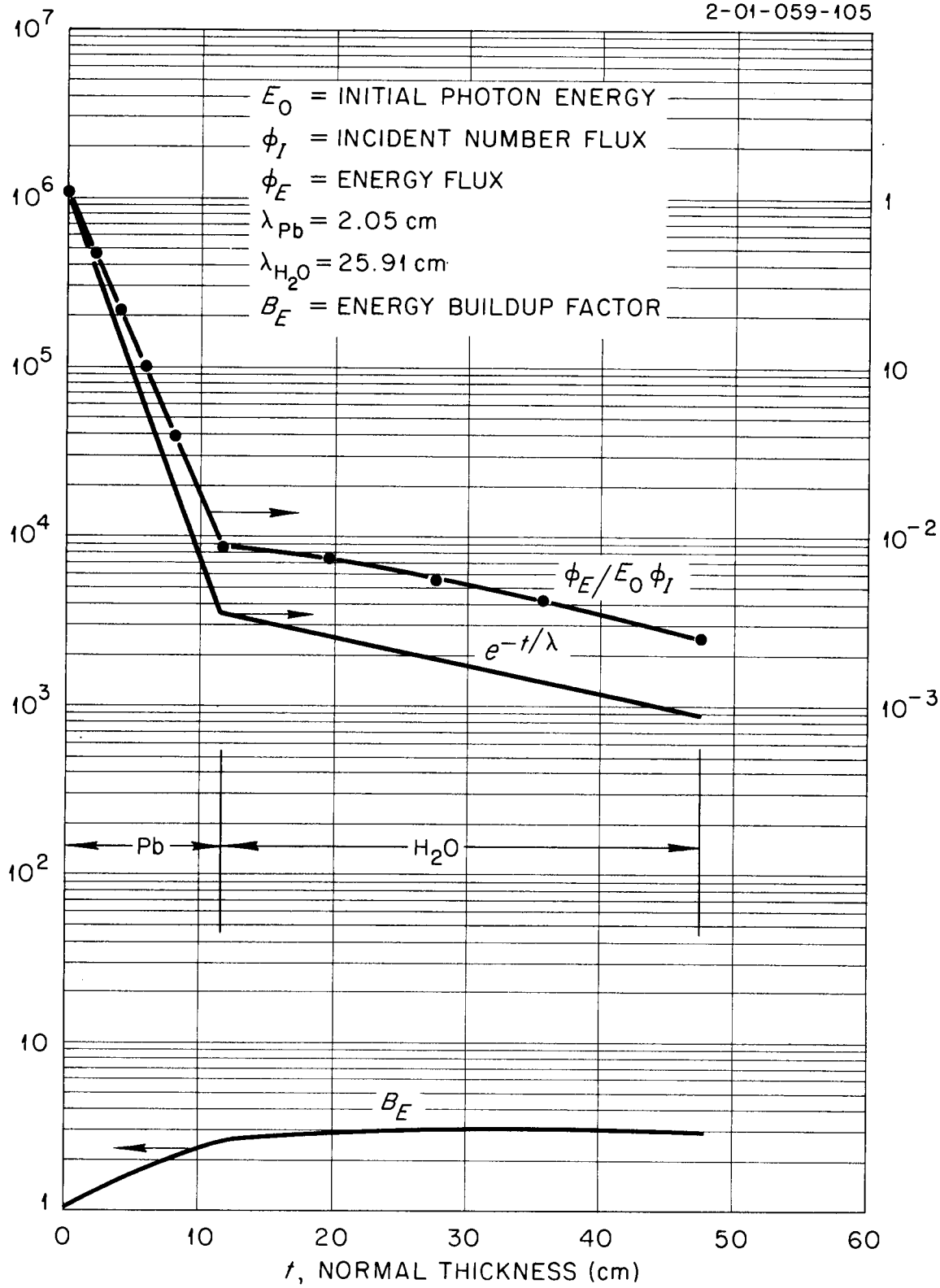

Fig. 5. Gamma-Ray Energy Flux and Energy Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 3-Mev Normally Incident Photons.

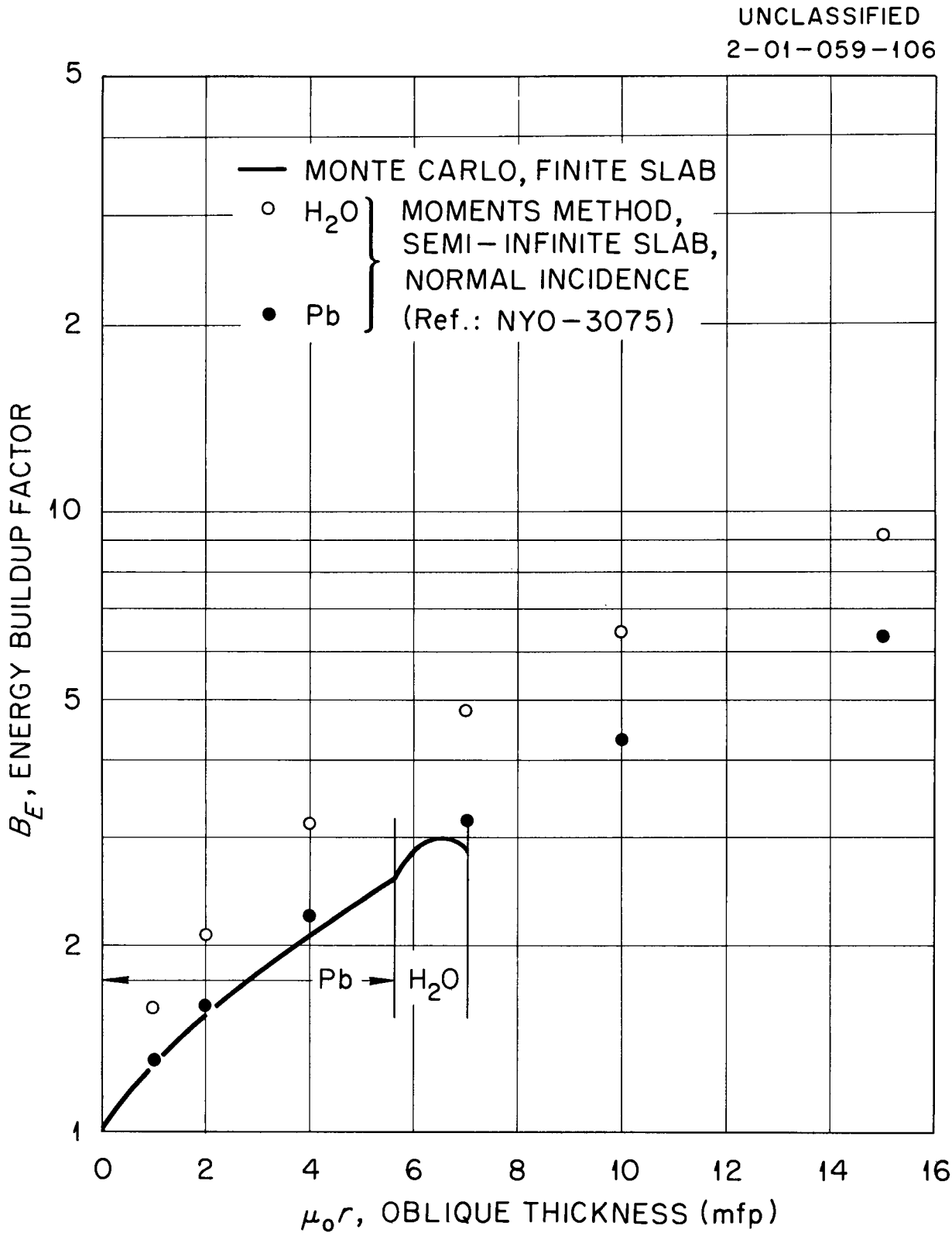

Fig. 6. Gamma-Ray Energy Buildup Factor as a Function of the Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield: 3-Mev Normally Incident Photons.

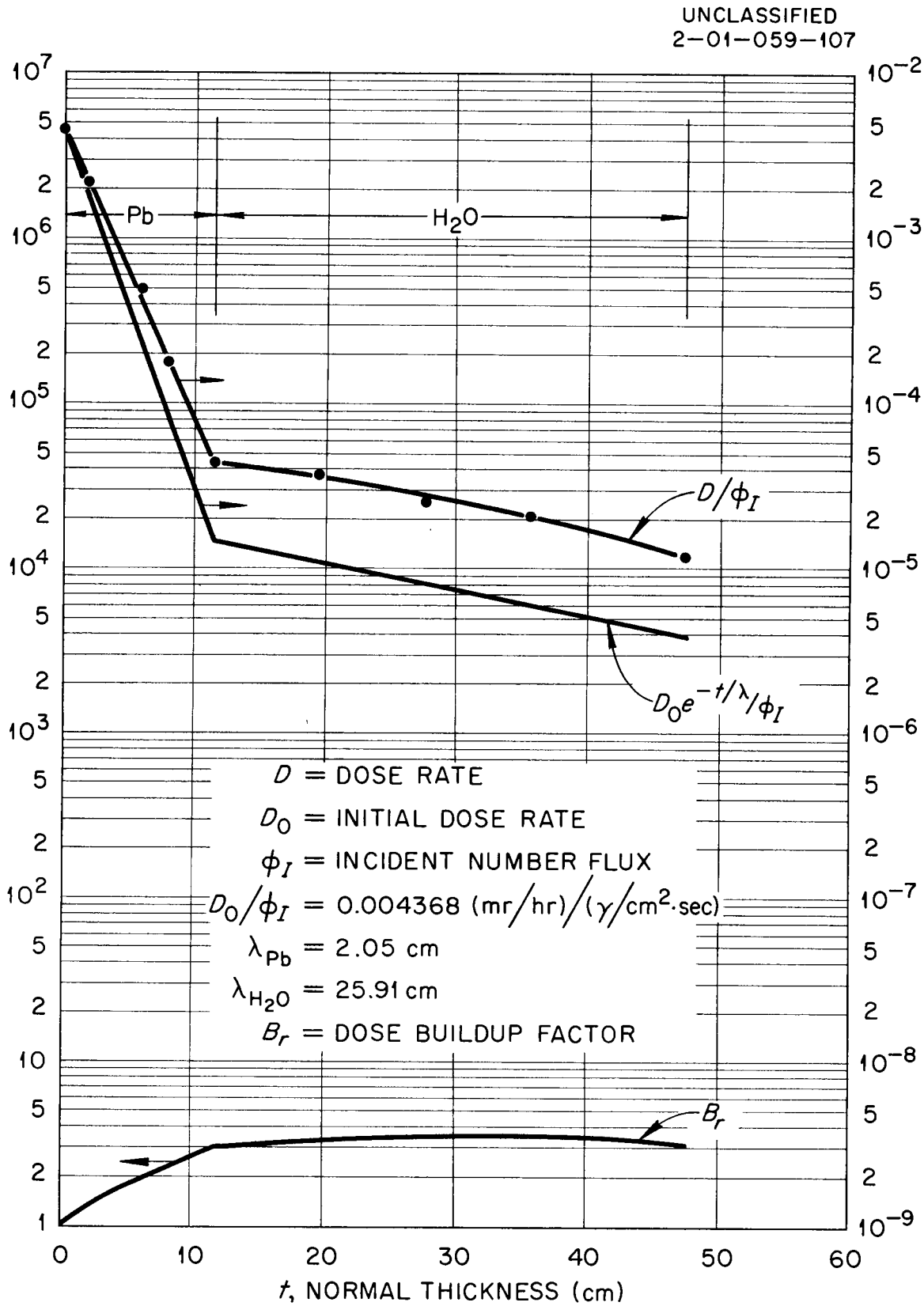

Fig. 7. Gamma-Ray Dose Rate and Dose Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 3 Mev Normally Incident Photons.

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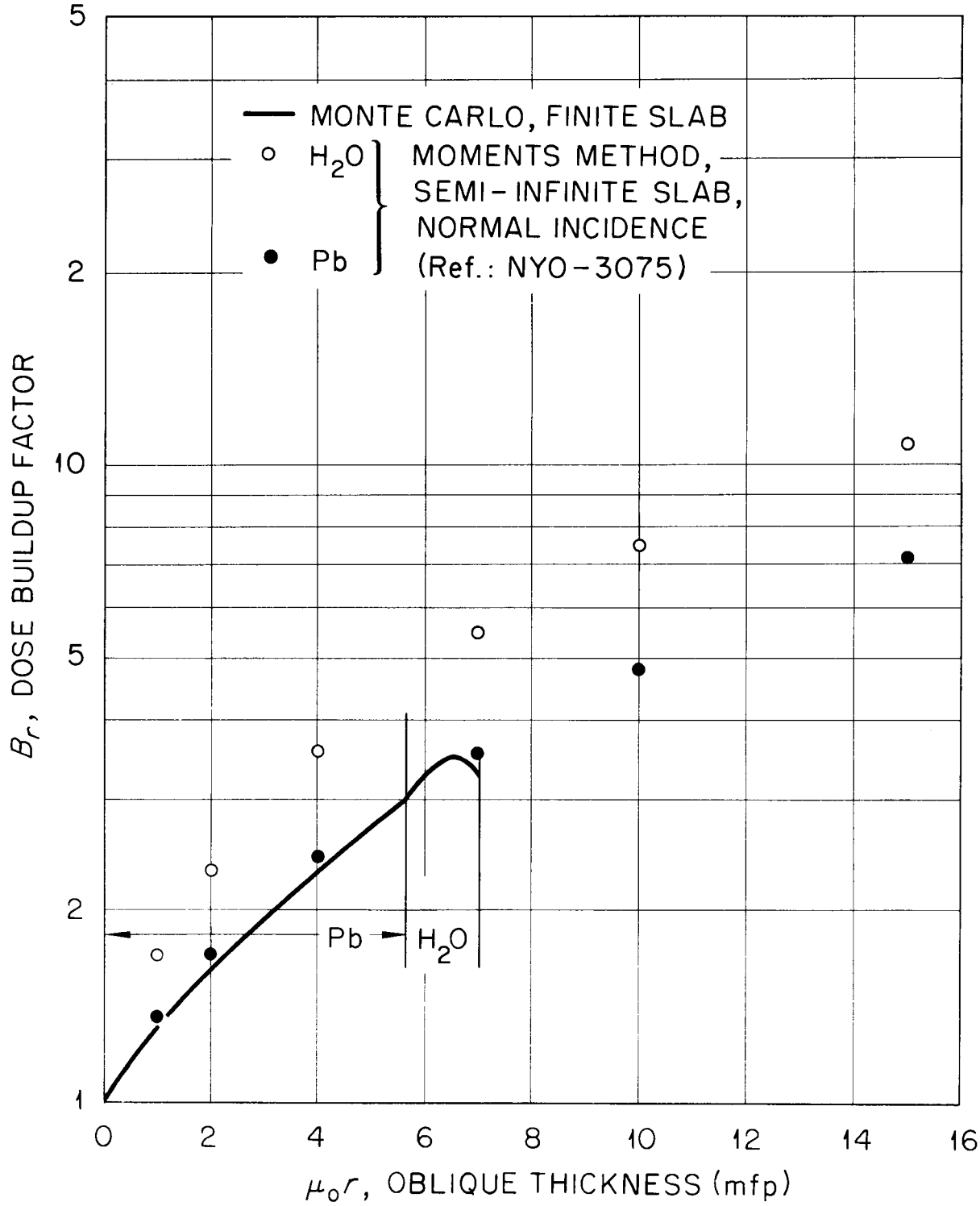

Fig. 8. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield. 3-Mev Normally Incident Photons.

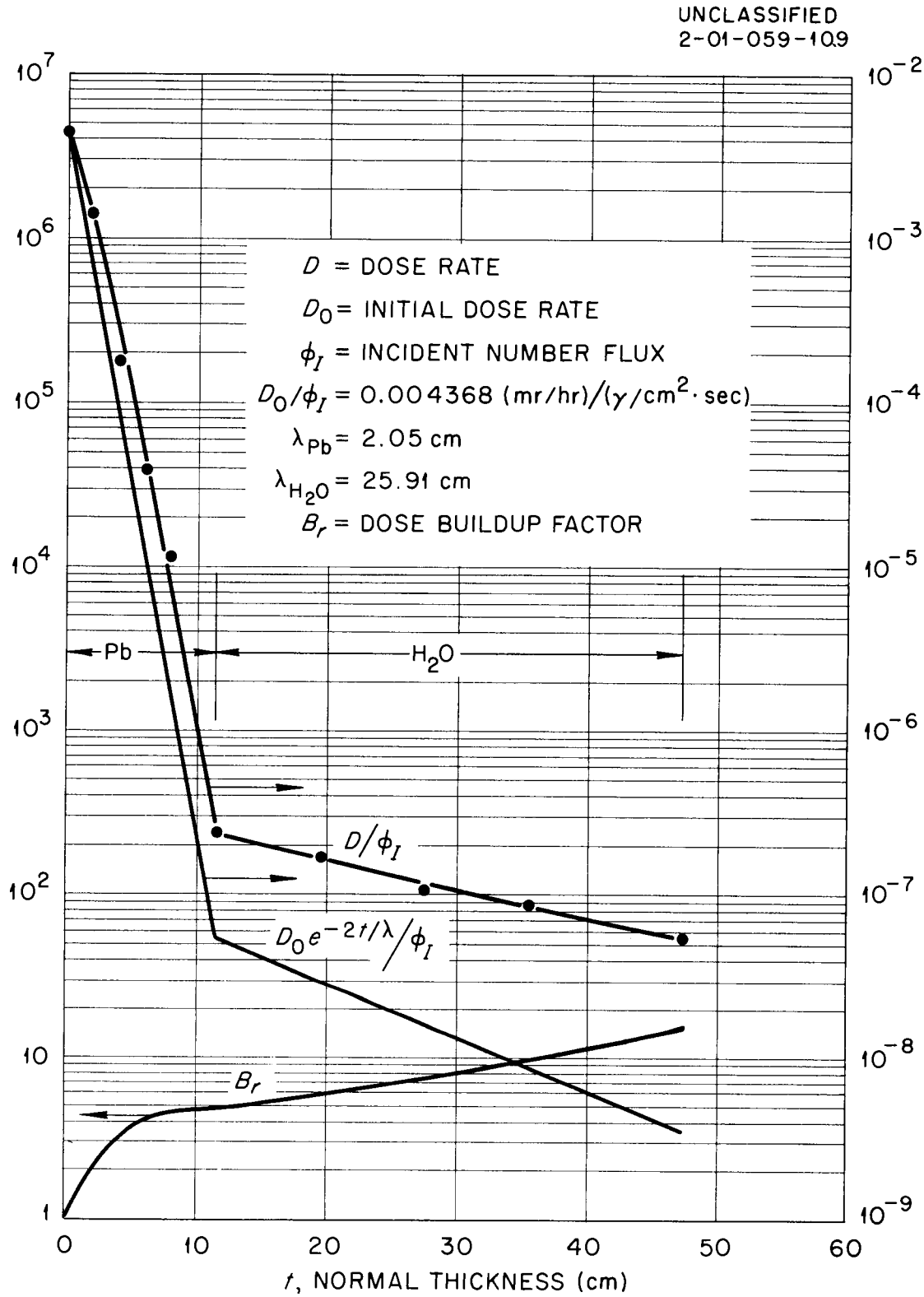

Fig. 9. Gamma-Ray Dose Rate and Dose Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 3-Mev Photons Incident at a 60-deg Angle.

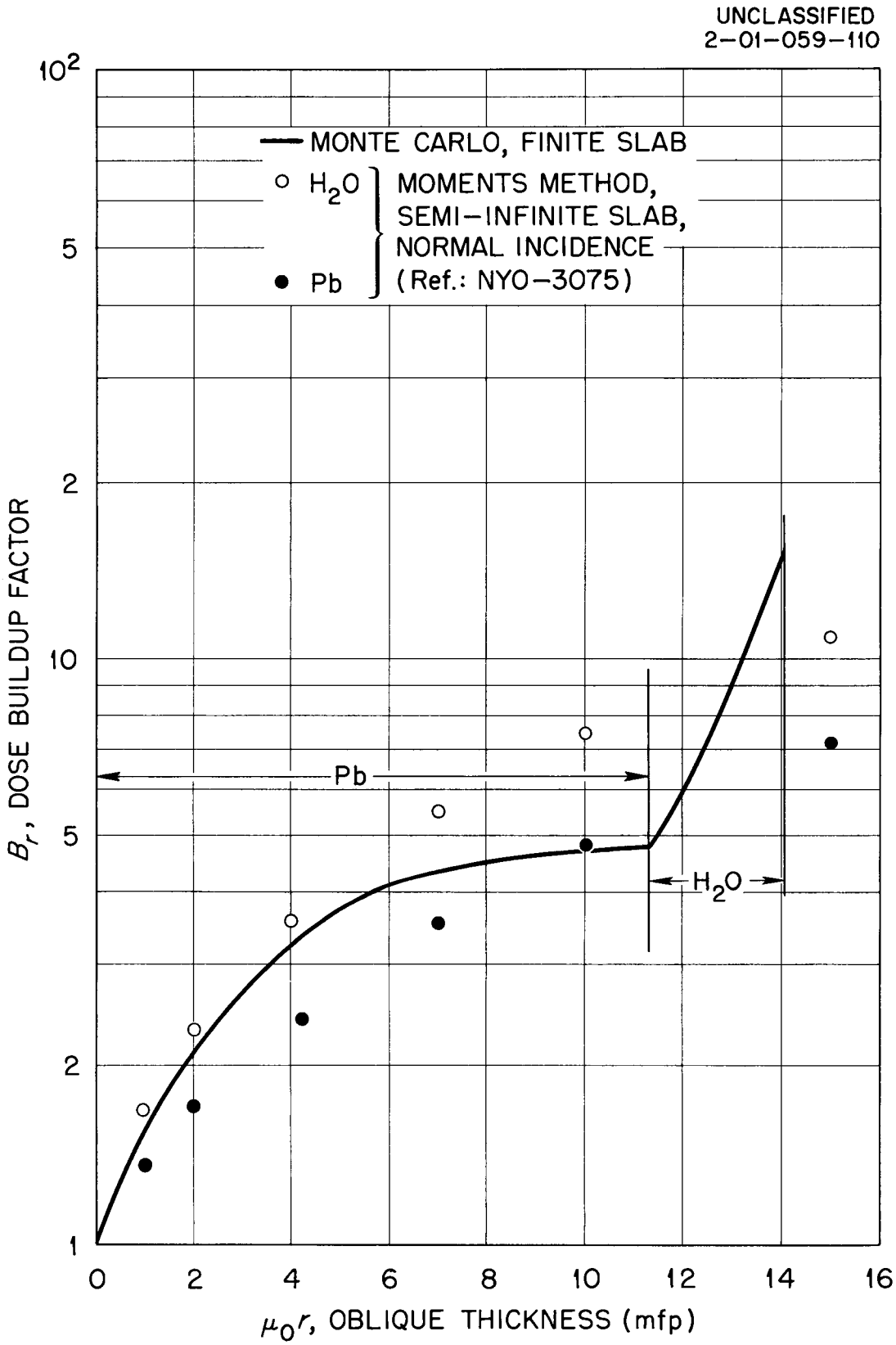

Fig. 10. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield. 3-Mev Photons Incident at a 60-deg Angle.

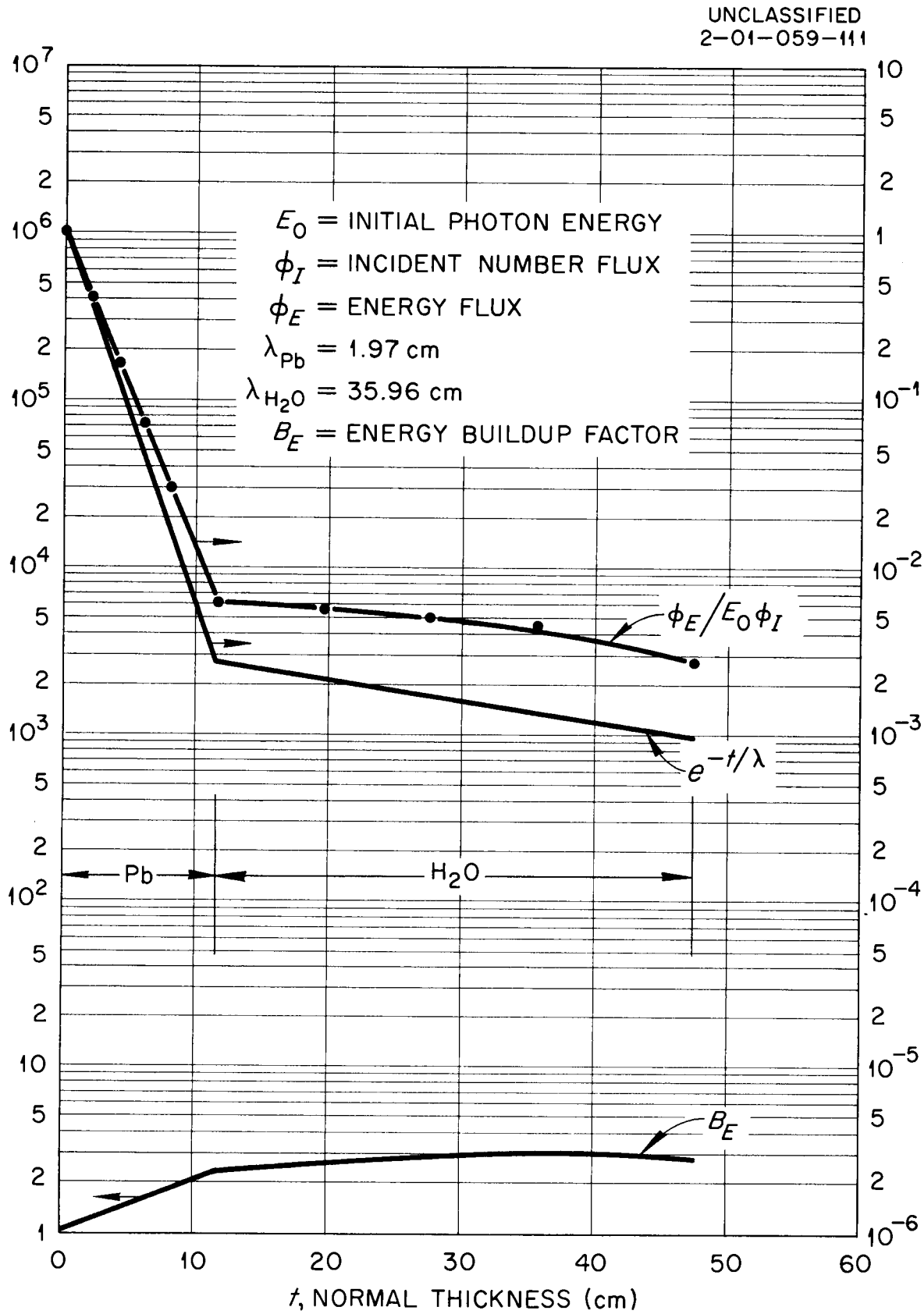

Fig. 11. Gamma-Ray Energy Flux and Energy Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 6-Mev Normally Incident Photons.

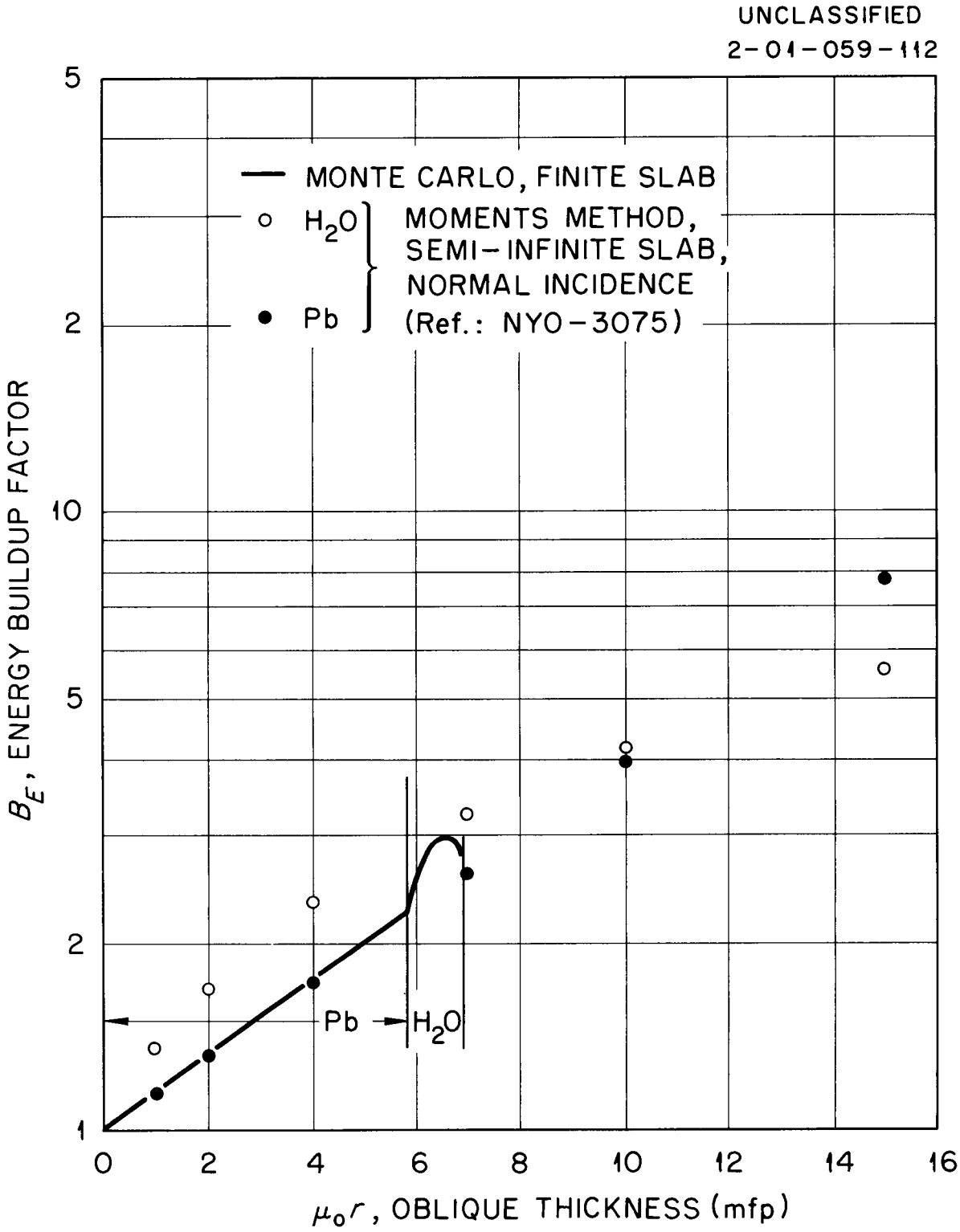

Fig. 12. Gamma-Ray Energy Buildup Factor as a Function of the Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield. 6-Mev Normally Incident Photons.

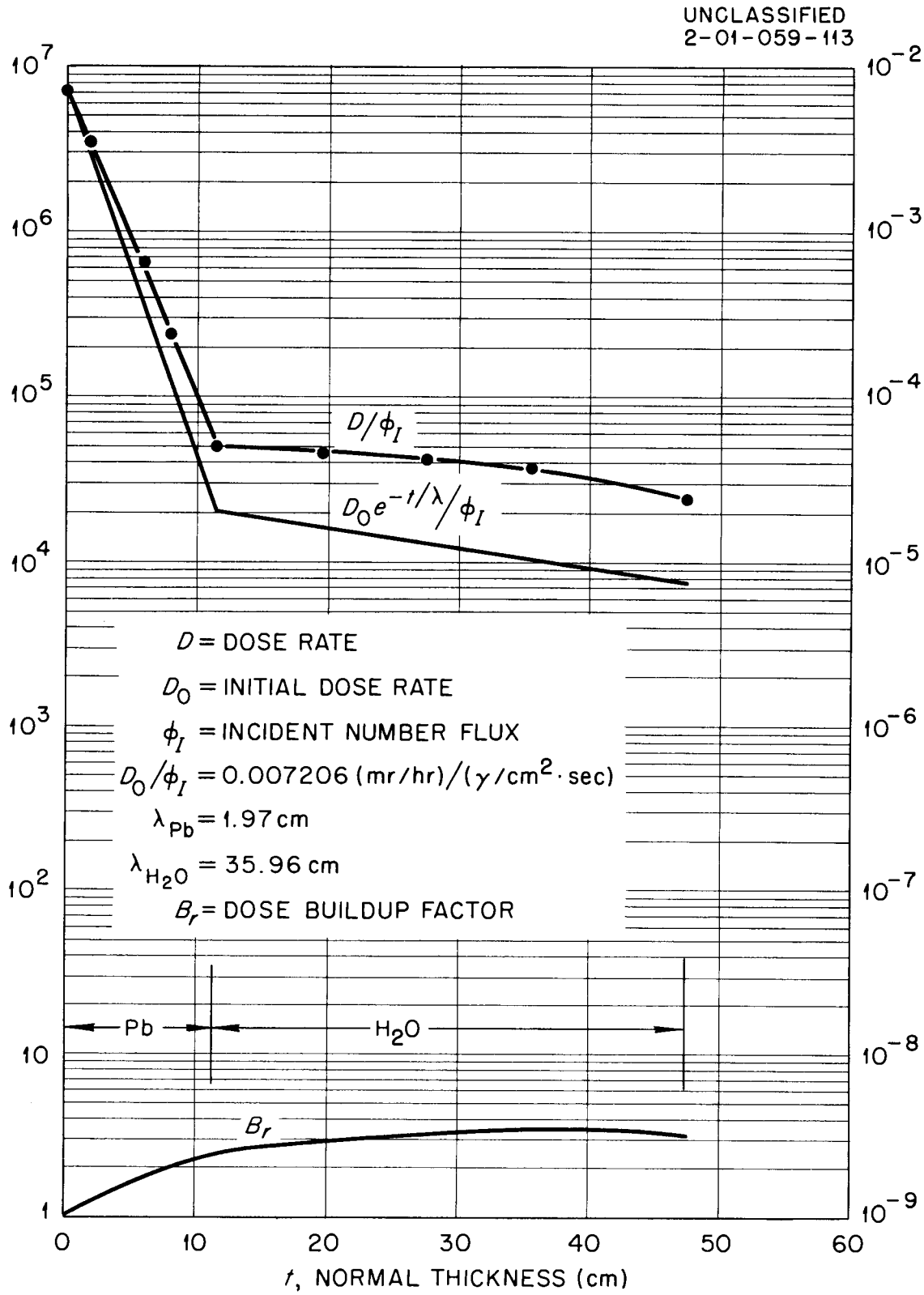

Fig. 13. Gamma-Ray Dose Rate and Dose Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Lead-Water Slab Shield: 6-Mev Normally Incident Photons.

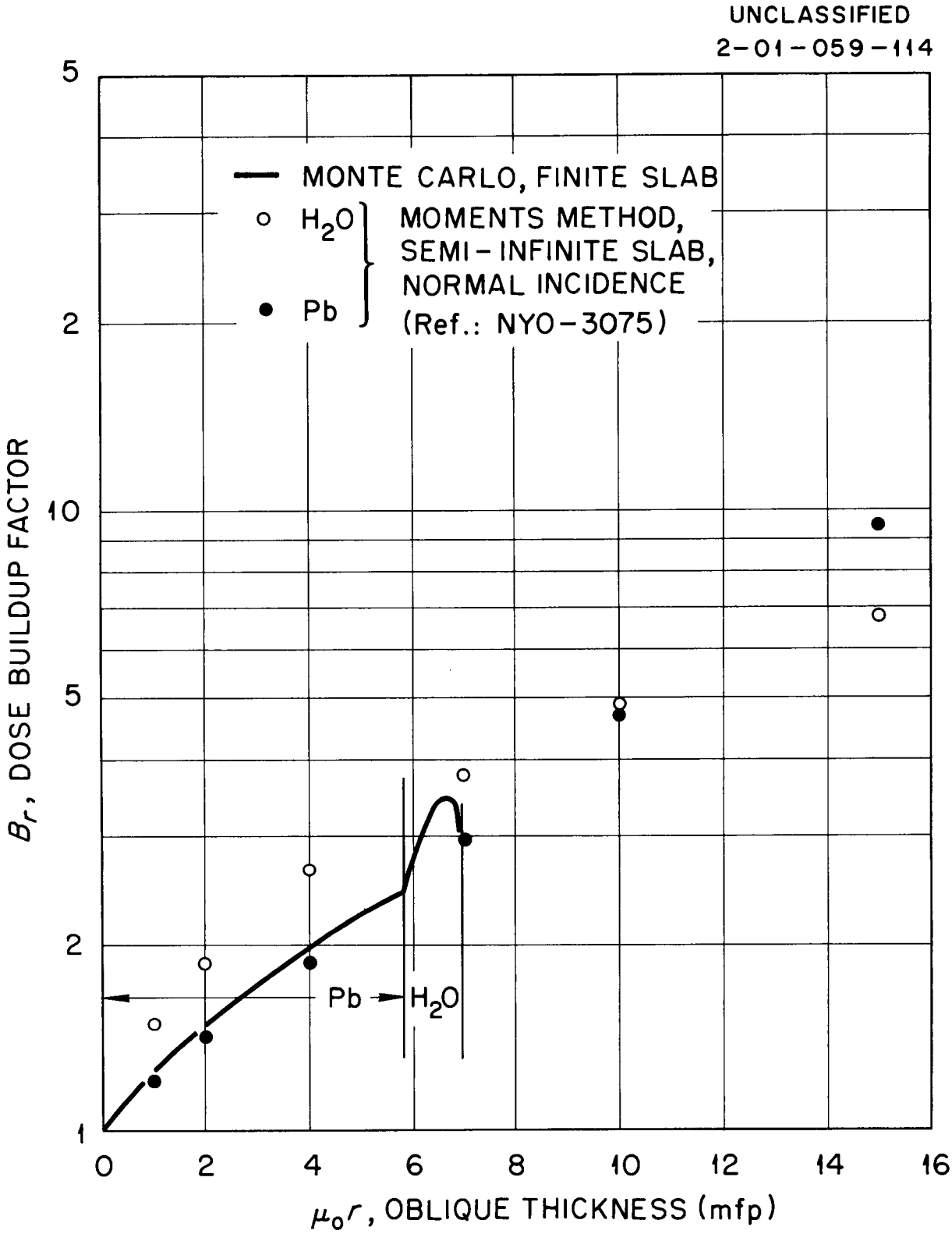

Fig. 14. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shield. 6-Mev Normally Incident Photons.

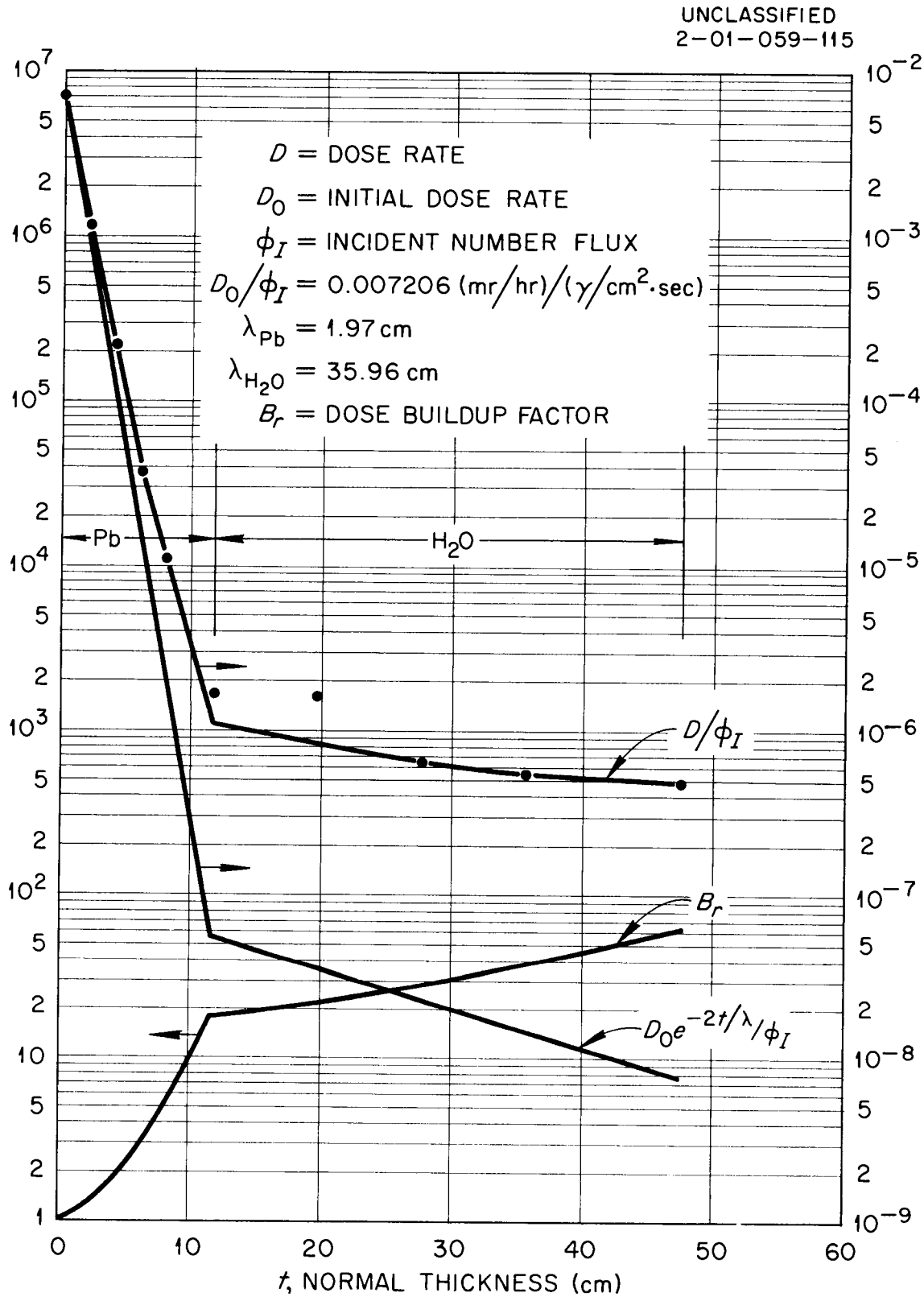

Fig. 15. Gamma-Ray Dose Rate and Dose Buildup Factor as a Function of the Normal Thickness (Centimeters) of a Finite Lead-Water Slab Shield: 6 Mev Photons Incident at a 60-deg Angle.

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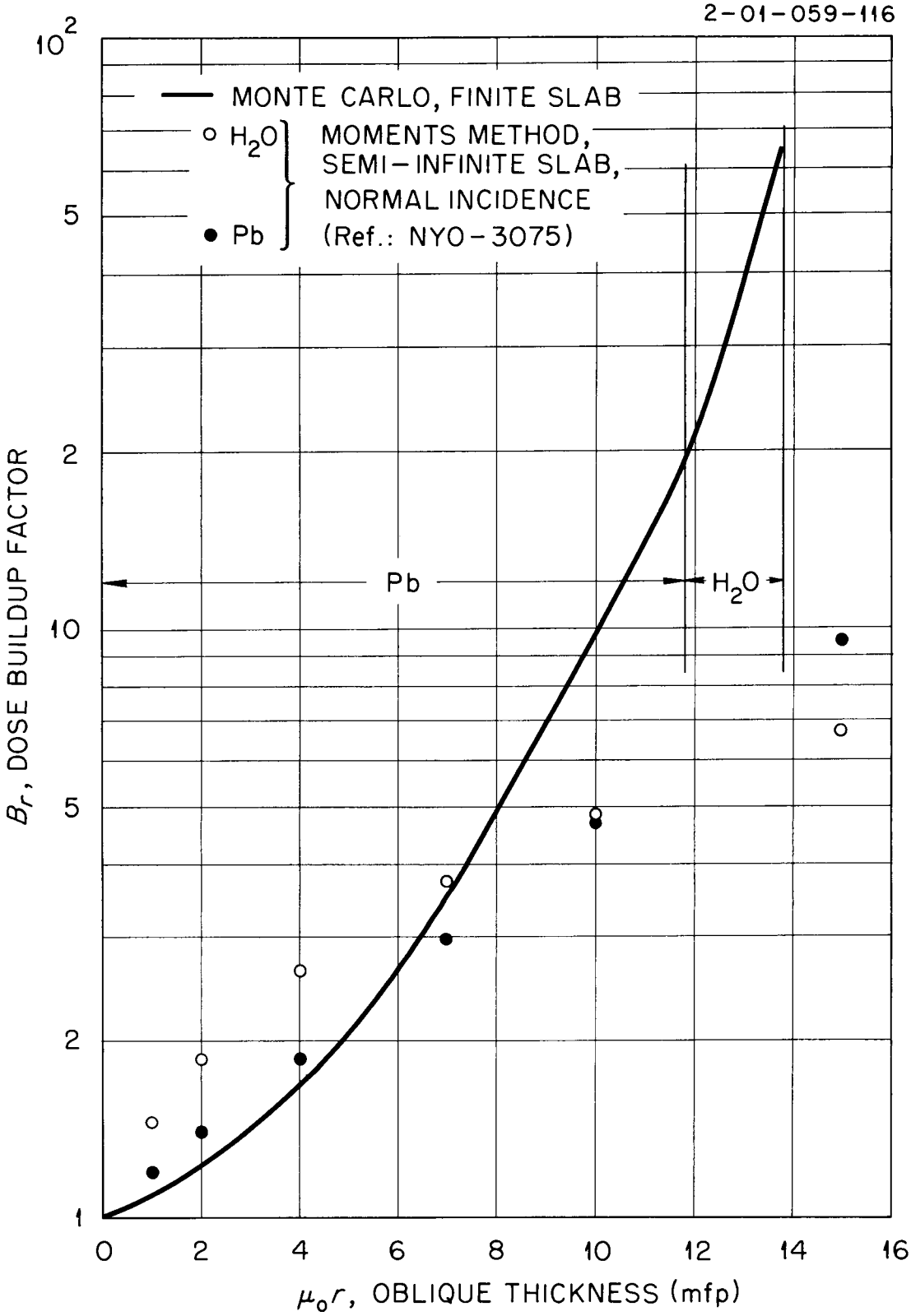

Fig. 16. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead-Water Slab Shields. 6-Mev Photons Incident at a 60-deg Angle.

Table 3. Index to Plotted Data

Fig. No.	Parameters: Shield: Pb-H_2O	Shield: Pb	Energy (Mev): 1	Energy (Mev): 3	Energy (Mev): 6	Angle of Incidence (deg): 0	Angle of Incidence (deg): 60	Plotted Data[a,b] — This Calculation: $\phi_E/E_o\phi_I$	$e^{-t/\lambda}$	B_E	D/ϕ_E	$D_o e^{-t \sec\theta/\lambda}/\phi_I$	B_r	Comparison Data: B_E	B_r
1	x		x			x		N	N	N					
2	x		x			x				O				O	
3	x		x			x					N	N	N		
4	x		x			x							O		O
5	x			x		x		N	N	N					
6	x			x		x				N				O	
7	x			x		x					N	N	N		
8	x			x		x							O		O
9	x			x			x				N	N	N		
10	x			x			x						O		O
11	x				x	x		N	N	N					
12	x				x	x				O				O	
13	x				x	x					N	N	N		
14	x				x	x							O		O
15	x				x		x				N	N	N		
16	x				x		x						O		O
17		x		x		x					N	O[c]	O		
18		x		x		x							O		O

a. N indicates a plot as a function of the normal thickness in centimeters, while O indicates a plot as a function of the oblique thickness in mean free paths. For a 0-deg angle of incidence the oblique and normal thicknesses are identical.

b. The definitions of the symbols are as follows:
ϕ_E = energy flux at the point of interest,
E_o = initial energy
D_o = initial dose rate,
B_r = dose buildup factor,
λ = relaxation length.
ϕ_I = number flux at the initial boundary,
B_E = energy buildup factor,
D = dose rate at the point of interest,
t = distance between the initial boundary and the point of interest.

c. Actually a plot of $D_o e^{-t/\lambda}/\phi_I$.

$E_o(\text{Mev}/\gamma)$ = initial photon energy,

$\phi_I(\gamma\text{'s/cm}^2\text{ sec})$ = number flux incident on shield,

$t(\text{cm})$ = distance between the initial boundary and the point of interest in the shield,

$\lambda(\text{cm})$ = relaxation length,

$e^{-t/\lambda}$ = uncollided energy flux at the point of interest.

In a similar manner the normalized dose rate and dose buildup factor, B_r, for the three energies are plotted in Figs. 3, 7, 9, 13, and 15. Here

$$B_r = \frac{D/\phi_I}{D_o e^{-t\ \sec\theta/\lambda}/\phi_I} = \frac{D}{D_o\ e^{-t\ \sec\theta/\lambda}}$$

where

$D(\text{mr/hr})$ = dose rate (tissue) at the point of interest,

$D_o(\text{mr/hr})$ = dose rate (tissue) of the uncollided incident photons at the initial boundary.

The various energy buildup factors as a function of oblique thickness, in mean free paths, are presented in Figs. 2, 6, and 12. Corresponding dose buildup factors are given in Figs. 4, 8, 10, 14, and 16. Data from the results of the moments method solution[1] are also plotted for purposes of comparison, although it must be remembered that those calculations were for infinite homogeneous media and are not directly comparable to the present calculations for a finite two-region slab. The calculations for lead do agree reasonably well for the first few relaxation lengths where the effects stemming from the dissimilarity of the slabs should be least.

The dose rate and dose buildup factors resulting from an earlier Monte Carlo calculation for 3-Mev photons normally incident upon a one-region

8-mfp-thick lead shield[2] are also presented (Figs. 17 and 18) as an example of a case intermediate between the Monte Carlo calculation for a two-region finite shield and the moments method solution for the one-region semi-infinite shield. A comparison of the dose rate in the one-region finite shield with the dose rate in the one-region semi-infinite shield (calculated from build-up factors reported in Ref. 1) shows good agreement. The characteristic dip near the final boundary of the finite lead shield is apparent.

The dose buildup factors for the 3-Mev incident photons in the two-region and one-region finite shields (Figs. 8 and 18) are identical to within 2 mfp of the lead-water interface. It is apparent that at this energy and angle of incidence the back scattering is important in lead for a distance of about 4 cm (λ_{Pb} = 2.05 cm at 3 Mev). The scattering in the water tends to compensate for the finite thickness of the lead-water slab. It can also be concluded that the back-scattered flux at that interface is about 12% of the total flux and about 20% of the scattered flux. The differences for the finite and the semi-infinite one-region shields (Fig. 18) are partially due to differences in the cross section data used for the calculations. An extensive discussion of the errors in the calculations from the moments method is included in Ref. 2. Consistent errors may exist that will bias the answers obtained with that method. The Monte Carlo data is much less subject to bias than to statistical fluctuation. (The large fluctuation of the data in Fig. 9 may indicate a relatively large error, but this is still probably less than 10%.)

Since the Monte Carlo calculations for the two-region finite shield and the moments method solution for the one-region semi-infinite shield were in

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2. S. Auslender, unpublished work.

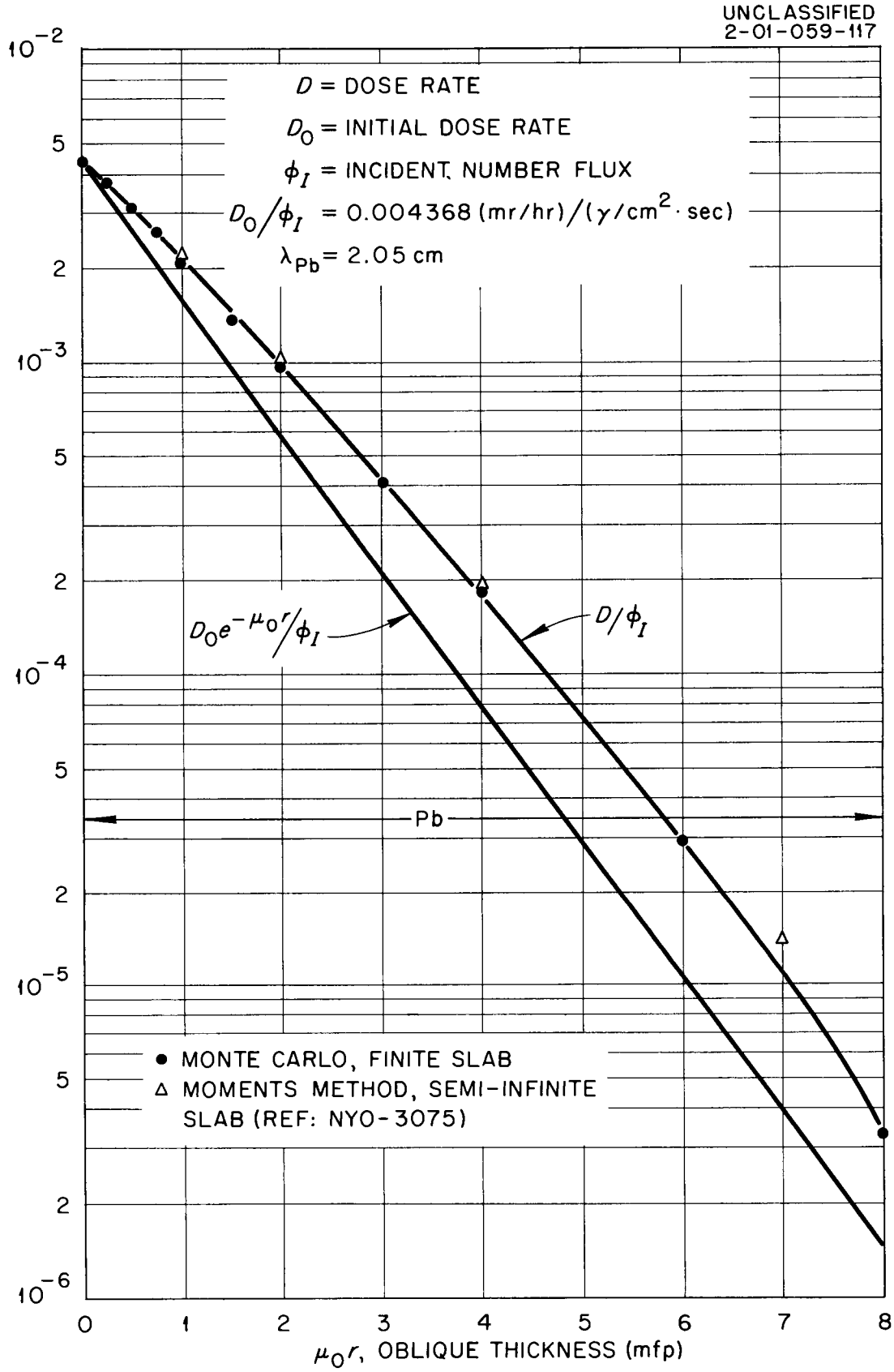

Fig. 17. Gamma-Ray Dose Rate as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead Slab Shield: 3-Mev Normally Incident Photons.

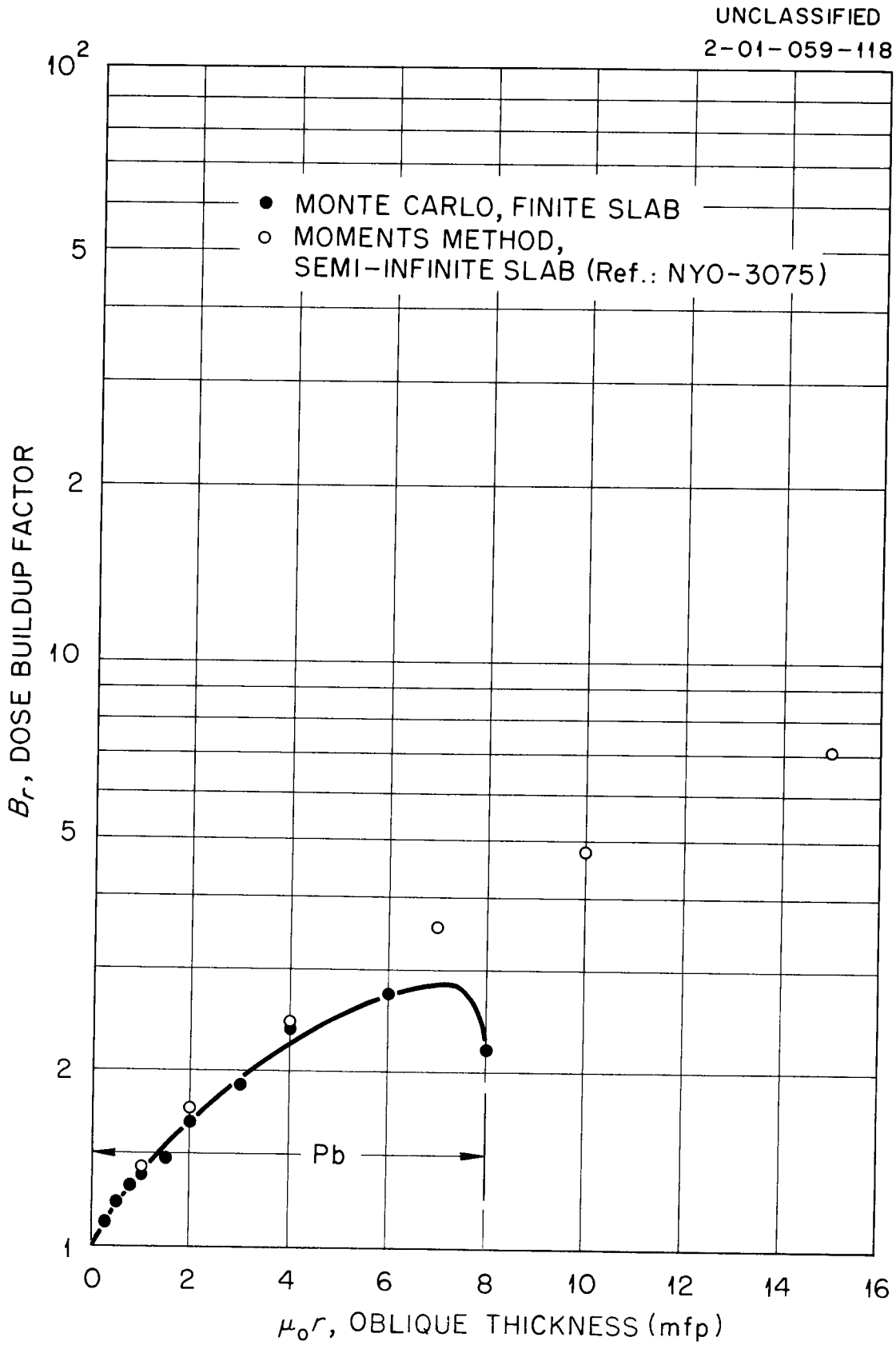

Fig. 18. Gamma-Ray Dose Buildup Factor as a Function of Oblique Thickness (Mean Free Paths) of a Finite Lead Slab Shield. 3-Mev Normally Incident Photons.

general agreement, the striking differences in the buildup factors near the lead-water interface and near the final boundary should be enlightening. In Figs. 2 and 4, for example, the energy and dose buildup factors for 1-Mev photons in a finite two-region shield increase sharply in water to a value about halfway between those for semi-infinite one-region shields of water and lead. At this energy the finite water region is 2-1/2 mfp-thick and at first the buildup increases almost at the same rate as it does initially in the semi-infinite water shield. This confirms that at this energy, which is below the minimum in the total cross section, the uncollided radiation dominates in the penetration of the lead, as it should.

In Figs. 6 and 8 the increase of the buildup factors in the water is very small since for the primary 3-Mev photons for both lead and water the major portion of the total cross section is attributable to scattering. Hence, the difference in the behavior of the flux in water and in lead is due to that small portion of the flux which is absorbed in the lead but is scattered in the water. For 6-Mev photons (Figs. 12 and 14) the absorption cross section of lead is no longer so small that the absorption in it is almost negligible. In this case the buildup factor increases rather abruptly in the water almost to the buildup factor for 6-1/2 mfp at water calculated using the moments method.

It is evident from the results of the calculations for radiation incident at 60 deg (Figs. 9, 10, 15, and 16) that the practice of using only normal incidence data for shield designs can lead to a poor approximation. This problem becomes most acute when the number of mean free paths across the shield is small or when the angular distribution is such that a large portion of

the radiation is not normal or nearly normal to the slab. Figure 16, which shows the flux depression near the initial boundary and the large buildup factor into the slab, is an excellent example of streaming (or short-circuiting).