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SUBJECT: Shielding of Pipes in the HFIR Primary Coolant System

TO: W. R. Gall

FROM: H. A. McLain and L. A. Haack

Summary

Thicknesses of ordinary concrete required to shield pipes in the HFIR primary water system have been computed for normal operating conditions and for abnormal conditions such as a defective fuel plate or a meltdown of the fuel within the reactor. About 6 ft of concrete is required for the pipes at the outlet of the reactor, and 2 ft of concrete is required for the pipes located about 1½ min. downstream from the reactor vessel. These thicknesses of concrete reduce the radiation levels to below the specified tolerances which are: a) 0.75 mr/hr during normal operation or operation with one defective fuel plate; b) 1 r/hr immediately after the meltdown of 1% of the fuel; and c) 1 r/hr 24 hrs after a total fuel meltdown. Shielding thicknesses required for other tolerances may be estimated from graphs and tables presented in the report.

NOTICE

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Introduction

Shielding is being provided for the HFIR primary coolant system to provide protection against the gamma photons released from this system during both the normal and the abnormal conditions in the reactor. During the normal conditions of reactor operation, the water coolant contains N^{16} and Na^{24}. During the abnormal conditions, fission products are present in the cooling water due to a defective fuel plate or a meltdown of the fuel in the reactor.

It is specified that the shielding for the primary coolant system must meet the most stringent of the following requirements:[1]

1. The dose rate at the shield surface is less than 0.75 mr/hr during the operation of the reactor under normal conditions or with a defective fuel plate.

2. The dose rate at the shield surface is less than 1 r/hr immediately following the meltdown of 1% of the fuel within the reactor.

3. The dose rate at the shield surface is less than 1 r/hr 24 hrs after a total meltdown of the fuel within the reactor.

The pipes are assumed to be of an infinite length and the shield material is assumed to be ordinary concrete.

General Method of Calculation

For the calculation of the dose rate from the active material circulating in the coolant water, the source is regarded as an infinite cylinder. The gamma flux then can be calculated by the relation,[2,3]

$$\phi = \frac{BS_V R_0^2 \, F(\frac{\pi}{2}, b_2)}{2(a + z)} \quad . \tag{1}$$

For the calculation of the dose rate from the active material deposited on the surfaces of coolant system, the source is approximated as a number of line sources, say N, by the relation $2\pi R_0 S_A = NS_L$. The gamma flux from each line source can be calculated by the relation,[2,3]

$$\phi = \frac{BS_L \, F(\frac{\pi}{2}, b_1)}{2\pi a} \quad . \tag{2}$$

The various symbols used in these equations are defined in the nomenclature section on page 9.

The buildup factor in these equations is assumed to be of the form[2]

$$B(E_0\ ,\ \mu x) = A_1 e^{-\alpha_1 \mu x} + A_2 e^{-\alpha_2 \mu x} = \sum_{n=1}^{2} A_n e^{-\alpha_n \mu x} \quad . \tag{3}$$

Combining this factor with the above relations,

$$\frac{\phi}{S_V} = \frac{R_0^2 \sum_{n=1}^{2} A_n F(\frac{\pi}{2}\ ,\ b_{2n})}{2(a + z)} \tag{4}$$

and

$$\frac{\phi}{S_L} = \frac{\sum_{n=1}^{2} A_n F(\frac{\pi}{2}\ ,\ b_{1n})}{2\pi a} \quad . \tag{5}$$

Only the buildup factor for ordinary concrete is used since the shield probably will be more than 2 or 3 relaxation lengths in thickness. Values of the constants in the buildup factor relation and factors for converting the gamma flux at the shield surface into the dose rate used in these calculations are those given by Rockwell.[2]

Four sizes of pipes which possibly may be used in the HFIR primary coolant system are considered. They are:

a. 1 in. Sch. 10

b. 16 in. with ½ in. wall

c. 24 in. with 5/8 in. wall

d. 36 in. with 1 in. wall .

For these calculations, the pipe walls are assumed to be iron of a density of 8.0 g/cc. The density of the ordinary concrete shield is assumed to be 2.3 g/cc.

Shielding of Gammas from N^{16} Decay

During the normal operation of the HFIR, the gamma activity in the water discharging from the reactor vessel is dominated by the gammas resulting from the rapid decay of the N^{16} in the water. A curve showing the N^{16} activity in the water discharging from the reactor vessel is shown in Fig. 1.[4] Gamma photons of 6.13 Mev energy are given off in 75.9% of the N^{16} disintgrations and of 7.10 Mev energy in 6.1% of the disintegrations.[5]

Factors for converting the N^{16} activity in the water into dose rates at the surface of various thicknesses of the concrete shield are shown in Figs. 2 through 5. These factors were obtained using equation 4. Assuming the permissible dose rate at the outside shield surface is 0.75 mr/hr, the required thicknesses of ordinary concrete to shield the pipes containing the water discharging from the pressure vessel were calculated using Figs. 1 through 5. Results of these calculations are shown in Figs. 6 through 9.

Shielding of Gammas from Na^{24} Decay

After the N^{16} in the coolant water has decayed, the gamma activity in the water is dominated by the gamma photons released during the decay of Na^{24}.[6] Since the half life of Na^{24}, 15.06 hr, is large compared to the water circuit time in the primary loop, about 2 min, the concentration of this isotope in the primary coolant is assumed to be uniform. The Na^{24} activity in the primary coolant water is estimated to be 9.3×10^3 dis/sec-ml for a water pH of 7 and 2.3×10^3 dis/sec-ml for a water pH of 5.[7] A water pH of 7 is assumed here because the activity is higher. Each disintegration of a Na^{24} isotope results in the release of a 1.38 Mev gamma photon and a 2.76 Mev gamma photon.

Factors for converting the Na^{24} activity in the water into dose rate at the surface of various thicknesses of the concrete shield are shown in Figs. 10 through 13. These factors were also obtained using equation 4. Again assuming the permissible dose rate at the outside shield surface is 0.75 mr/hr, the required thicknesses of ordinary concrete to shield the pipes containing the water were calculated using the conversion factors shown in Figs. 10 through 13 and a Na^{24} activity of 9.3×10^3 dis/sec-ml. Results of these calculations are shown in Figs. 6 through 9.

Shielding of Gammas from the Decay of Fission Products Released during a Fuel Meltdown

Shielding also is being provided for the primary coolant system for protection in case of a meltdown of the fuel within the reactor. The gamma photon sources immediately following the meltdown of 1% of the fuel within the reactor and 24 hrs following the meltdown of all of the fuel within the reactor have been estimated[8] and are shown in Table I. Since part of the fission products released during the meltdown are adsorbed on the surfaces of the coolant system, the gamma sources are divided into volumetric sources and surface sources. For the convenience of the shielding calculations, these sources are divided also into four energy ranges.

To calculate an average energy for each of the energy ranges shown in Table I, a gamma spectrum is assumed. It is assumed that the number of gamma photons of energy E Mev given off per decay is proportional to a $e^{-1.24E}$ which is the same as that given off per fission in the reactor.[9] Although this assumption is incorrect, it is sufficiently accurate for the purposes of these calculations. A more accurate method is to consider each gamma photon energy separately, but this amount of effort is not warranted here. Assuming this proportionality, the average energy for each energy range is calculated to be

Energy Range	Average Energy
$\leqslant$ 0.25 Mev	0.147 Mev
0.26 $\leqslant$ 1.00	0.544
1.01 $\leqslant$ 1.70	1.308
$\geqslant$ 1.71	2.506

Factors for converting the gamma activity due to the decay of fission products dissolved in the water into dose rates at the surface of various thicknesses of concrete shield are shown in Table II. These were obtained using equation 4. Similar factors for converting the gamma activity due to the decay of fission products deposited on the pipe surfaces are shown in Table III. These were obtained using equation 5. The number of conversion factors for the latter case is limited since the effort for making these particular calculations is relatively large. Such an amount of work is not warranted at the present time.

The dose rates at a concrete shield surface following a fuel element meltdown are shown in Table IV and Figs. 14 and 15. Of course, the number of cases shown here is limited also because of the limited number of conversion factors in Table III. Assuming that the permissible dose rate at the shield surface is 1 r/hr immediately following the meltdown of 1% of the fuel and 1 r/hr 24 hours after a total fuel meltdown, it appears that 2 ft of ordinary concrete is sufficient for protection.

Shielding of Gammas from the Decay of Fission Products Released from a Defective Fuel Plate

A crude estimate of the fission product activity in the HFIR primary cooling system resulting from a defective fuel plate is made with the following assumptions:

a. Clad defect area is 0.01 in.^{2}

b. Activity is added to the water by the corrosion of the U-Al alloy (activity added by recoil is neglected)

c. Corrosion rate of the U-Al alloy is 2 mils per day

d. Volume percent of uranium in the alloy is 5.8

e. Density of uranium is 18.5 g/cc

f. Uranium in core is 6.0 kg

g. Reactor power level is 100 Mw

h. Coolant system volume is 30,000 gal

i. Coolant system cleanup rate is 200 gpm .

On the bases of the buildup of activity in uranium shown by Blomeke and Todd[10] and the above assumptions, the rate of addition of the activity to the water after 10 days operation at 100 Mw is 16.7 curies per day. Neglecting the decay of the fission products and the deposition of the fission products on the coolant system surfaces, the fission product activity in the water is

$$\frac{(16.7)(3.7 \times 10^{10})}{(200)(24)(60)(3.785 \times 10^{3})} = 5.7 \times 10^{2} \frac{\text{dis}}{\text{sec ml}} \quad .$$

Referring back momentarily to the total meltdown of the fuel within the reactor, the fission product activity in water (neglecting the fission product deposition on the walls) is 1.4×10^{10} dis/sec-ml immediately after the meltdown of the fuel and 1.8×10^{8} dis/sec-ml 24 hours after the meltdown of the fuel.[8] As shown in Figs. 14 and 15, these activities are equivalent to dose rates at the surface of a 2 ft concrete shield of 30 r/hr and 66 mr/hr. Comparing these activities and dose rates with the water activity due to a defective fuel plate shown above, the dose rate at the surface of a 2 ft concrete shield due to a defective fuel plate is estimated to be

$$\frac{(30 \times 10^{3})(5.7 \times 10^{2})}{(1.4 \times 10^{10})} = 1.2 \times 10^{-3} \text{ mr/hr}$$

or

$$\frac{(66)(5.7 \times 10^{2})}{(1.8 \times 10^{8})} = 2.1 \times 10^{-4} \text{ mr/hr} \quad .$$

These dose rates are negligible to that due to the Na^{24} in the water.

A more sophisticated method of estimating the water activity due to a defective fuel plate is to make use of fission product escape coefficients measured for UO_2 elements with defective cladding[12] and consider the wall deposition effects. This requires that each fission product be considered separately. Such a thorough and time-consuming study does not seem to be necessary to specify shielding thicknesses for the HFIR coolant lines.

Discussion

During the ordinary operation of the HFIR, about 6 ft of ordinary concrete is required to shield the coolant water discharging from the reactor vessel and about 2 ft is required about 1½ min. later as shown in Figs. 6 through 9. The two isotopes which dominate the gamma activity in the water are N^{16} and Na^{24}. Other additional isotopes such as Al^{28} are present in the water during the normal operation of the reactor, but they can be neglected for the purpose of these calculations.

In these calculations, 4 pipe sizes are considered. Shielding requirements for other size pipes may be estimated roughly by plotting the required shield thickness versus the logarithm of the pipe diameter. It should be noted again that the pipes are assumed to be of infinite lengths, and that the gamma activity is assumed to be uniform for the entire length of pipe at any specified time.

For the case of a total meltdown of the fuel in the HFIR, the dose rate at the pipe surface is estimated to be 1.4×10^4 to 1.7×10^4 r/hr as shown in Table IV. The dose rate at the surfaces of the WTR head tank downcomer which is a 30 in. pipe was measured to be 40 r/hr 3 hours after a meltdown of a fuel element in that reactor.[11] The amount of U-235 in a WTR fuel element is about 200 g compared to 6 kg for the HFIR fuel element and the volume of the WTR primary cooling system is 150,000 gal compared to 30,000 gal for the HFIR primary cooling system. Hence, a meltdown of a fuel element in the WTR is equivalent to approximately a 1% meltdown of the fuel in the HFIR. A decay curve showing the WTR head tank radiation level as a function of time after the meltdown of a fuel element meltdown of a fuel element in that reactor[11] indicates that the dose rate at the downcomer surface immediately after the incident was about 4 times that measured 3 hours later. On the bases of the WTR results and these assumptions, the dose rate at the HFIR pipe surface immediately after a total fuel meltdown is estimated to be 1.6×10^4 r/hr. This is in excellent agreement with the calculated results.

Twenty-four hours after the meltdown, the dose rate from the HFIR primary coolant pipe is lower by a factor of an order of 10^2 to 10^3. Most of the remaining activity directly or indirectly is due to the fission products adhering to the coolant system surface. These factors are of a larger magnitude than the factor of 40 obtained on the WTR.[11] The difference can be explained that the cleanup rates and procedures used on the WTR system are very different from those assumed here for the HFIR system.

As mentioned above, about 2 ft of ordinary concrete shielding meets the specifications stated in the introduction in case of a meltdown of the fuel within the reactor. It should be mentioned that these specifications[1] are somewhat arbitrary. For a 24 in. pipe, the radiation level at the surface of a 2 ft concrete shield is 300 mr/hr immediately after the meltdown of 1% of the fuel within the reactor and 66 mr/hr 24 hours after the meltdown of all of the fuel within the reactor. Extrapolating the dose rates shown in Fig. 14 for a 24 in. pipe, about 4¼ ft of concrete is required to reduce the radiation level to 0.75 mr/hr immediately after the meltdown of 1% of the fuel within the reactor. A similar extrapolation of the dose rates shown in Fig. 15 indicates that 3½ ft of concrete is required to reduce the radiation levels to 0.75 mr/hr 24 hours after a total meltdown of the fuel within the reactor.

The calculations pertaining to the shielding of the primary coolant system during the operation of the reactor with a defective fuel plate are very crude. The assumptions used were arbitrary, and the results should not be considered as definite. It is felt, however, that the operation of the reactor with a defective fuel plate should not present a hazard provided that the defect does not become greatly enlarged such as by blistering.

In case of a rupture of a fuel plate in the HFIR, a conservative assumption of the fission products released in 10% of those released from a meltdown of one fuel plate. Since there are about 570 plates in the HFIR fuel element, the amounts of fission products released following a fuel place rupture would be 1/5700 of those released following a total fuel element meltdown. On this basis, the dose rate at the pipe surface is estimated to be 2 to 3 r/hr. Dose rates up to 3 r/hr were measured at the surface of the MTR water pipes following a rupture of a fuel element in that reactor.[6] At the surface of a 2 ft concrete shield around the HFIR system, the dose rate is estimated to be 5 to 6 mr/hr.

For all situations where fission products are released into the coolant due to the melting or rupture of a break in the fuel element, it was assumed that the reactor had been operated at 100 Mw for 10 days.[8] An incident prior to the end of the 10 days operation would result in lower dose rates since the buildup of the fission products would not be as high. Also, an actual meltdown of the fuel in the HFIR probably would not be complete, which would result in lower dose rates.

Conclusions

About 6 ft of ordinary concrete for the pipes located at the outlet of the HFIR pressure vessel and 2 ft of ordinary concrete for the pipes located about 1½ min. downstream from the reactor vessel are required to shield the primary coolant system to or below the tolerances stated in the introduction. The calculated results are presented in graphical and tabular forms in order to predict the shielding requirements for other tolerances.

Nomenclature

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

B = Symbolic buildup factor

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

S_A = Surface source strength, $\frac{\text{photons}}{\text{cm}^2\ \text{sec}}$

S_L = Line source strength, $\frac{\text{photons}}{\text{cm sec}}$

R_0 = Inside pipe radius, cm

a = Distance between source and point of measurement, cm

z = Self-attenuation distance, cm

$$F(\tfrac{\pi}{2}, b_i) = \int_0^{\frac{\pi}{2}} e^{-b_i \sec \theta} \, d\theta$$

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

$b_2 = b_1 + \mu_s z$

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_i = Constant in the buildup factor

α_i = Constant in the buildup factor

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Table I

Gamma Sources in the HFIR Primary Coolant System

after a Fuel Meltdown

Energy Range	Volume Source	Surface Source
Immediately after Meltdown of 1% of the Fuel		
$\leq$ 0.25 Mev	2.4×10^7 $\frac{\text{photons}}{\text{sec-ml}}$	3.8×10^6 $\frac{\text{photons}}{\text{cm}^2\ \text{sec}}$
0.26 $\leq$ 1.00 "	1.0×10^7 "	1.9×10^7 "
1.01 $\leq$ 1.70 "	1.8×10^6 "	6.2×10^6 "
$\geq$ 1.71 "	8.8×10^6 "	3.0×10^6 "
24 hours after Meltdown of all of the Fuel		
$\leq$ 0.25 Mev	1.8×10^6 $\frac{\text{photons}}{\text{sec ml}}$	1.2×10^8 $\frac{\text{photons}}{\text{cm}^2\ \text{sec}}$
0.26 $\leq$ 1.00 "	4.2×10^6 "	4.7×10^8 "
1.01 $\leq$ 1.70 "	3.3×10^4 "	3.3×10^7 "
$\geq$ 1.71 "	2.5×10^4 "	2.6×10^7 "

Table II

Conversion Factors for Volume Fission Product Sources in Pipes

Concrete Thickness ft	$\leq$ 0.25 Mev r/hr/$\frac{photon}{sec\ ml}$	0.26 $\leq$ 1.00 Mev r/hr/$\frac{photon}{sec\ ml}$	1.01 $\leq$ 1.70 Mev r/hr/$\frac{photon}{sec\ ml}$	$\geq$ 1.71 Mev r/hr/$\frac{photon}{sec\ ml}$
A. 1 in. Sch. 10 Pipe				
Inner Concrete Surface 0 ft from Pipe				
0	1.1×10^{-10}	5.5×10^{-7}	1.2×10^{-6}	1.7×10^{-6}
1	3.4×10^{-12}	8.6×10^{-10}	4.6×10^{-9}	1.3×10^{-8}
2	2.6×10^{-16}	1.3×10^{-12}	7.7×10^{-11}	5.3×10^{-10}
3	2.5×10^{-20}	3.9×10^{-15}	1.6×10^{-12}	2.6×10^{-11}
Inner Concrete Surface 1 ft from Pipe				
0	4.5×10^{-9}	3.8×10^{-8}	8.7×10^{-8}	1.5×10^{-7}
1	1.7×10^{-12}	4.3×10^{-10}	2.3×10^{-9}	6.4×10^{-9}
2	1.7×10^{-16}	8.5×10^{-13}	5.2×10^{-11}	3.5×10^{-11}
3	1.8×10^{-20}	3.0×10^{-15}	1.2×10^{-12}	2.0×10^{-11}
Inner Concrete Surface 2 ft from Pipe				
0	2.3×10^{-9}	1.9×10^{-8}	4.4×10^{-8}	7.8×10^{-8}
1	1.2×10^{-12}	2.9×10^{-10}	1.5×10^{-9}	4.3×10^{-9}
2	1.3×10^{-16}	6.4×10^{-13}	3.9×10^{-11}	2.6×10^{-10}
3	1.5×10^{-20}	2.4×10^{-15}	9.4×10^{-13}	1.6×10^{-11}
B. 16 in. Pipe (½ in. wall)				
Inner Concrete Surface 0 ft from Pipe				
0	1.1×10^{-8}	1.3×10^{-6}	4.6×10^{-6}	1.1×10^{-5}
1	1.2×10^{-11}	9.0×10^{-9}	1.3×10^{-7}	5.9×10^{-7}
2	7.4×10^{-16}	2.4×10^{-11}	3.5×10^{-9}	3.0×10^{-8}
3	4.3×10^{-20}	6.1×10^{-14}	5.8×10^{-11}	1.7×10^{-9}
Inner Concrete Surface 1 ft from Pipe				
0	1.4×10^{-8}	5.2×10^{-7}	1.9×10^{-6}	5.1×10^{-6}
1	7.2×10^{-12}	6.0×10^{-9}	9.6×10^{-8}	3.5×10^{-7}
2	5.0×10^{-16}	1.5×10^{-11}	2.2×10^{-9}	2.0×10^{-8}
3	4.4×10^{-20}	5.4×10^{-14}	4.1×10^{-11}	1.4×10^{-9}
Inner Concrete Surface 2 ft from Pipe				
0	1.6×10^{-9}	3.0×10^{-7}	1.3×10^{-6}	2.9×10^{-6}
1	5.4×10^{-12}	3.4×10^{-9}	7.9×10^{-8}	2.4×10^{-7}
2	5.6×10^{-16}	1.3×10^{-11}	1.5×10^{-9}	1.8×10^{-8}
3	4.6×10^{-20}	6.1×10^{-14}	3.9×10^{-11}	1.2×10^{-9}

Table II contd

Concrete Thickness ft	≤ 0.25 Mev r/hr/photon/sec ml	0.26 ≤ 1.00 Mev r/hr/photon/sec ml	1.01 ≤ 1.70 Mev r/hr/photon/sec ml	≥ 1.71 Mev r/hr/photon/sec ml
C. 24 in. Pipe (5/8 in. wall)				
	Inner Concrete Surface 0 ft from Pipe			
0	1.4×10^{-8}	9.6×10^{-7}	4.0×10^{-6}	1.3×10^{-5}
1	8.8×10^{-12}	8.6×10^{-9}	1.4×10^{-7}	7.4×10^{-7}
2	6.5×10^{-16}	2.5×10^{-11}	4.3×10^{-9}	4.5×10^{-8}
3	4.7×10^{-20}	6.9×10^{-13}	6.9×10^{-10}	2.9×10^{-9}
	Inner Concrete Surface 1 ft from Pipe			
0	1.0×10^{-8}	5.2×10^{-7}	2.0×10^{-6}	6.1×10^{-6}
1	6.0×10^{-12}	7.5×10^{-9}	1.1×10^{-7}	4.8×10^{-7}
2	4.2×10^{-16}	1.8×10^{-11}	2.9×10^{-9}	3.2×10^{-8}
3	4.4×10^{-20}	5.4×10^{-14}	4.8×10^{-11}	2.1×10^{-9}
	Inner Concrete Surface 2 ft from Pipe			
0	9.0×10^{-9}	5.3×10^{-7}	1.9×10^{-6}	3.9×10^{-6}
1	4.5×10^{-12}	6.6×10^{-9}	9.6×10^{-8}	3.5×10^{-7}
2	3.5×10^{-16}	1.8×10^{-11}	2.6×10^{-9}	2.5×10^{-8}
3	-	6.4×10^{-14}	4.9×10^{-11}	1.6×10^{-9}
D. 36 in. Pipe (1 in. wall)				
	Inner Concrete Surface 0 ft from Pipe			
0	3.1×10^{-9}	3.9×10^{-7}	2.1×10^{-6}	7.9×10^{-6}
1	1.6×10^{-12}	6.0×10^{-9}	9.7×10^{-8}	5.8×10^{-7}
2	9.5×10^{-17}	1.8×10^{-11}	3.1×10^{-9}	4.4×10^{-8}
3	-	5.4×10^{-14}	5.5×10^{-11}	2.9×10^{-9}
	Inner Concrete Surface 1 ft from Pipe			
0	2.1×10^{-9}	3.4×10^{-7}	1.3×10^{-6}	4.7×10^{-6}
1	1.5×10^{-12}	4.6×10^{-9}	8.5×10^{-8}	4.8×10^{-7}
2	7.1×10^{-17}	1.3×10^{-11}	2.6×10^{-9}	3.7×10^{-8}
3	-	3.9×10^{-14}	4.0×10^{-11}	2.2×10^{-9}
	Inner Concrete Surface 2 ft from Pipe			
0	2.0×10^{-9}	2.2×10^{-7}	1.1×10^{-6}	3.7×10^{-6}
1	1.1×10^{-12}	4.1×10^{-9}	6.7×10^{-8}	3.8×10^{-7}
2	-	1.0×10^{-11}	2.1×10^{-9}	2.8×10^{-8}
3	-	3.3×10^{-14}	3.7×10^{-11}	1.7×10^{-9}

Table III

Conversion Factors for Surface Fission Product Sources in Pipes

Concrete Thickness ft	≤ 0.25 Mev r/hr/photon/sec ml	0.26 ≤ 1.00 Mev r/hr/photon/sec ml	1.01 ≤ 1.70 Mev r/hr/photon/sec/ml	≥ 1.71 Mev r/hr/photon/sec ml
1 in. Sch. 10 Pipe				
		Inner Concrete Surface 0 ft from Pipe		
0	5.9×10^{-8}	6.8×10^{-7}	1.1×10^{-6}	3.1×10^{-6}
24 in. Pipe (5/8 in. wall)				
		Inner Concrete Surface 0 ft from Pipe		
0	8.7×10^{-11}	3.6×10^{-8}	1.5×10^{-6}	6.1×10^{-7}
24 in. Pipe (5/8 in. wall)				
		Inner Concrete Surface 1 ft from Pipe		
0	1.3×10^{-9}	6.1×10^{-8}	1.8×10^{-7}	4.5×10^{-7}
1	8.3×10^{-13}	5.8×10^{-10}	1.1×10^{-8}	4.6×10^{-8}
2	9.3×10^{-17}	2.3×10^{-12}	2.9×10^{-10}	2.1×10^{-9}
36 in. Pipe (1 in. wall)				
		Inner Concrete Surface 0 ft from Pipe		
0	8.3×10^{-13}	5.0×10^{-9}	4.2×10^{-8}	2.0×10^{-7}
36 in. Pipe (1 in. wall)				
		Inner Concrete Surface 1 ft from Pipe		
2	1.9×10^{-17}	1.2×10^{-12}	1.3×10^{-10}	1.5×10^{-9}

Table IV

Dose Rates at Concrete Shield Surfaces from Fission Product Sources in Pipes

Pipe Size	Distance between Pipe and Concrete ft	Concrete Thickness ft	Volume Fission Product Source Contribution r/hr	Surface Fission Product Source Contribution r/hr	Total r/hr
			Immediately after Meltdown of 1% of the Fuel		
1 in. Sch. 10	0	0	2.3×10	2.9×10	5.2×10
24 in. (5/8 in. wall)	0	0	1.3×10^{2}	1.2	1.4×10^{2}
"	1	0	6.3×10	3.7	6.7×10
"	1	1	4.5	2.2×10^{-1}	4.7
"	1	2	2.9×10^{-1}	8.1×10^{-3}	3.0 x 10-1
36 in. (1 in. wall)	0	0	7.8×10	9.6×10	1.7×10^{2}
"	1	2	3.4×10^{-1}	5.3×10^{-3}	3.5×10^{-1}
			24 hours after Meltdown of all of the Fuel		
1 in. Sch. 10	0	0	2.4	4.4×10^{2}	4.4×10^{2}
24 in. (5/8 in. wall)	0	0	4.5	8.3×10	8.8×10
"	1	0	2.4	4.7×10	5.0×10
"	1	1	4.8×10^{-2}	1.8	1.8
"	1	2	9.7×10^{-4}	6.6×10^{-2}	6.6×10^{-2}
36 in. (1 in. wall)	0	0	1.9	9.0	1.1×10
"	1	2	9.2×10^{-3}	3.9×10^{-2}	1.9×10^{-2}

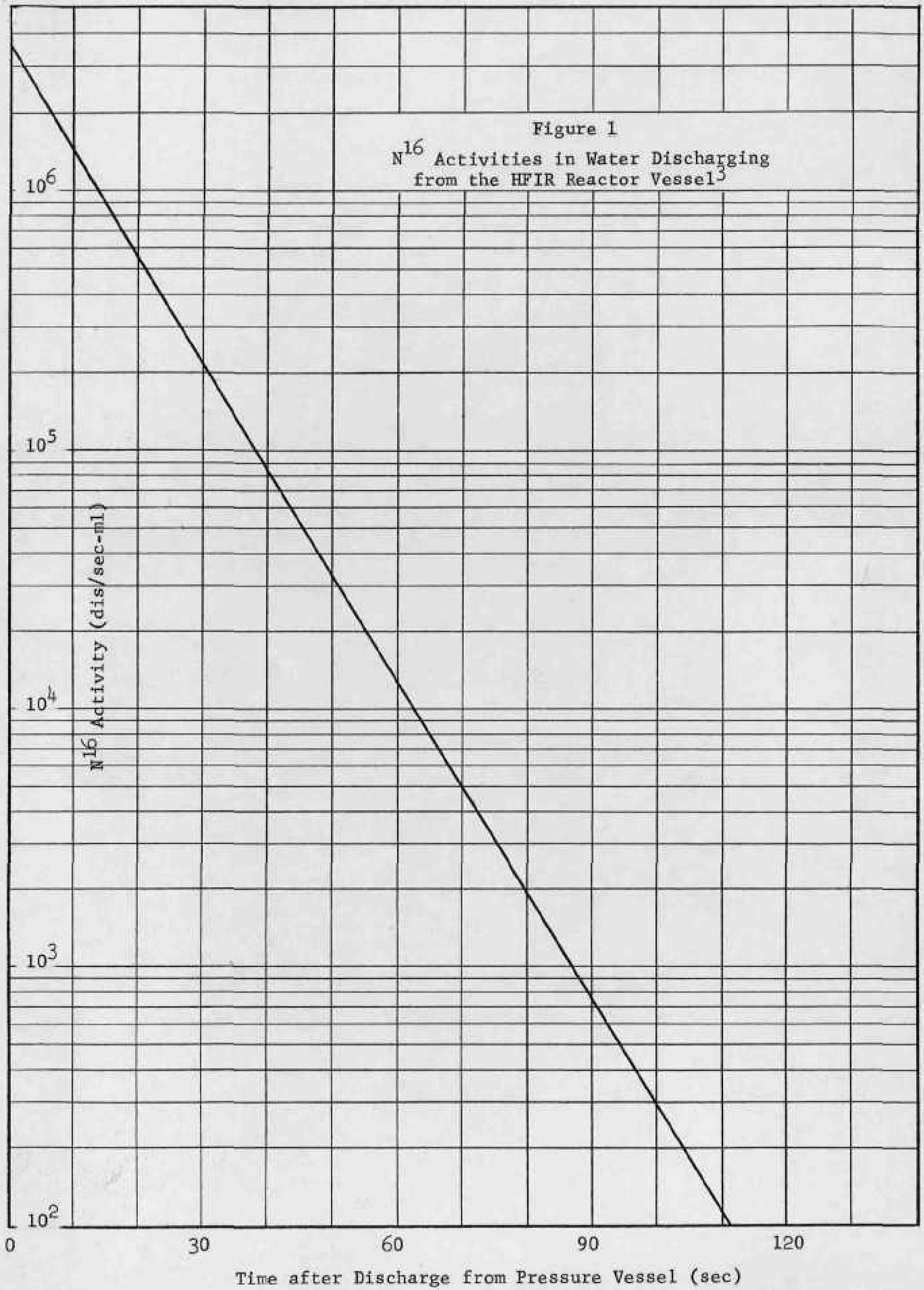

Figure 1
N^{16} Activities in Water Discharging from the HFIR Reactor Vessel[3]
10^6
10^5
10^4
10^3
10^2
N^{16} Activity (dis/sec-ml)
0
30
60
90
120
Time after Discharge from Pressure Vessel (sec)

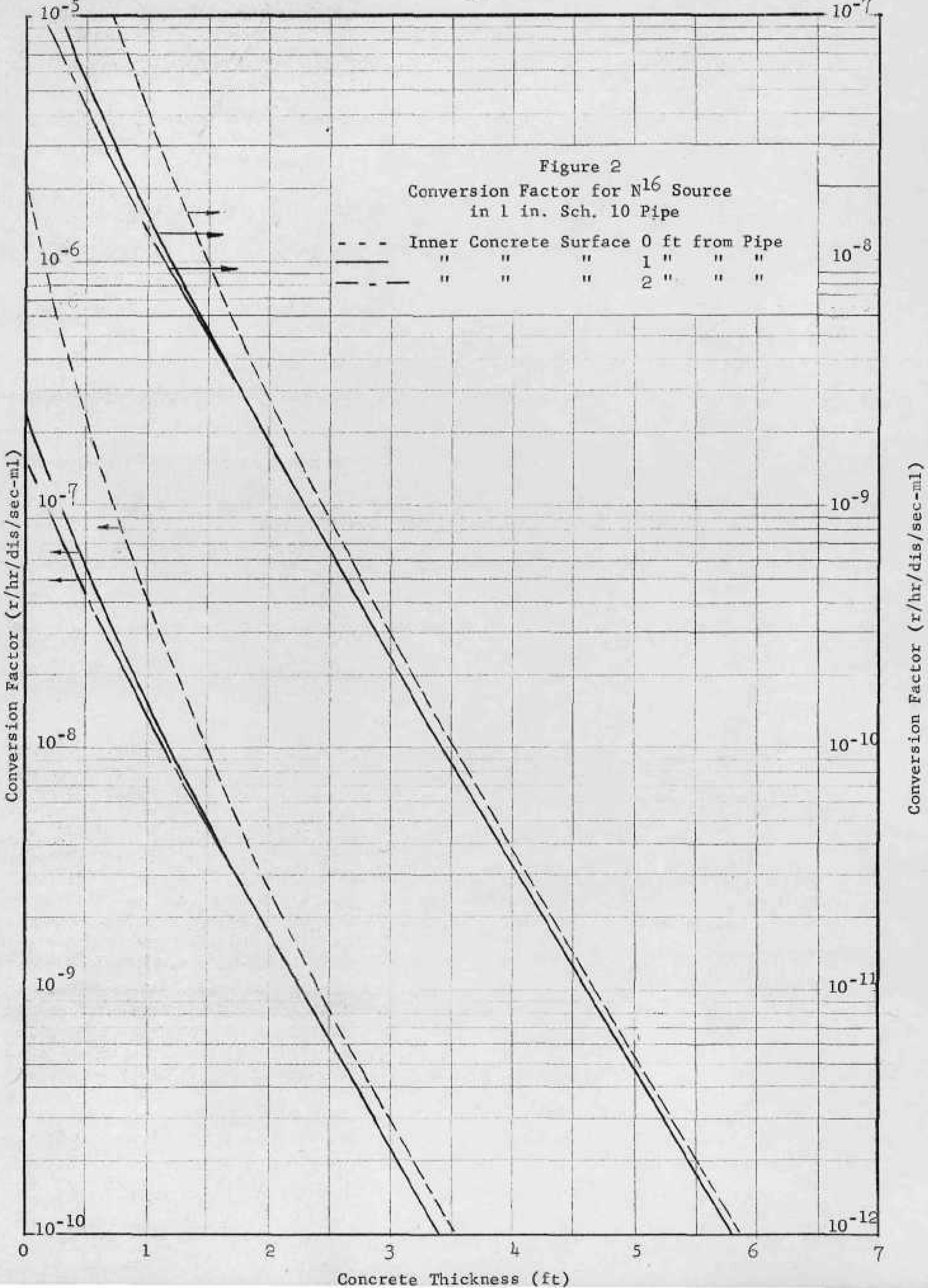
Figure 2
Conversion Factor for N^{16} Source
in 1 in. Sch. 10 Pipe
- - - Inner Concrete Surface 0 ft from Pipe
—— " " " 1 " " "
— - — " " " 2 " " "
Conversion Factor (r/hr/dis/sec-ml)
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

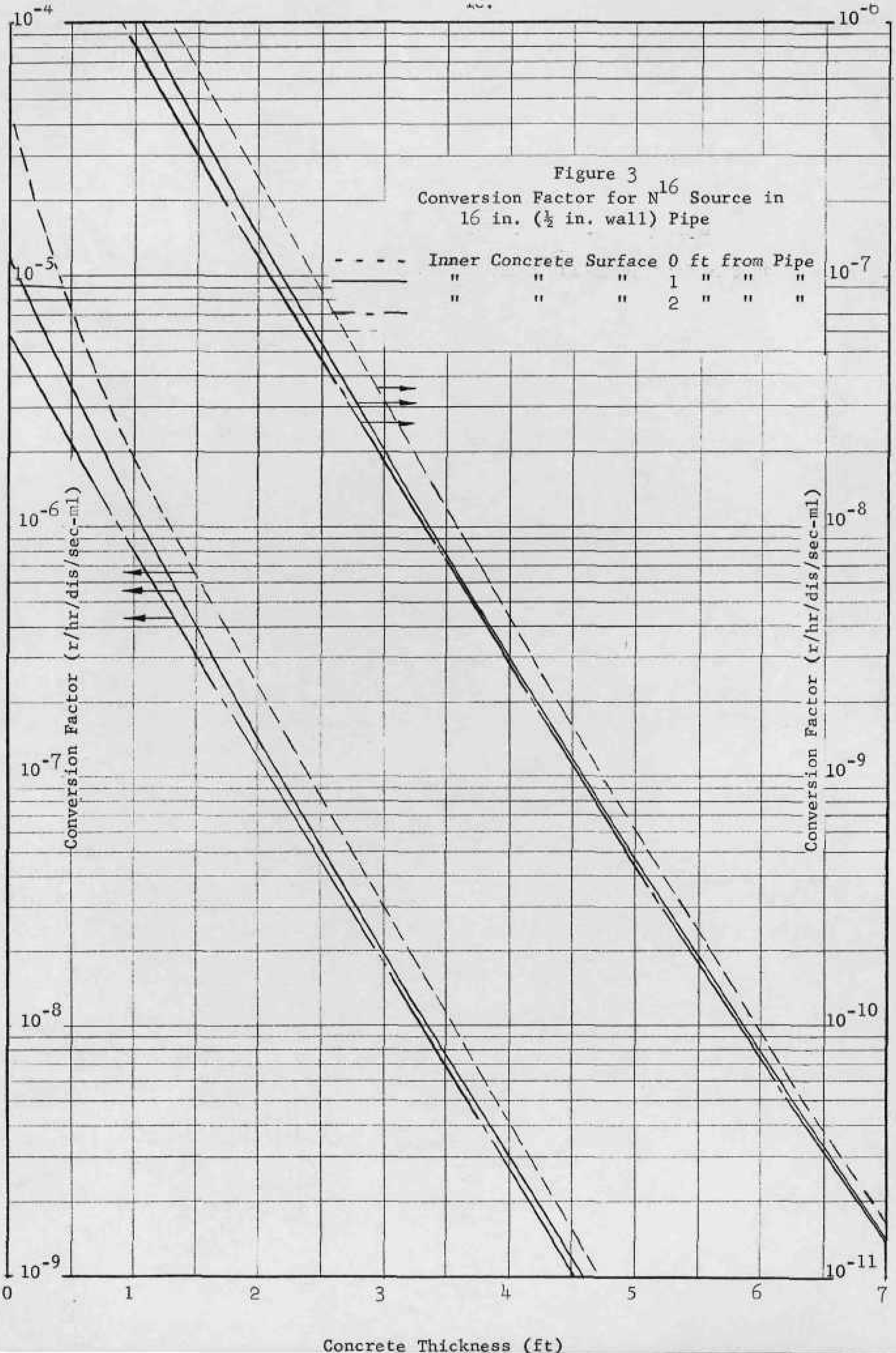

Figure 3
Conversion Factor for N^{16} Source in 16 in. (½ in. wall) Pipe

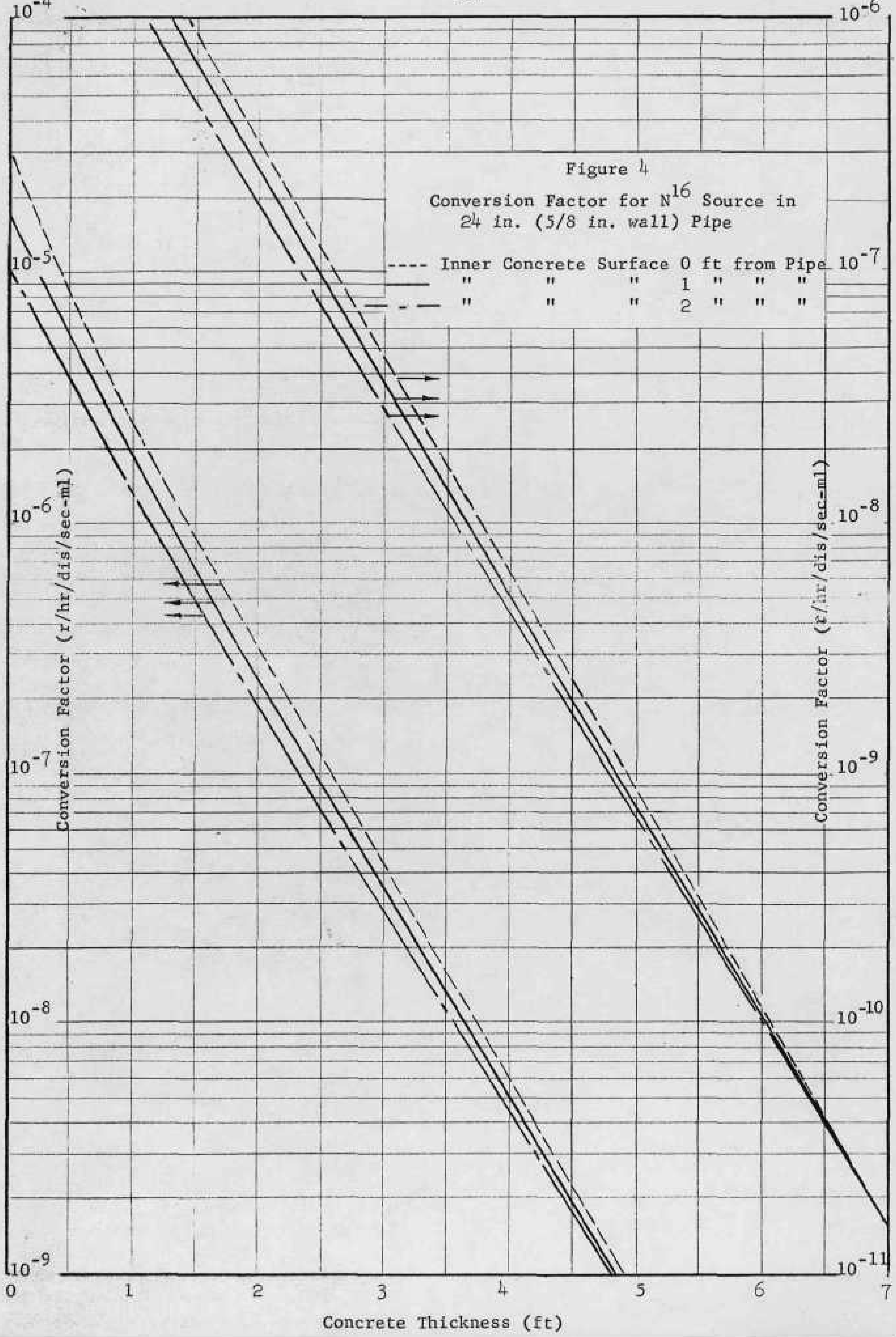
Figure 4
Conversion Factor for N16 Source in
24 in. (5/8 in. wall) Pipe
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
Conversion Factor (r/hr/dis/sec-ml)
Conversion Factor (r/hr/dis/sec-ml)
Concrete Thickness (ft)
10-4
10-5
10-6
10-7
10-8
10-9
10-6
10-7
10-8
10-9
10-10
10-11
0
1
2
3
4
5
6
7

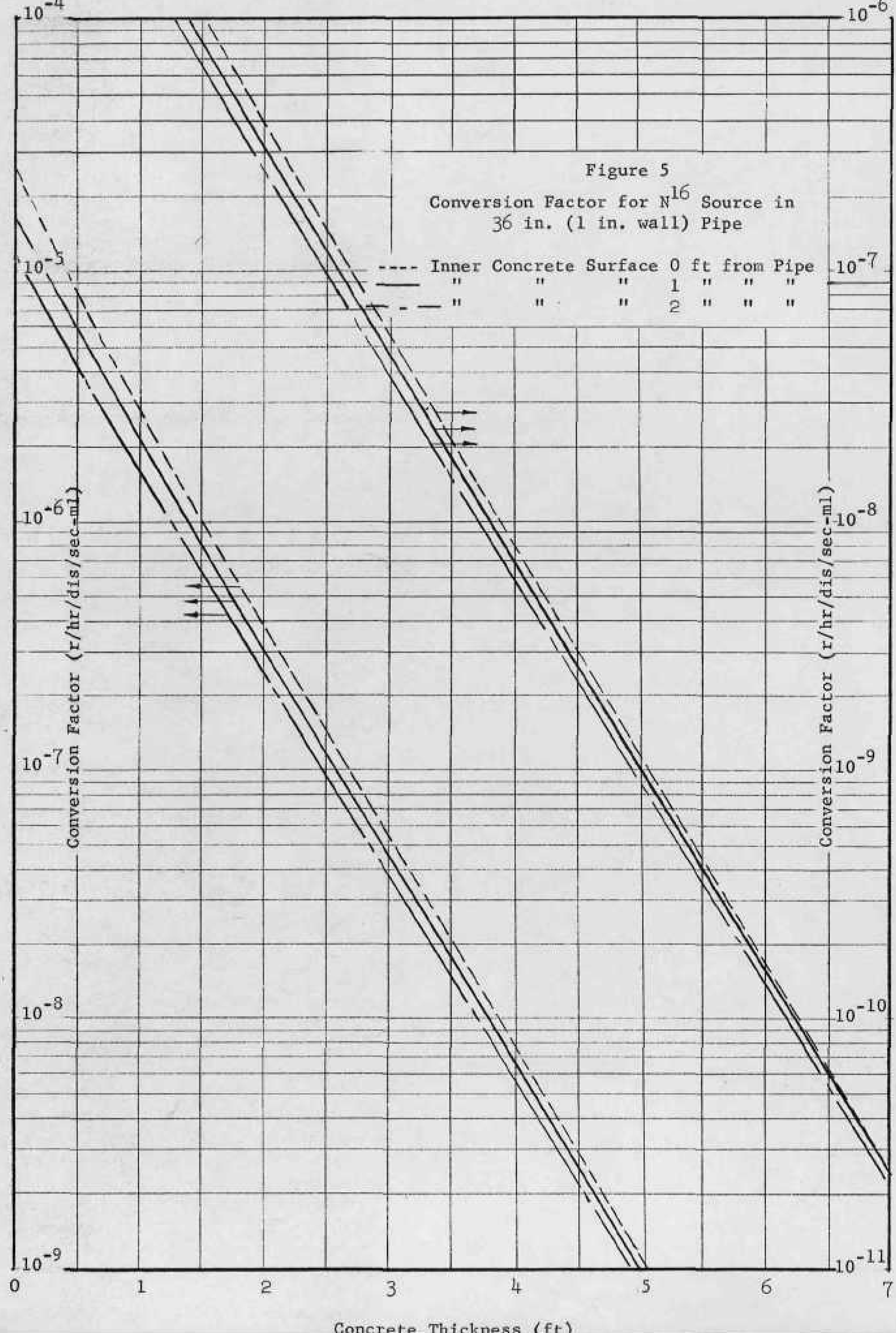
Figure 5
Conversion Factor for N16 Source in 36 in. (1 in. wall) Pipe
---- Inner Concrete Surface 0 ft from Pipe
—— " " " 1 " " "
— - — " " " 2 " " "
Conversion Factor (r/hr/dis/sec-ml)
10-4
10-5
10-6
10-7
10-8
10-9
10-6
10-7
10-8
10-9
10-10
10-11
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

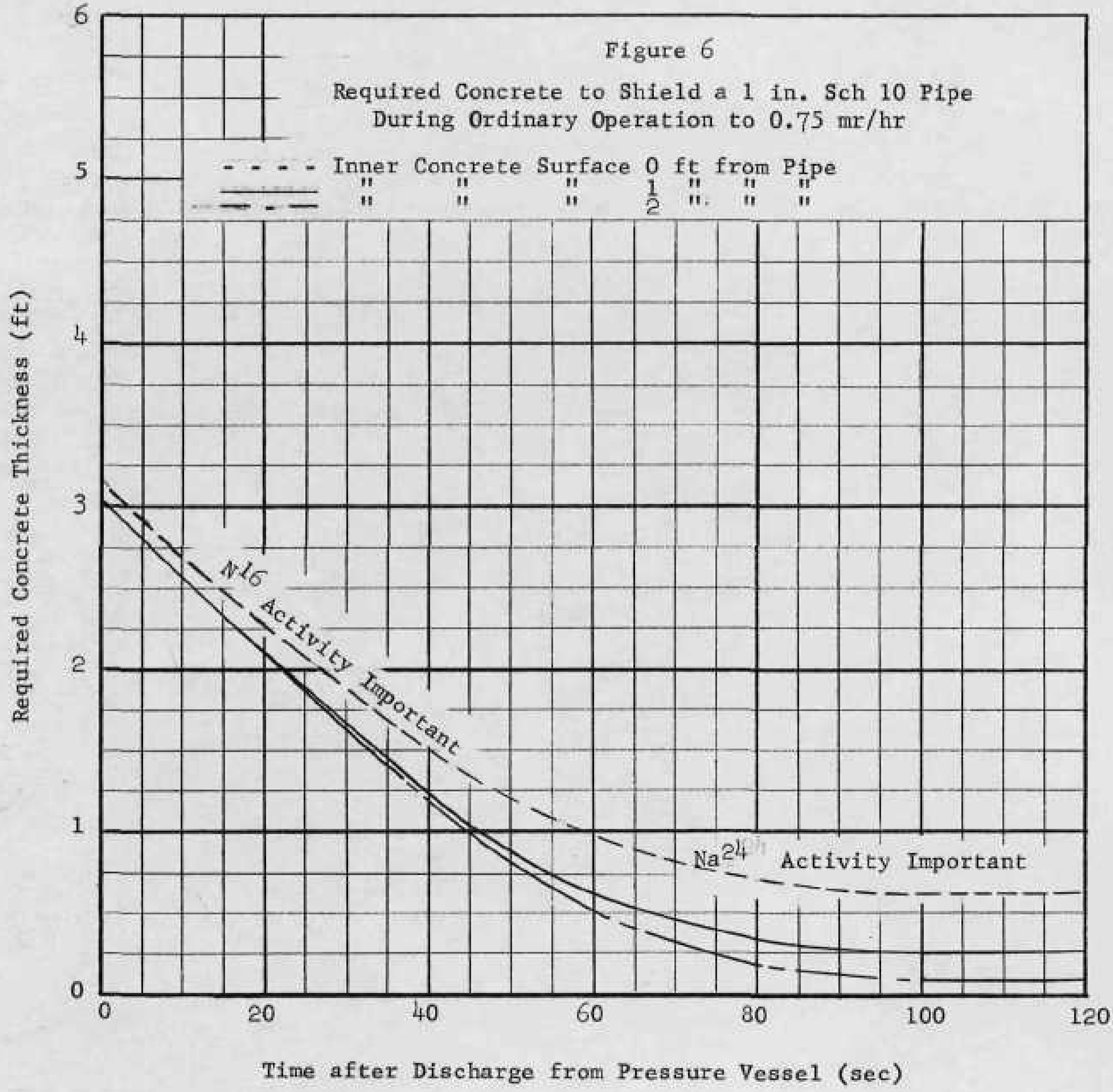
Figure 6
Required Concrete to Shield a 1 in. Sch 10 Pipe
During Ordinary Operation to 0.75 mr/hr
Inner Concrete Surface 0 ft from Pipe
" " " 1/2 " " "
" " "
N16 Activity Important
Na24 Activity Important
Required Concrete Thickness (ft)
Time after Discharge from Pressure Vessel (sec)
0
1
2
3
4
5
6
0
20
40
60
80
100
120

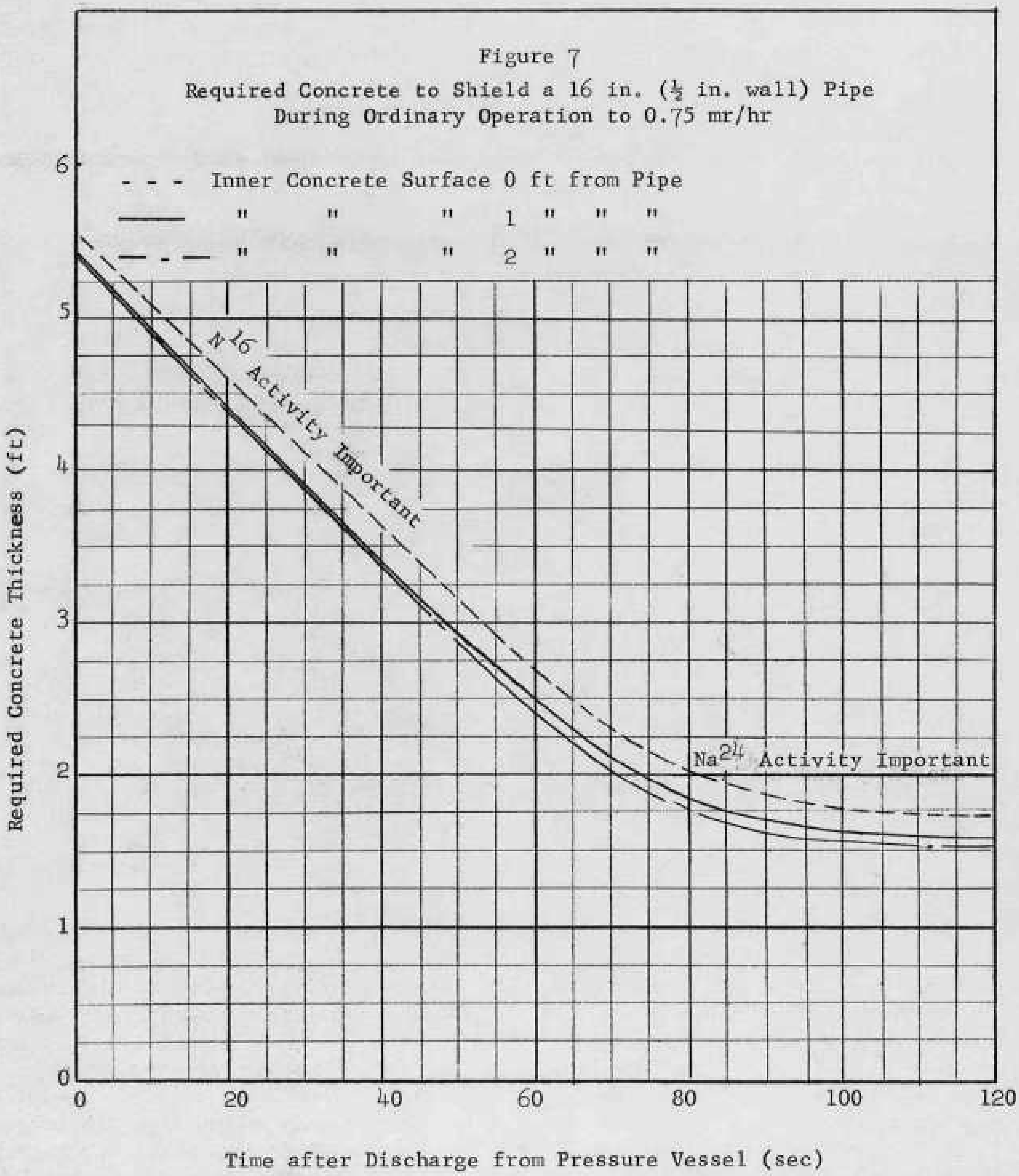
Figure 7
Required Concrete to Shield a 16 in. (½ in. wall) Pipe
During Ordinary Operation to 0.75 mr/hr
Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
N16 Activity Important
Na24 Activity Important
Required Concrete Thickness (ft)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
Time after Discharge from Pressure Vessel (sec)

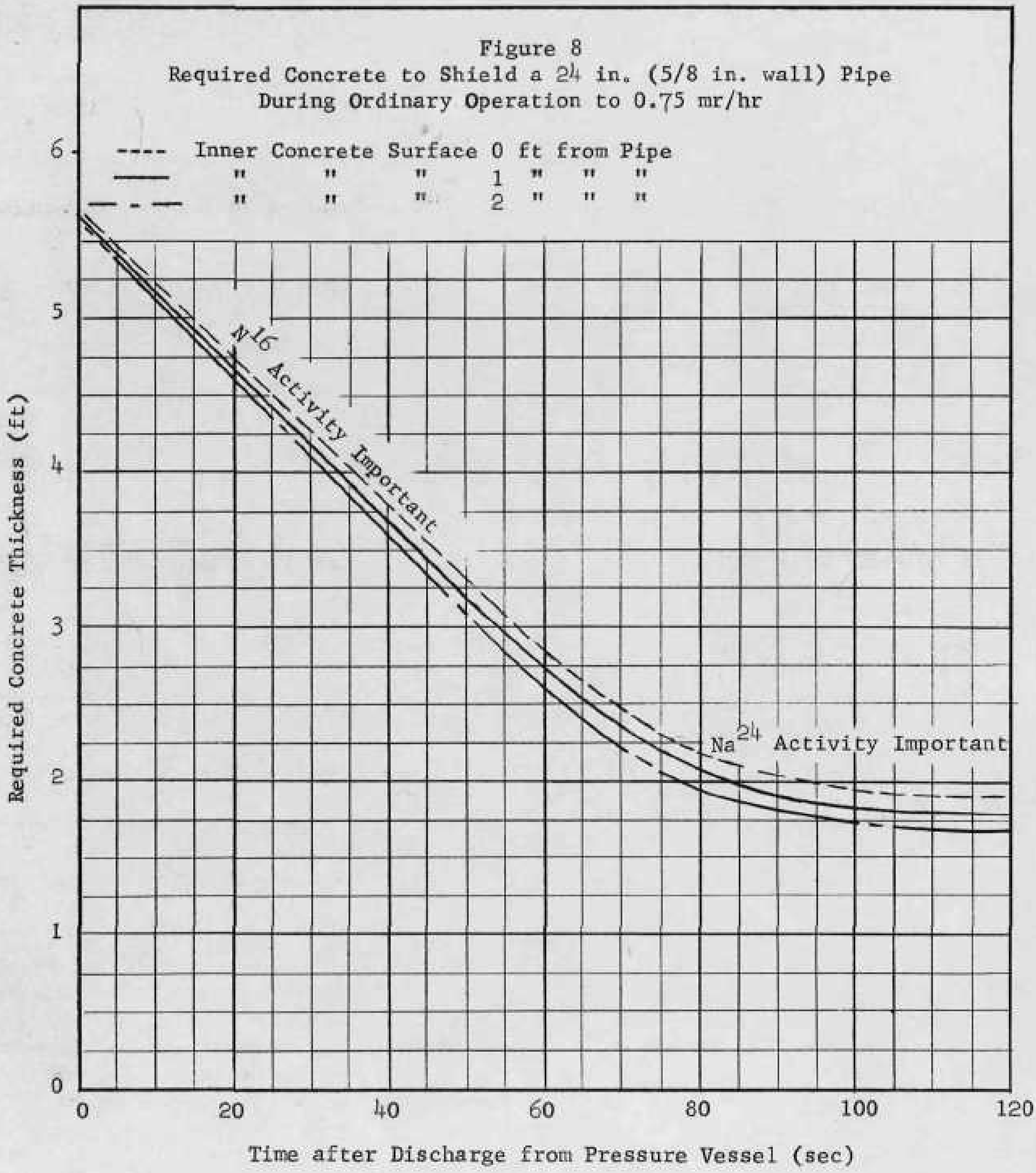
Figure 8
Required Concrete to Shield a 24 in. (5/8 in. wall) Pipe
During Ordinary Operation to 0.75 mr/hr
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
N^{16} Activity Important
Na^{24} Activity Important
Required Concrete Thickness (ft)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
Time after Discharge from Pressure Vessel (sec)

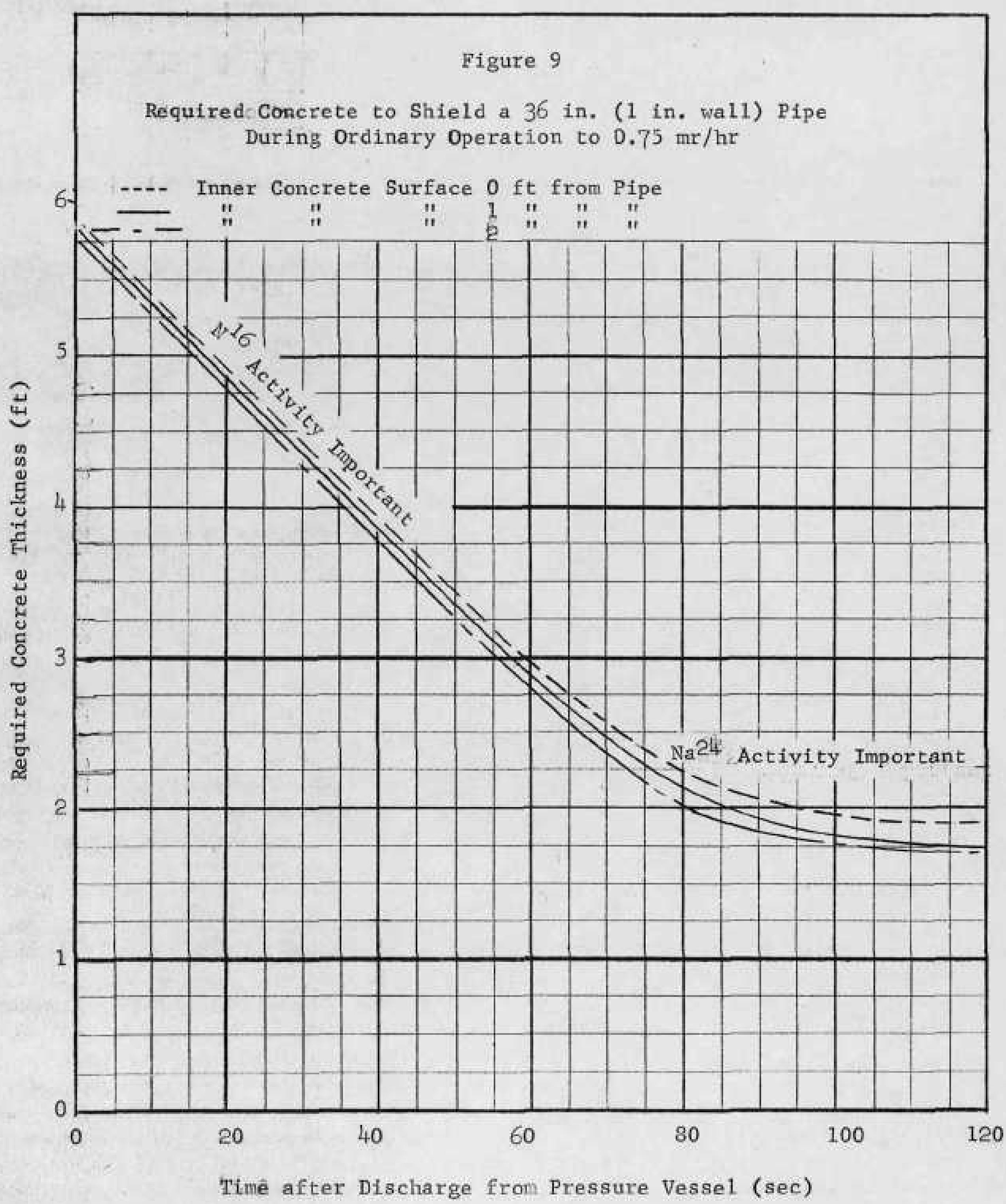
Figure 9
Required Concrete to Shield a 36 in. (1 in. wall) Pipe During Ordinary Operation to 0.75 mr/hr
---- Inner Concrete Surface 0 ft from Pipe
" " " 1/2 " " "
N16 Activity Important
Na24 Activity Important
Required Concrete Thickness (ft)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
Time after Discharge from Pressure Vessel (sec)

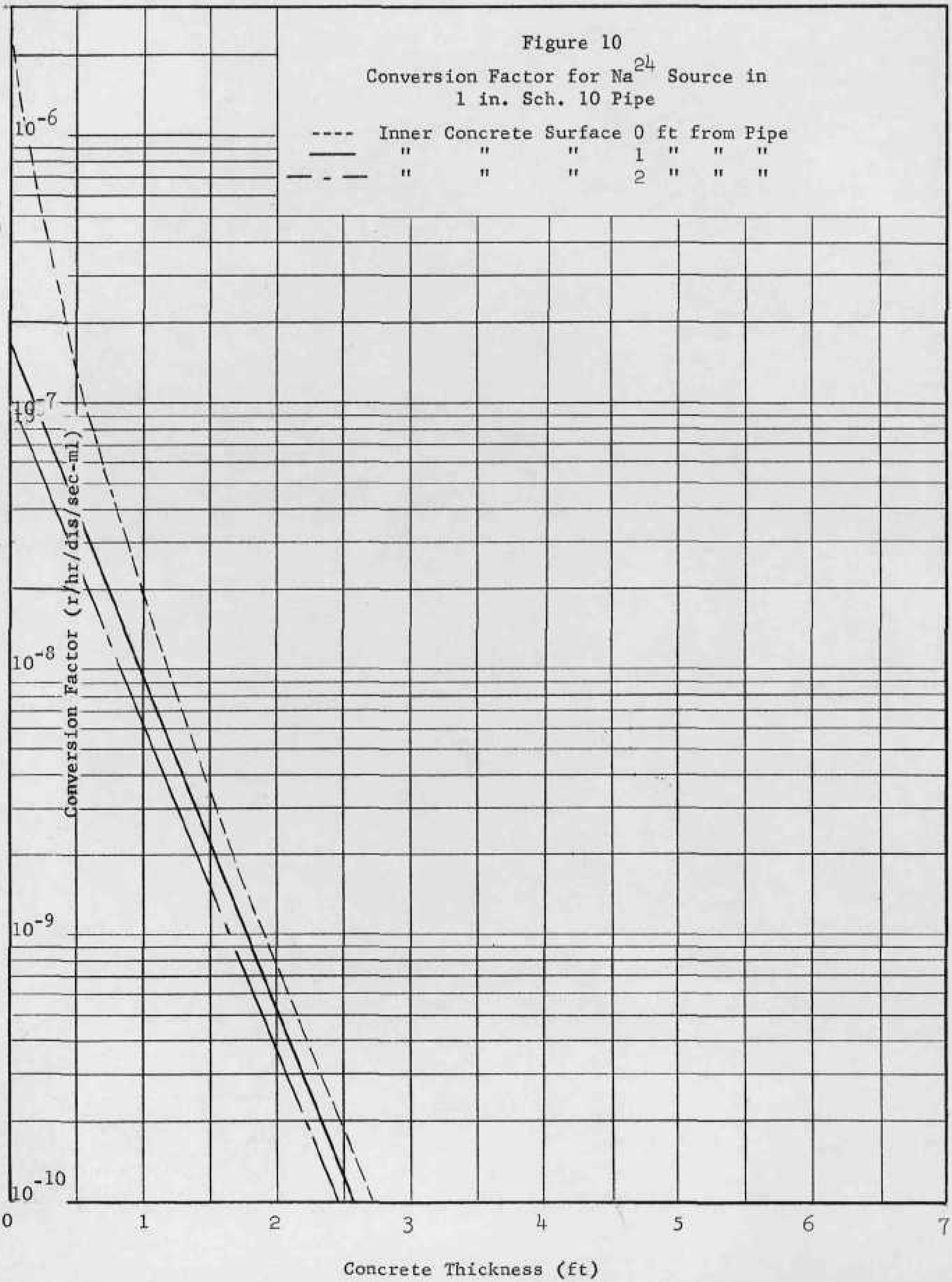
Figure 10
Conversion Factor for Na24 Source in
1 in. Sch. 10 Pipe
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
10-6
10-7
10-8
10-9
10-10
Conversion Factor (r/hr/dis/sec-ml)
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

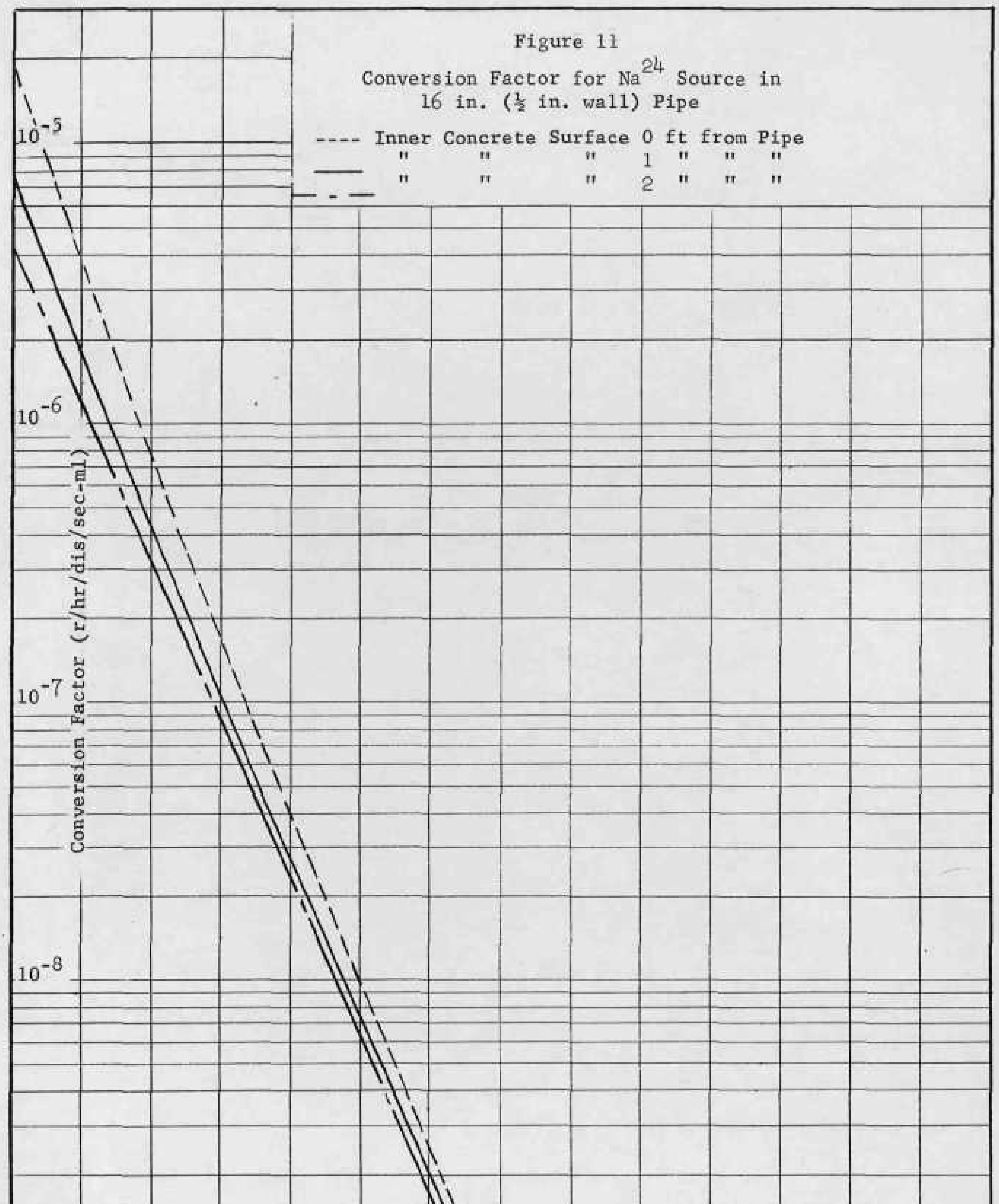
Figure 11
Conversion Factor for Na24 Source in
16 in. (½ in. wall) Pipe
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
10-5
10-6
10-7
10-8
10-9
Conversion Factor (r/hr/dis/sec-ml)
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

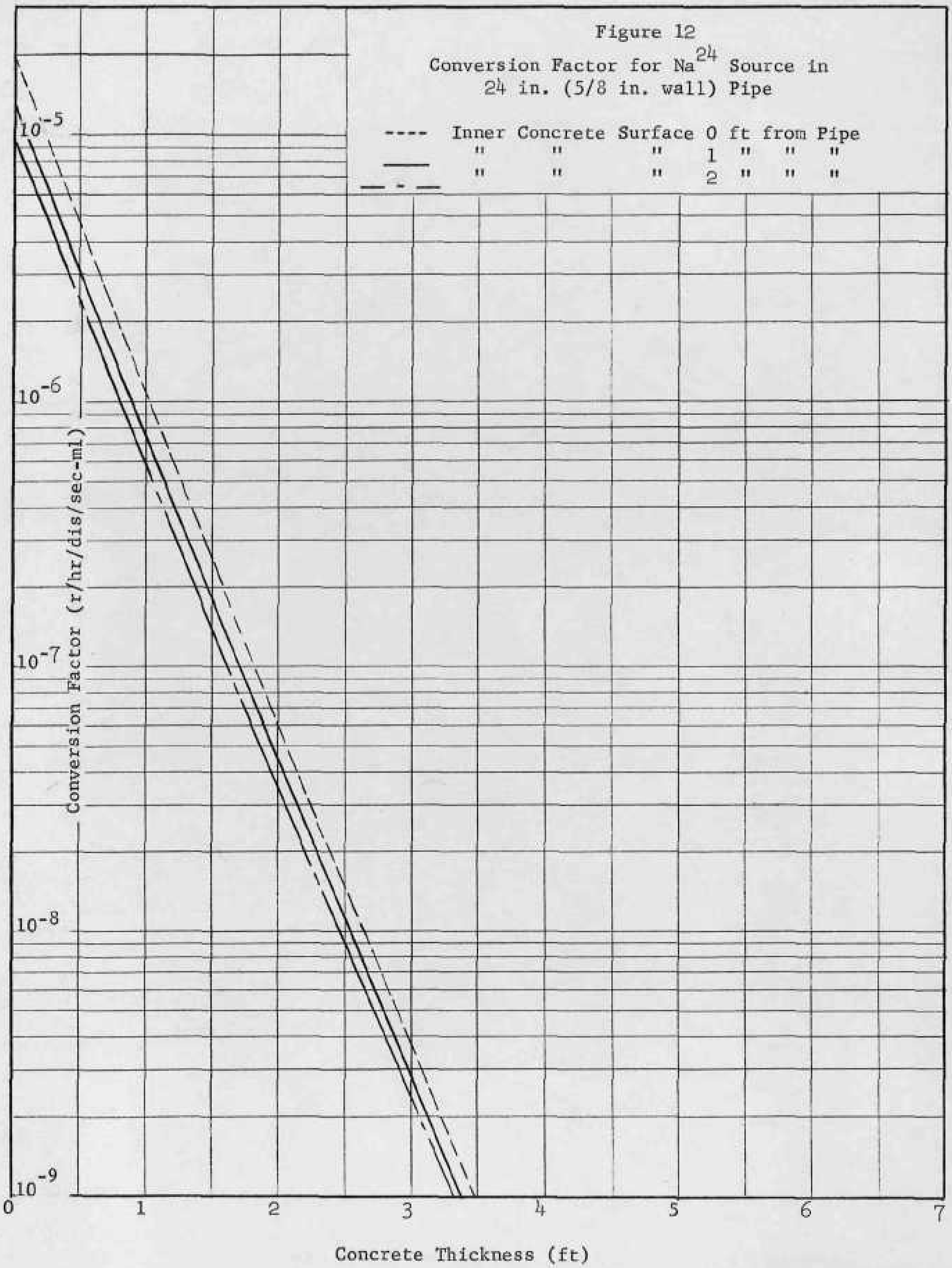
Figure 12
Conversion Factor for Na^{24} Source in
24 in. (5/8 in. wall) Pipe
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Conversion Factor (r/hr/dis/sec-ml)
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

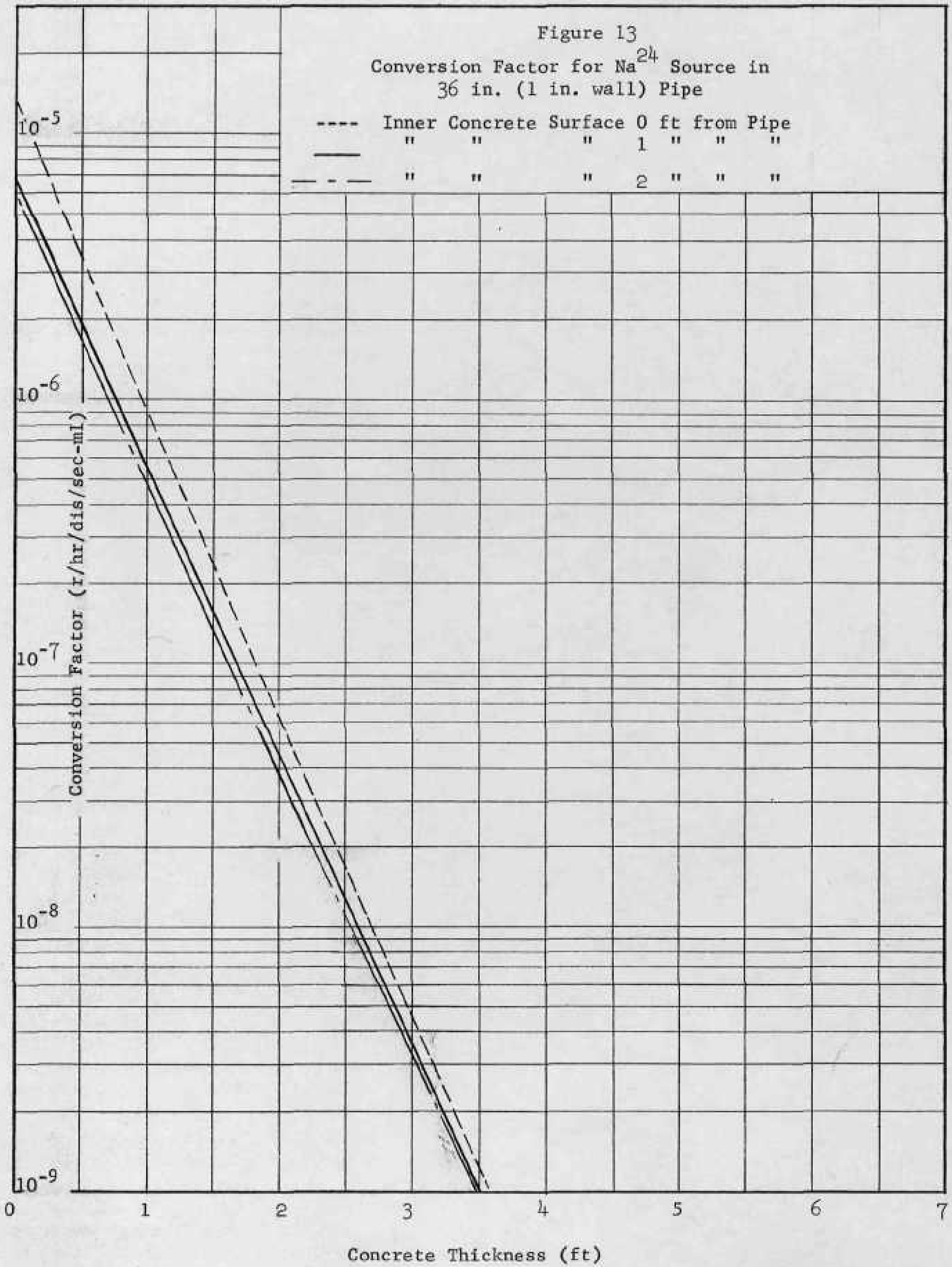
Figure 13
Conversion Factor for Na24 Source in
36 in. (1 in. wall) Pipe
---- Inner Concrete Surface 0 ft from Pipe
" " " 1 " " "
" " " 2 " " "
10-5
10-6
10-7
10-8
10-9
Conversion Factor (r/hr/dis/sec-ml)
0
1
2
3
4
5
6
7
Concrete Thickness (ft)

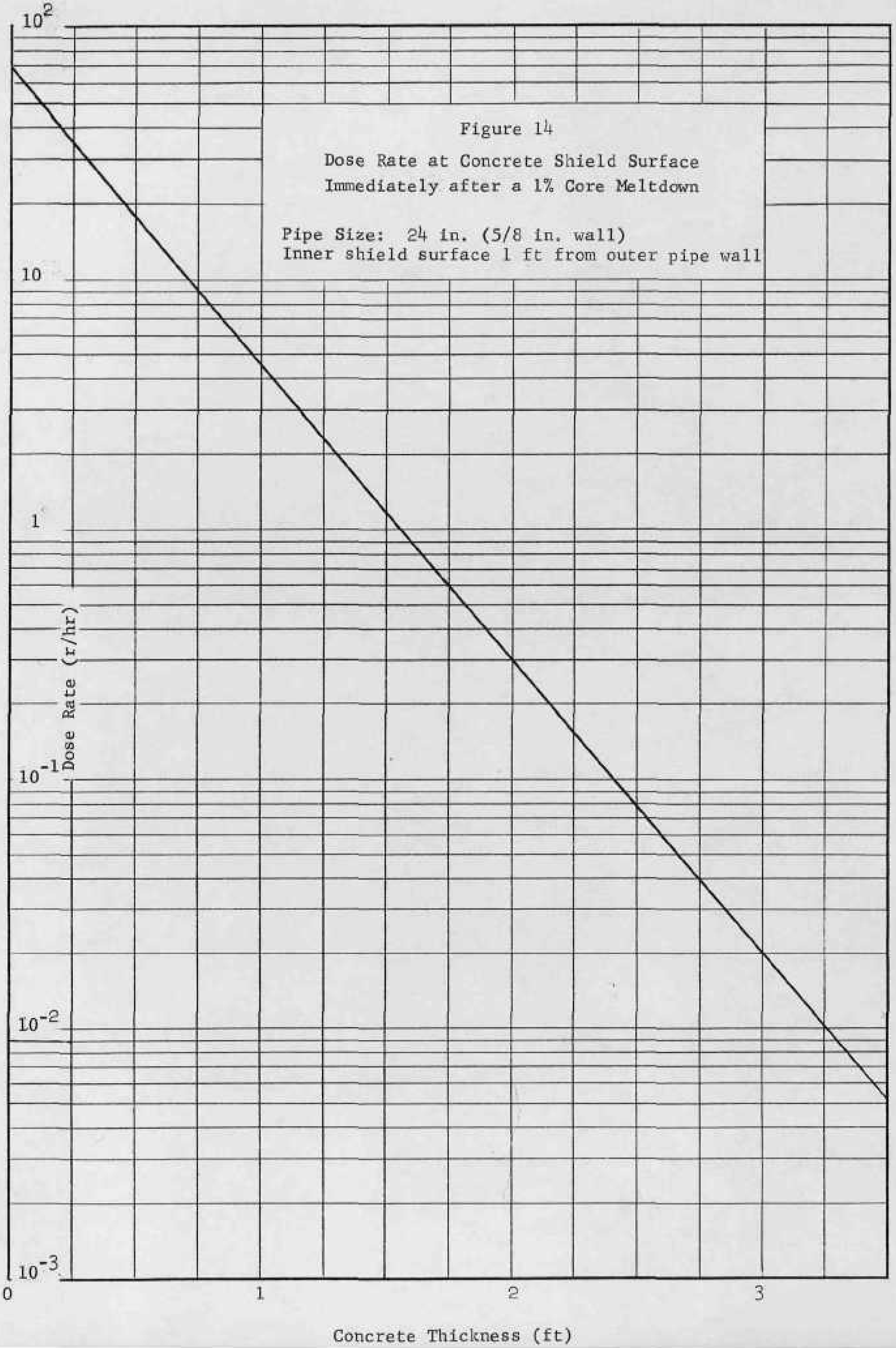
Figure 14
Dose Rate at Concrete Shield Surface
Immediately after a 1% Core Meltdown
Pipe Size: 24 in. (5/8 in. wall)
Inner shield surface 1 ft from outer pipe wall
10^2
10
1
10^-1
10^-2
10^-3
Dose Rate (r/hr)
0
1
2
3
Concrete Thickness (ft)

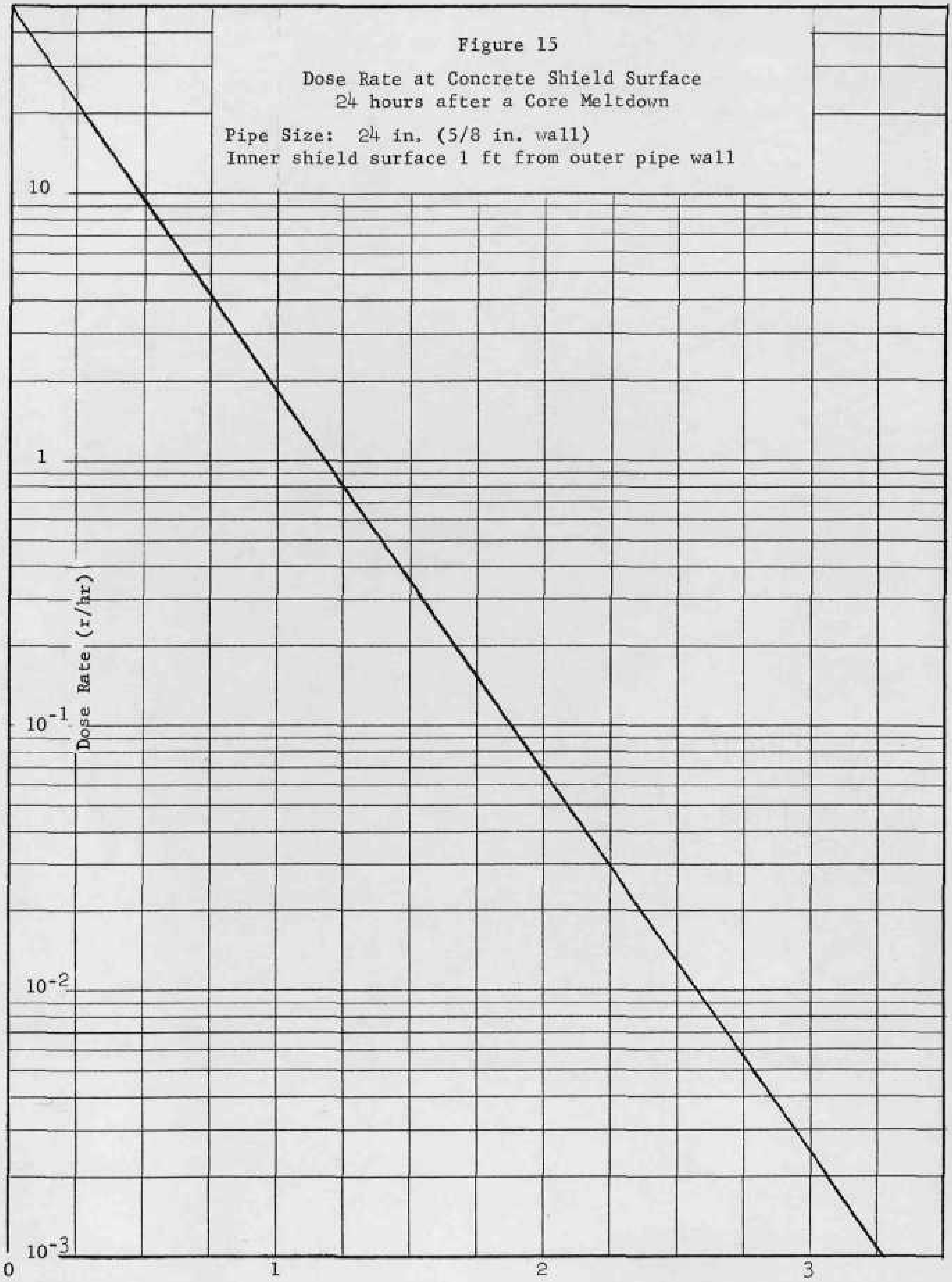
Figure 15
Dose Rate at Concrete Shield Surface
24 hours after a Core Meltdown
Pipe Size: 24 in. (5/8 in. wall)
Inner shield surface 1 ft from outer pipe wall
10
1
10^{-1}
10^{-2}
10^{-3}
Dose Rate (r/hr)
0
1
2
3
Concrete Thickness (ft)

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