DASARA-3 938.22

21 April 1960

OSD1.941207.029

The Decay of Nuclear Weapon Fallout Debris

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Incl 2

WNRC: 17-28 Oct 94
RG: 330
ACCESSION# 68A-5329
BOX# 1
FILE NAME: OAP Radiation Dec 1957-Jul 1964

A knowledge of the decay of fallout debris from nuclear bursts plays a crucial role in prediction calculations of fallout patterns, casualty estimates and civil defense planning. Hence it is extremely desirable to obtain the best possible data on the decay to provide good input information for these calculations and estimates.

Unfortunately, it is difficult to obtain a sample of fission products and bomb debris as formed at the time of explosion in order to experimentally measure the decay properties, although this was attempted during Operation GREENHOUSE. It is possible to obtain samples of fallout debris, however, and obtain estimates of decay. The drawback with this scheme is that the properties vary with location in the fallout pattern (due to fractionation and other mechanisms), type of soil at burst point, weather, and the type of weapon.

Another approach is to calculate the decay properties of the debris from the known or theoretically estimated properties of the individual isotopes contained in the debris. It is the results of such calculations which will be discussed here.

Several groups have published data on the decay of the fission products due to thermal fission of U^{235} in recent years. The most extensive and applicable results are given by the workers at the U. S. Naval Radiological Defense Laboratory.[1,2] The values of decay rate vs time given in these publications are rather different from those published in The Effects of Nuclear Weapons[3] (EMW), as was brought out in the 1959 Joint Committee on Atomic Energy hearings.[4,5] The NRDL data show larger H + 1 hour dose rates than those given in the EMW and much smaller dose rates at very long times.

Now it must be noted that the NRDL results do not represent the exact decay characteristics of actual weapon debris, since they are the theoretical decay rates of pure U^{235} fission products only, using experimental and theoretical values for the yields, half-lives, gamma energies, etc., of the individual isotopes produced or believed to be produced. But the actual radioactive fallout debris has characteristics different from that of the fission products due to thermal fission of U^{235} as a result of fractionation of the isotopes, induced activities, non-thermal fission, and U^{238} fissions. In addition there will be "weathering" of the debris after arrival on the ground, and in actuality the debris will be on rough terrain rather than the ideal smooth infinite plane almost universally used to calculate the dose rate due to a given concentration of activity on the ground.

In order to obtain a better approximation to the true fallout debris properties, calculations similar to those used to obtain the U^{235} fission product decay were carried out at DASA[6] which resulted in curves for the dose rate at 3 ft above the surface as a function of time due to:

1. Pure U^{238} fission products

2. U^{235} and U^{238} fission products with fractionation of Kr, Xe and their daughters

3. Fractionated U^{235} and U^{238} plus the induced activities produced in the bomb materials, i.e., U^{237}, U^{239}, Np^{239}, Np^{240}.

The amount of fractionation and induced activities were deduced from experimental data obtained in weapons tests. A final curve was obtained for r/hr per KT/mi^2 vs time from a typical KT range weapon, and a similar curve for a MT range weapon, using fractionated U^{235} plus induced activities for the KT weapon, and fractionated U^{238} plus induced activities for the MT weapon. It was found that the properties of U^{238} fission products are not significantly different from those of U^{235} fission products, the largest differences occurring at late times. Fractionation resulted in a depression of the decay rate at early times but did not affect the decay rate at times greater than 3 months. The induced activities are short lived and their tendency to increase the early time dose rate is overshadowed by the reduction in dose rate at early times as compared to a pure U^{235} or U^{238} dose rate curve. For times greater than ~ 3 months, the curves for KT and MT weapons become identical with those for pure U^{235} and U^{238} fission products, respectively.

The units KT/mi^2 refer to the concentration (or surface density) of radioactivity on the surface at any given point which would exist if the radioactivity due to one kiloton equivalent of fission yield is spread uniformly over a one square mile area. It is directly proportional to the amount of fission product activity per square mile, through the relation 1.45×10^{23} fissions = 1 KT. The fallout debris is, of course, not spread uniformly over any large area, but within a small area, say a circle of radius 50 feet or so, where most of the dose at a point at the center of the circle derives, the surface density of activity can be considered constant and expressed in these units. These units are particularly useful with some of the fallout models in use, which express the dose rate at a given point in terms of the "fraction of the device" (f.o.d.) per square mile on the surface at that point. Thus, if one multiplies the above "f.o.d." by the total yield of a given weapon, the results are expressed in KT/mi^2.

For weapon debris, it is seen from figures 1-3 that the theoretical dose rate is very nearly linear when plotted on logarithmic paper for times up to 100 days. When the points on this curve up to t = 100 days are fitted to a power law by least squares analysis, the following relations are obtained:

$$\text{Dose rate from KT weapon} = 2{,}600\ t^{-1.23}\ \frac{\text{r/hr}}{\text{KT/mi}^2},$$

$$\text{Dose rate from MT weapon} = 2{,}750\ t^{-1.23}\ \frac{\text{r/hr}}{\text{KT/mi}^2},$$

where t is measured in hours. For times up to 100 days the relation for KT weapons is within ± 9% of the theoretical curve, while the relation for MT weapons is accurate to within ± 25%.

For times greater than 100 days it is obviously wiser to use the pure U^{235} or U^{238} fission product curve, as the power law approximation greatly overestimates the dose rate at these times, by as much as a factor of nine.

Integration of the dose rate curve for KT weapons, starting at H + 1 hour, yields the integrated dose curves shown in figures 4 and 5. These curves show the dose accumulated from H + 1 hour to any time, t, relative to the H + 1 hour dose rate. Thus, in order to obtain the dose received from H + 1 hour to some time t, the value obtained from figure 4 or 5 must be multiplied by the H + 1 hour dose rate. Values of the dose relative to the H + 1 hour dose rate and the actual dose received for a one KT/mi^2 concentration of activity, for which the H + 1 hour dose rate is 2,750 r/hr, are given for certain time intervals in Table I. The dose relative to the H + 1 hour dose rate, $\dot{D}(H+1)$, is given in column 2, the dose due to one KT/mi^2 in column 3.

These results are probably as valid as one can give theoretically at this time for the decay of fallout debris. Since weathering effects and rough terrain will both act to decrease the dose rate and the slope of the decay curve, the dose rates given here should represent upper limits. The actual dose rate above rough terrain will be on the order of two-thirds the theoretical dose rate above a smooth infinite plane.

Activities induced in the weapon structure and the environment will of course tend to increase the dose rate above the values given in figures 1-3. The amount of this activity and its time behavior depend on the particular weapon and environment and can only be estimated if these factors are known.

Measurements have been made of the dose rates from actual fallout samples for periods up to about 200 days.[7,8] Attempts to fit the observed decay of activity with a power law of the form

$$A = A_1 \, t^{-k}$$

have required values of k ranging from 0.90 to 2.0. At least some of the variability must be due to variability in yield and type of burst, since the measurements referred to included both MT and KT bursts, and bursts at various heights above the Pacific Proving Ground and Nevada Test Site. At least one barge shot was also reported.

In view of the rather large variability in the measured rate of decay of fallout debris which is not subject to weathering, attempts to predict the decay of actual fallout fields on the basis of any given decay law or curve are almost certain to be grossly inaccurate. If prediction must be done, the $t^{-1.2}$ law seems to be as good as any for times up to 100 days, after which the actual U^{235} decay curve may give a closer approximation to the actual decay.

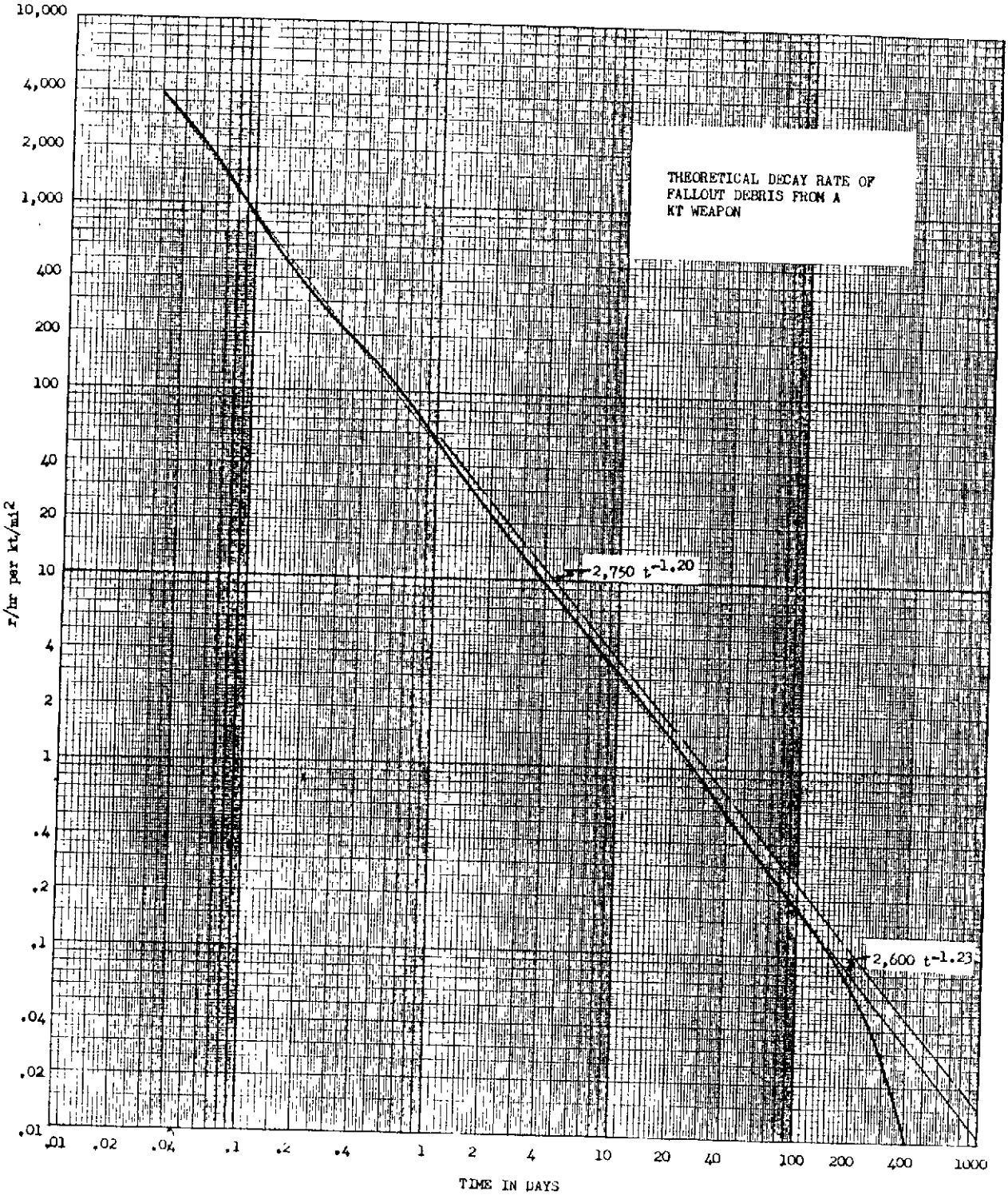

THEORETICAL DECAY RATE OF FALLOUT DEBRIS FROM A KT WEAPON
2,750 t^-1.20
2,600 t^-1.23
r/hr per kt/mi^2
TIME IN DAYS
10,000
4,000
2,000
1,000
400
200
100
40
20
10
4
2
1
.4
.2
.1
.04
.02
.01
.01
.02
.04
.1
.2
.4
1
2
4
10
20
40
100
200
400
1000

Figure 1

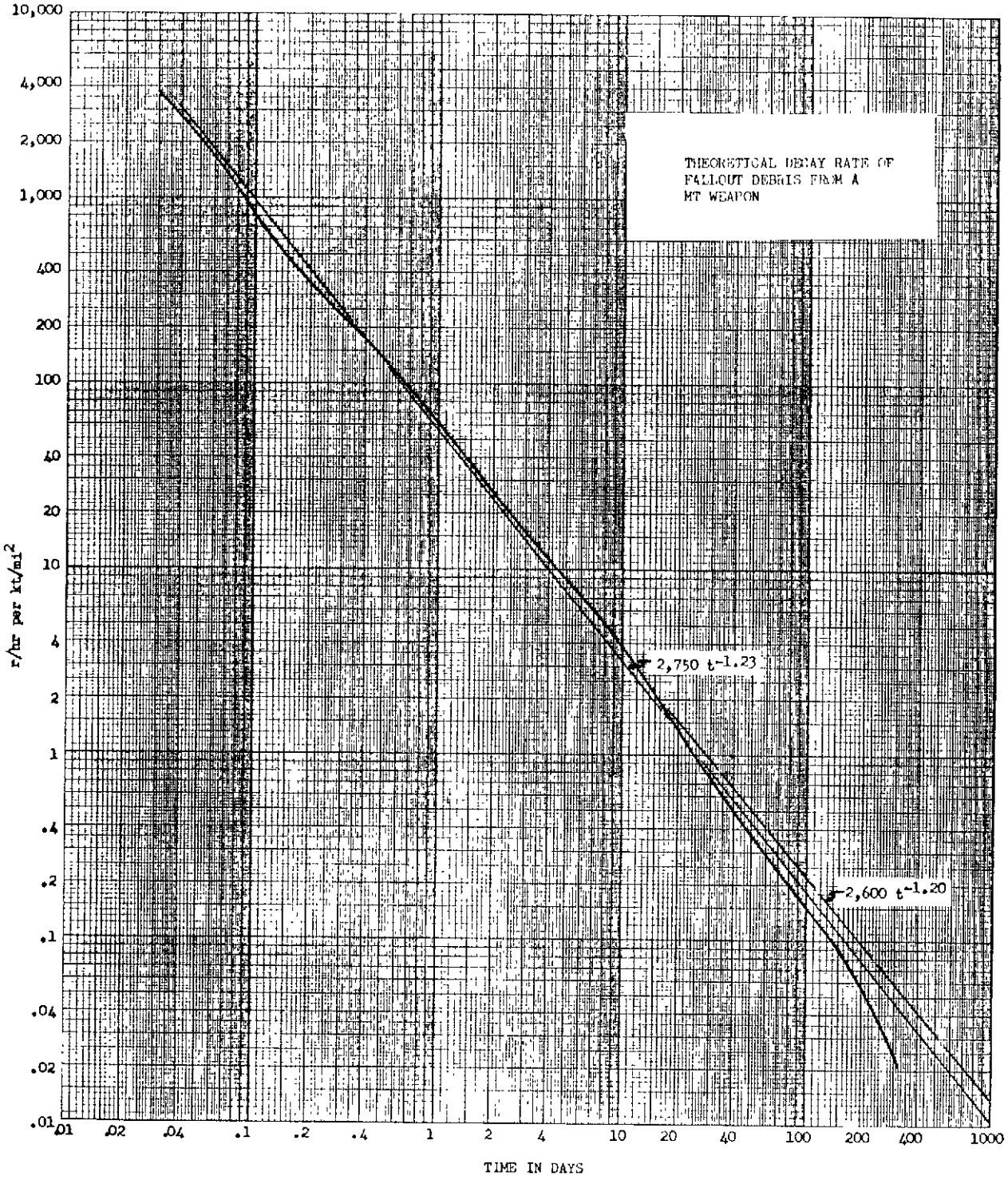

THEORETICAL DECAY RATE OF
FALLOUT DEBRIS FROM A
MT WEAPON
2,750 t^-1.23
2,600 t^-1.20
r/hr per kt/mi^2
10,000
4,000
2,000
1,000
400
200
100
40
20
10
4
2
1
.4
.2
.1
.04
.02
.01
.01
.02
.04
.1
.2
.4
1
2
4
10
20
40
100
200
400
1000
TIME IN DAYS

Figure 2

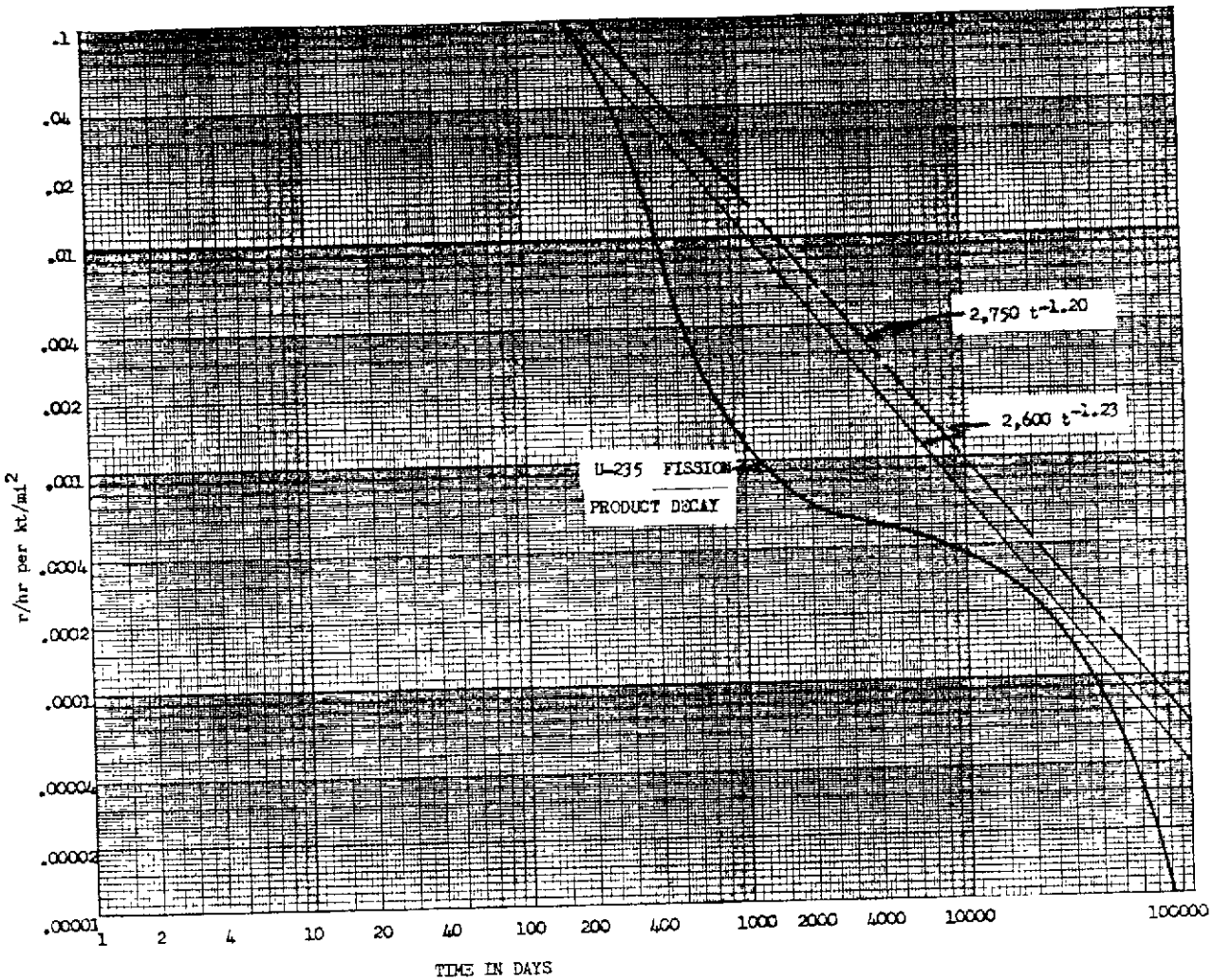

.1
.04
.02
.01
.004
.002
.001
.0004
.0002
.0001
.00004
.00002
.00001
r/hr per kt/mi^2
1
2
4
10
20
40
100
200
400
1000
2000
4000
10000
100000
TIME IN DAYS
2,750 $t^{-1.20}$
2,600 $t^{-1.23}$
U-235 FISSION
PRODUCT DECAY

Figure 3

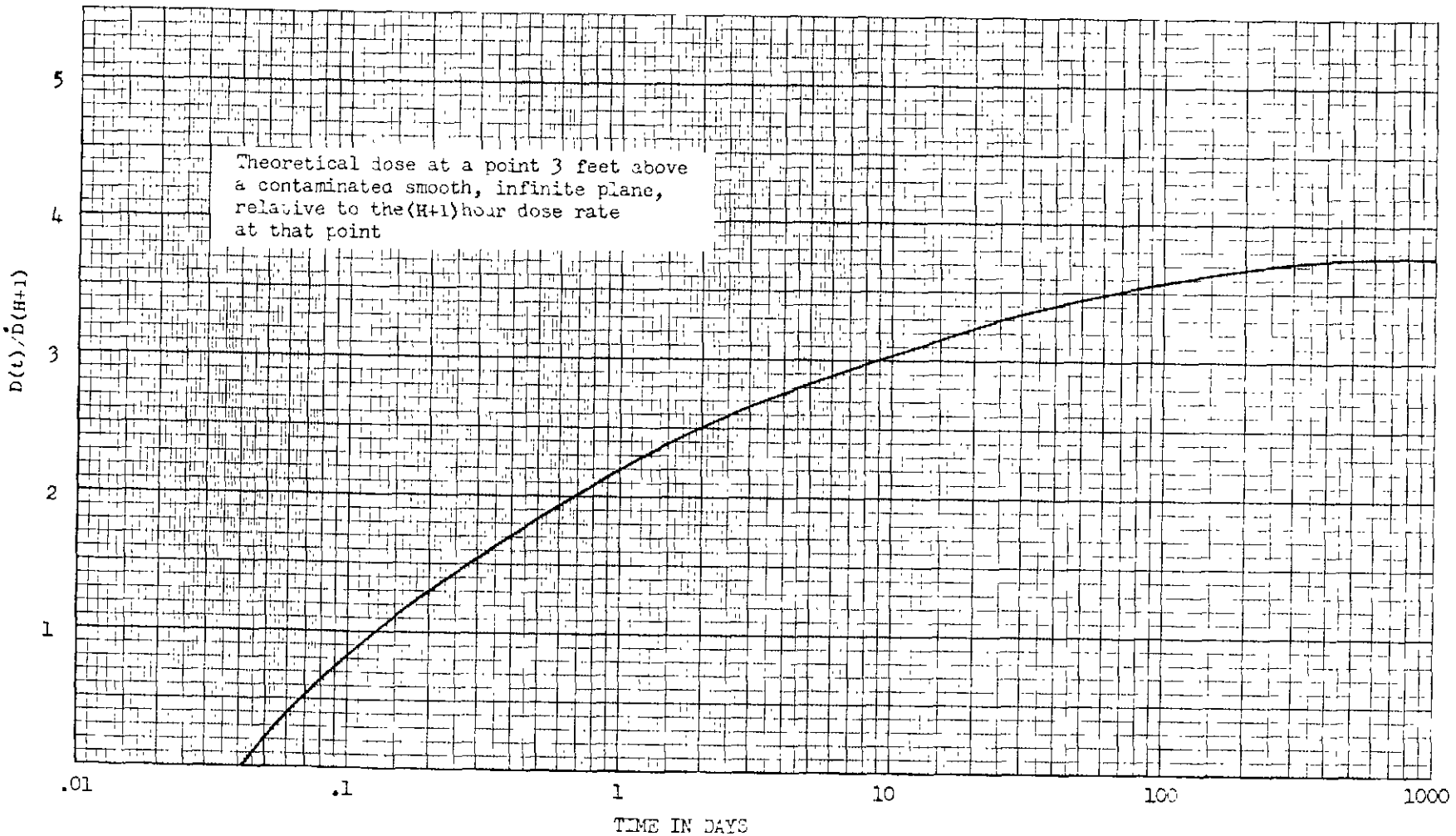
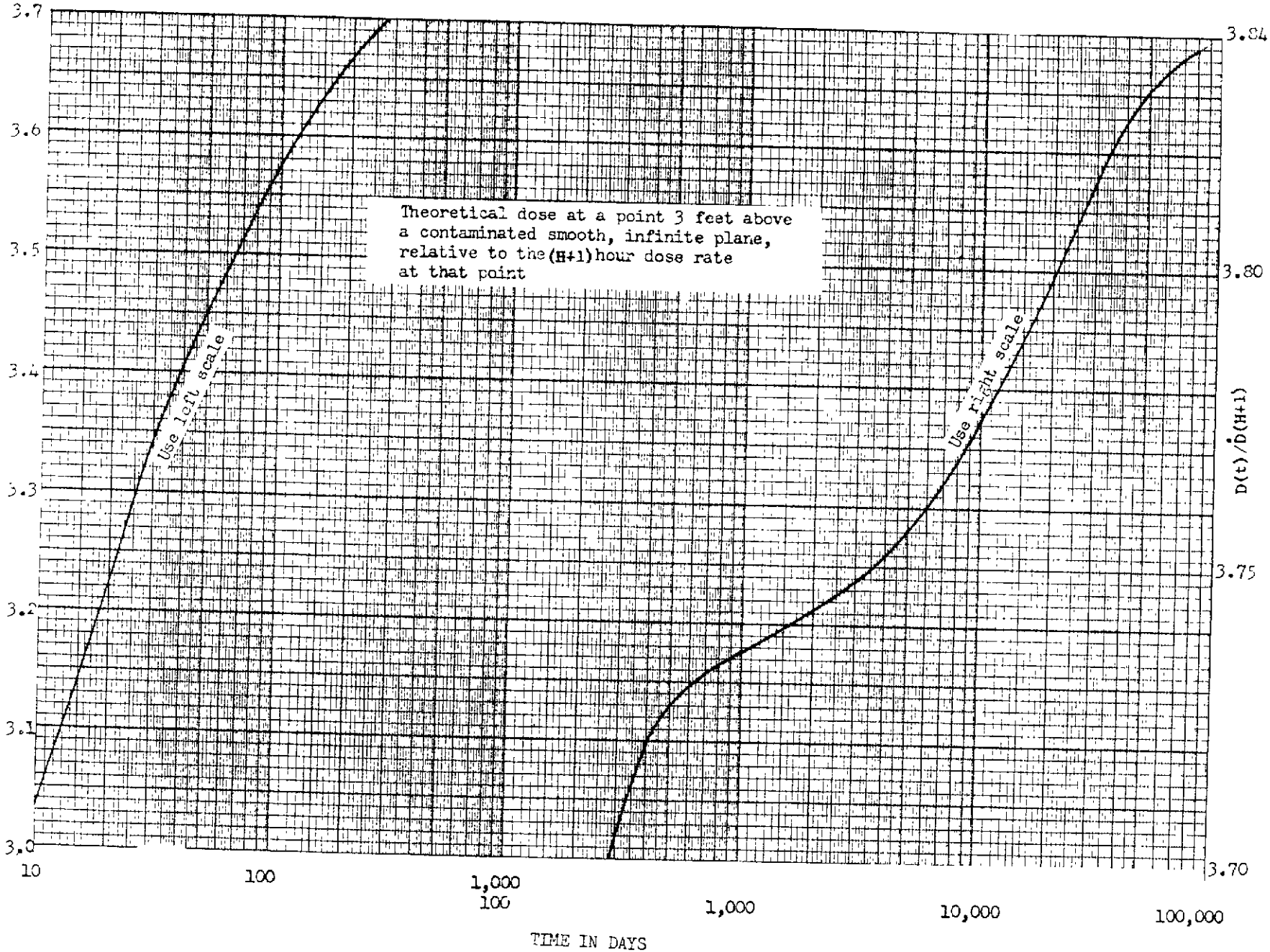

Theoretical dose at a point 3 feet above
a contaminated smooth, infinite plane,
relative to the (H+1) hour dose rate
at that point
D(t)/Ḋ(H+1)
5
4
3
2
1
.01
.1
1
10
100
1000
TIME IN DAYS

FIGURE 4


Theoretical dose at a point 3 feet above a contaminated smooth, infinite plane, relative to the (H+1) hour dose rate at that point
Use left scale
Use right scale
D(t)/Ḋ(H+1)
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
3.84
3.80
3.75
3.70
10
100
1,000
100
1,000
10,000
100,000
TIME IN DAYS

Figure

Table I

Dose relative to H+1 hour dose rate received during the following time intervals

Δt	$\frac{D(\Delta t)}{\dot{D}(H+1)}$, r/hr	$D(\Delta t)$, r / Kt/mi^2
1 - 6 hr.	1.42	3,905
6 - 12 hr.	0.38	1,045
12 - 24 hr.	0.40	1,100
2nd day	0.30	825
3rd day	0.10	275
4th day	0.08	220
5th day	0.05	138
6th day	0.05	138
7th day	0.05	138
1st week	2.93	8,060
2nd week	0.19	523
3rd week	0.11	311
4th week	0.089	245
5th week	0.054	149
6th week	0.039	107
7th week	0.033	91
1st month	3.31	9,100
2nd month	0.17	468
3rd month	0.075	206
4th month	0.045	124
5th month	0.031	85
6th month	0.025	69
7th month	0.015	41
8th month	0.015	41
9th month	0.012	33
10th month	0.007	19
11th month	0.007	19
12th month	0.005	14
1st year	3.72	10,230
2nd year	0.016	44
3rd year	0.004	11
4th year	0.003	8.3
5th year	0.0025	6.9

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