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AIRCRAFT IONIZING DOSES AND DOSE RATES FROM RADIOACTIVE CLOUDS AND FALLOUT

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Final Report

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AIR FORCE WEAPONS LABORATORY

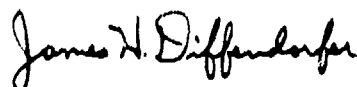Air Force Systems Command

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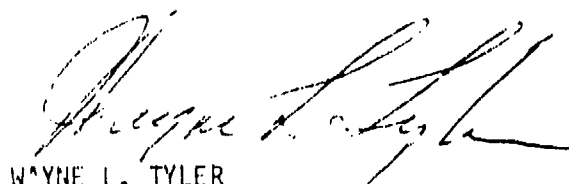
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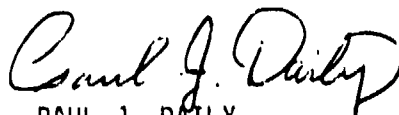This technical report has been reviewed and is approved for publication.
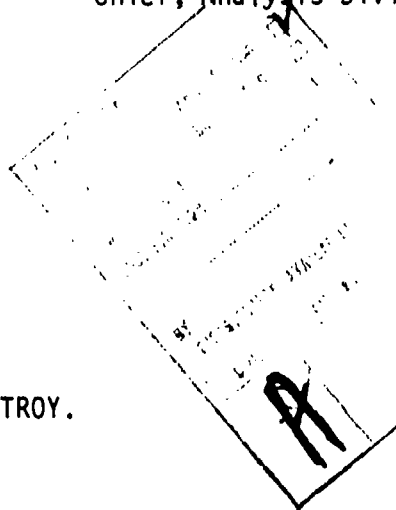

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Aircraft flying over surface areas contaminated by fallout from radioactive clouds from surface nuclear detonations accumulate ionizing doses. An investigation of this situation was accomplished, and the dose and dose rate resulting from such fly-overs are presented. The dose rates were also determined for aircraft approaching radioactive clouds and fallout contaminated surface areas. The results are presented in general terms, and examples are presented to illustrate the manner of applying the general results to specific situations.

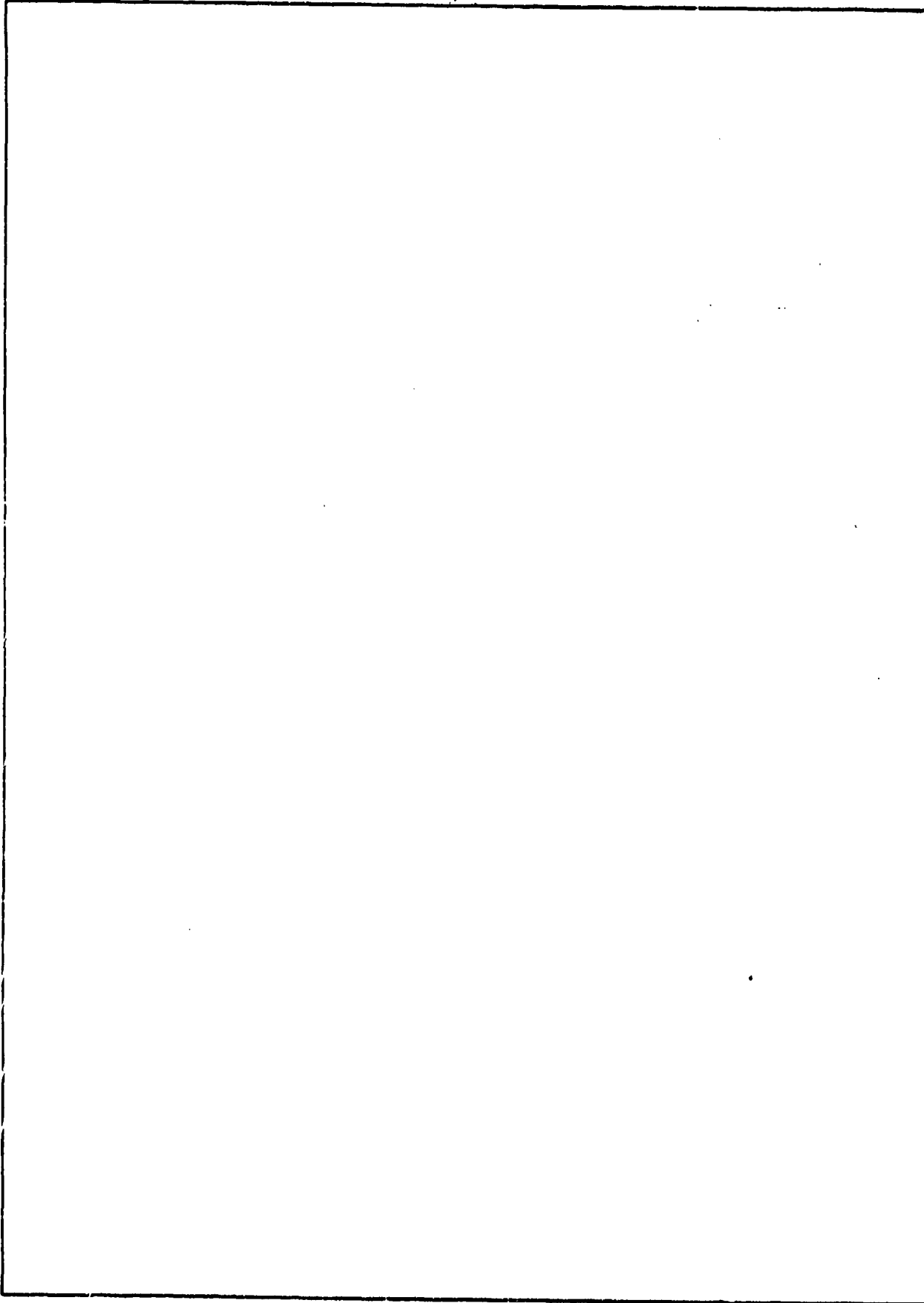DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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ILLUSTRATIONS (Continued)

SECTION I

INTRODUCTION

Aircraft with a strategic mission in a general war or in any conflict involving nuclear weapons could be subjected to various environments generated by the detonations of nuclear weapons. During a representative mission, the aircraft could be targeted by enemy submarine-launched ballistic missiles (SLBMs) during base escape, it could penetrate late-time radioactive clouds generated by detonations of enemy nuclear weapons at missile sites or other hard targets, it could be targeted by surface to air missiles (SAMs) and/or by air to air missiles (AAMs), it could be exposed to environments generated by collateral weapon detonations, and it could be subjected to ionizing radiation during damage assessment surveys.

At the present time there are analytical tools available and documented to aid the analyst in investigating the majority of the postulated situations. Nuclear blast and thermal environments can be predicted with reasonable accuracy using computer codes such as SPARK* (ref. 1) and SNARE* (ref. 2). The aircraft response can be estimated using VIBRA-4 (ref. 3), a nuclear gust response code; NOVA* (ref. 1), a nuclear overpressure response code, and TRAP* (ref. 2), a nuclear thermal response code. Electromagnetic pulse (EMP) environments can be estimated using the EMP Phenomenology Handbook (reference 4) or EMP environmental prediction codes. The system EMP response is not straightforward, but efforts are underway at the Air Force Weapons Laboratory to develop the technology base required for such analyses. Reference 5 can be used to estimate system responses to EMP.

Prompt nuclear radiation environments can be predicted using SMAUG (ref. 6) and initial nuclear radiation environments by using FIREFLY** (ref. 7).

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*SPARK and SNARE are environmental subroutines contained in the NOVA and TRAP computer codes.

**Prompt nuclear radiation environments are those generated by detonation and are associated with pulse durations of a few microseconds in duration. Initial nuclear radiation environments include fission product gamma radiation and are associated with times up to one minute after detonation. Initial nuclear radiation environments include the prompt environments.

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Ionizing dose accumulated during radioactive cloud penetrations can be esti-
mated using the results presented in reference 8. Response to nuclear
radiation generally is associated with electronic equipment and/or the aircrew
and can be estimated using available techniques. For example, equipment
response can be estimated using manual circuit analysis techniques or computer
codes such as SCEPTRE (refs. 9 & 10) and human response can be estimated using
techniques and information from such publications as references 11, 12, and 13.

However, there is one situation in which the tools noted above are inade-
quate, namely damage assessment surveys. A part of the mission of some air-
craft, e.g., manned bombers, is the surveying of targets of previous attacks
to insure that adequate damage has been inflicted. This survey could involve
the low-altitude fly-over of ground areas contaminated by neutron activation
of surface material and fallout of radioactive dust and weapon debris from the
radioactive cloud. This report addresses this deficiency by developing an
engineering model of the ground accumulation of fallout and by calculating the
ionizing doses (and dose rates) which an aircraft above this material would
accumulate.

One additional area is also investigated, i.e., the dose rate as a function
of horizontal distance from the radioactive area of ground and from the radio-
active dust cloud. These results may prove useful to nuclear survivability/
vulnerability (S/V) analysts investigating the feasibility of using radiation
sensors to detect radioactive clouds and surface areas at distances sufficient
for avoidance maneuvers.

SECTION II

CALCULATIONS

SURFACE ACTIVITY CALCULATION

The calculations of the ionizing dose, D, accumulated by an aircraft flying over an infinite* radiating plane and the associated ionizing dose rate, $\dot{D}$, are conceptually quite simple. The governing equations can be derived from the geometries depicted in figure 1.

$$\dot{D}(t) = \int_0^{2\pi} \int_0^{\infty} \frac{A_s(t)\ e^{-\mu'(h^2 + X^2)^{1/2}}\ XdXd\theta}{4\pi\ (h^2 + X^2)} \tag{1}$$

$$D(t) = \int_t \dot{D}(t)\ dt \tag{2}$$

where A_s is the surface activity in photons/cm^2-hr., h is the aircraft altitude in meters, t is time in hours after detonation, and μ' is the atmospheric absorption factor. ($\mu' = 6.767 \times 10^{-3}$ m^{-1} at 1000 meters above sea level).

Although conceptually simple, the above calculations in practice are almost impossible to perform because of the difficulty in defining the surface activity. The above equations are based on the implicit assumption that the surface activity is the result of uniformly distributed radioactive material and is therefore only a function of time. In reality, the surface activity is a complicated function and varies with location as well as time. There are "hot spots" and gradients caused by winds, surface irregularities, detonation geometries, nonuniform cloud fallout, and numerous other factors. To obtain even approximate results, simplifying assumptions must be made. The major ones

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*Infinite in this context implies a radius, R_p, such that the majority of photons emitted from sources outside a sphere of radius R_p, are absorbed by the atmosphere. For an altitude of 30,000 feet, R_p is about 3000 meters, and for an altitude of 1000 meters, R_p is about 1100 meters.
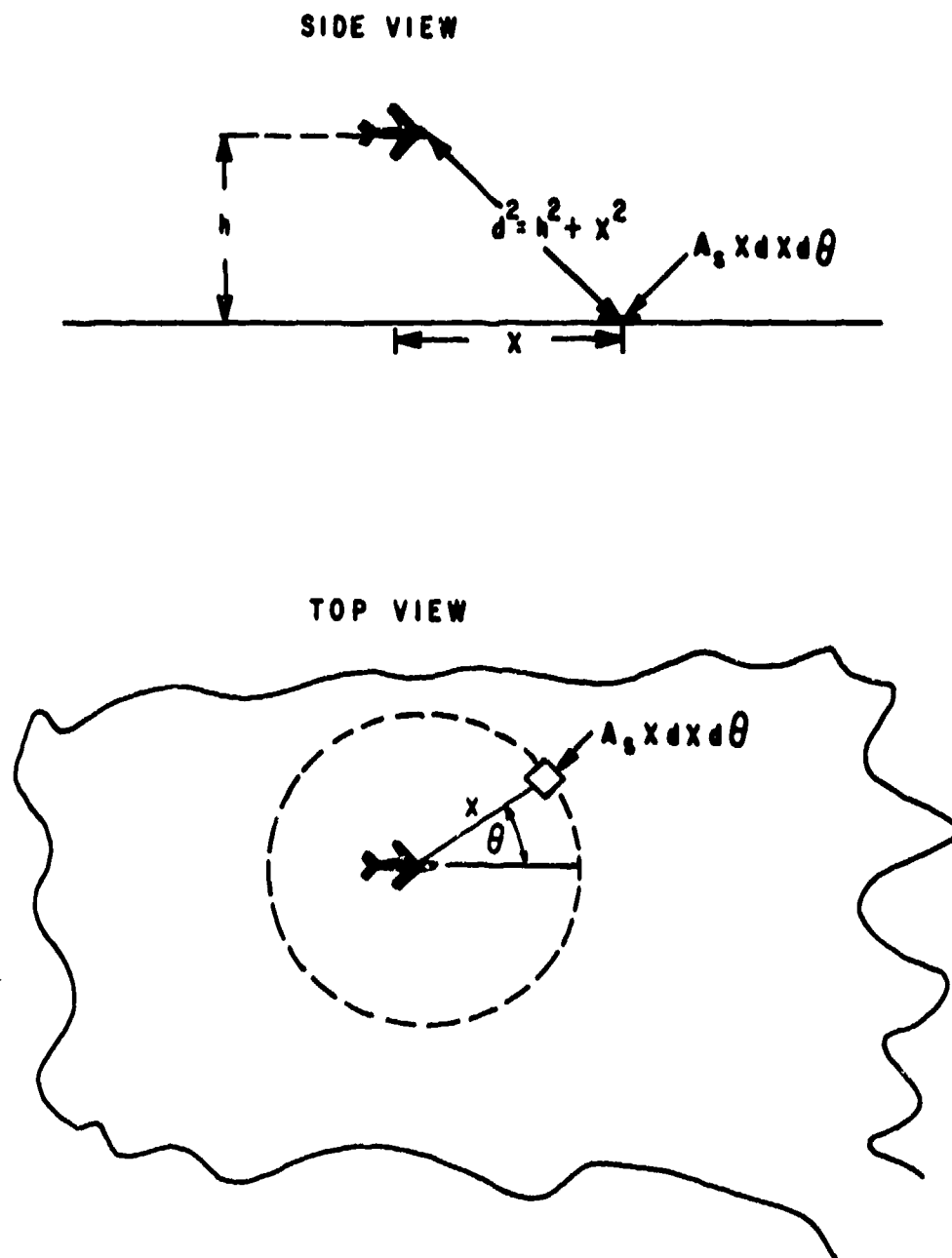
SIDE VIEW

TOP VIEW

Figure 1. Geometries for Fly-over of Radioactive Surface Area

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made in this report are that the surface activity is only a function of time
and that it can be approximated by using the simple engineering cloud model
developed in reference 8. This uniform distribution assumption can be argued
to yield representative results for a flyover of the contaminated area because
the integrated results for a flyover should be similar in value for a uniform
distribution of radioactive material as for the complicated, real distribution.
However, local results could vary by large margins.

The surface activity, $A_s(t)$, of the surface is assumed to be a result of
two mechanisms, neutron activation of surface materials and fallout of radio-
active material. At early times, i.e., less than 10 minutes after detonation,
there is so much turbulence and large airborne crater ejecta that aircraft could
not survive near the detonation point. Therefore this analysis shall limit
consideration to times greater than 10 minutes after detonation. (The same
assumption was made in reference 7 in the investigation of radioactive cloud
penetrations.) At 10 minutes after detonation, the larger crater ejecta and
other surface material swept up into the cloud during and immediately after
detonation should have fallen out and accumulated on the ground. Associated
with this material and the neutron activated surface material is some activity,
$A_{s_1}(t)$, termed the 10 minute surface activity. The remainder of the radio-
active material is suspended in the atmosphere and forms the radioactive dust
cloud. As the time after detonation increases, the material in the cloud falls
out of the cloud and accumulates on the surface. This cloud fallout material
results in additional surface activity, $A_{s_2}(t)$, termed fallout surface activity.
The total surface activity at time t is the sum of the 10 minute and fallout
activities.

$$A_S(t) = A_{s_1}(t) + A_{s_2}(t) \tag{3}$$

The amount of radioactivity associated with the very large particles (those
which have impacted the surface by 10 minutes after detonation) and with neutron
activated surface material is significant, especially at early times, and must
be considered. However, the majority of the radioactive material is contained
in the radioactive cloud.

For conservation, it was assumed in reference 8 that at 10 minutes, all of
the radioactivity resulting from the detonation was contained in the cloud as
coatings on dust particles or as condensed weapon debris. In this analysis,

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it is postulated that the total surface radioactivity at 10 minutes is 10 percent of the total cloud radioactivity at 10 minutes. The only time dependence exhibited by the 10 minute surface activity then should be the standard one used in Glasstone (ref. 14).

Total activity in the cloud is just the specific activity of the cloud, A, in photons/gram (dust) - hour, multiplied by the total dust mass in the cloud, i.e., A · surface area · cloud height · cloud dust density. The 10 minute surface activity then is this total cloud activity multiplied by 10 percent and then divided by the surface area. Performing these operations yields the relation

$$\frac{A_{s1}}{K_8} = 1.75t^{-1.2} \tag{4}$$

where $K_8 = 100\ h_0 a_1 A_1$ photons/hour - centimeter^2, $a_1 = 3.46 \times 10^{-6} L_f$ grams (dust)/centimeters^3, $A_1 = 4.22 \times 10^{12}$ photons/gram (dust)-hour, L_f is the load factor in megatons of yield per kilometers^2, and h_0 is the height of the cloud in meters.

The fallout surface activity, by definition, is zero at 10 minutes after detonation. However, as radioactive material falls out of the cloud and accumulates on the ground, the fallout surface activity level begins to acquire significance. The fallout surface activity is a complex function of time. It tends to increase with time because radioactive material is continually accumulating on the surface. But, at the same time, it tends to decrease because of the standard radioactive decay process.

To estimate the behavior of the fallout activity an engineering model representative of the after-10-minute surface fallout accumulation is needed. Since the cloud model developed in reference 8 is judged to be reasonably representative of the actual cloud, it will be a basis for the surface fallout model. The cloud model is based on several assumptions. The major ones are 100 percent fusion yield of the warheads, 1 megaton of dust lofted per megaton of yield, zero wind, fallout of dust particles based on Stokes Law type behavior of small particles, representative soil at the detonation site, and postulated specific activities based on particle size. The cloud model, although simple conceptually, was forced to agree with the output of complex computer codes (see reference 8) in terms of dust density as a function of time,

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and hence should be indicative of the actual cloud. Another significant assumption is that the early time turbulence results in a uniform mixture of particle sizes over the pertinent surface area to an altitude of 15 kilometers. For single detonations, the pertinent surface area is a circle with radius of R_c kilometers, where

$$R_c = 5.7W^{0.4}$$

where W is the yield in megatons. For a massive attack, i.e., many detonations over a relatively small area, the cloud radii may overlap, and the total surface area must be estimated by other techniques.

The cloud is characterized by two parameters: the dust density, ρ_d, in grams (dust) per centimeter^3, and the specific activity, A, in photons per gram (dust)-hour. These relations are expressed in the form

$$\rho_d(r,t) - 3.42 \times 10^{-6} L_f \ r^{-0.5} \quad 0.1\mu < r < R'(t) \quad (5)$$

$$A(r,t) = 5 \times 10^{13} \ t^{-1.2} \quad\quad 0.1\mu < r < 20\mu$$

$$A(r,t) = 10^{15} \ t^{-1.2} \ r^{-1.0} \quad\quad 20\mu < r < 10^4\mu \quad (6)$$

where $R'(t)$ = particle size fallout function in microns
$= \left[5.04 \ (t^{-1.6} + 1.313 \ t^{-0.3}) + 0.316\right]^2$, r is the particle radius in microns, and t is the time after detonation in hours.

For the fallout activity model, the 10 minute cloud will be assumed to be uniformly distributed over the volume discussed previously. All of the particles in the cloud are falling with some vertical velocity, V. It is assumed the particles are spherical and that there are two vertical forces acting on each particle: the weight of the particle and the aerodynamic drag. Figure 2 shows these forces. Summing vertical forces yields the relationship

$$\frac{4}{3} \pi r^3 \rho_d \ g = \frac{1}{2} \rho_a \ V^2 \ C_D \pi r^2$$

Solving for the vertical velocity yields

$$V = \left(\frac{8}{3} \frac{\rho_d}{\rho_a} \frac{r \ g}{C_D}\right)^{1/2} \quad (7)$$

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$$F_c = 1/2 \, \rho_a \, v^2 \, \pi r^2 \, C_D$$

DRAG FORCE

DUST
PARTICLE

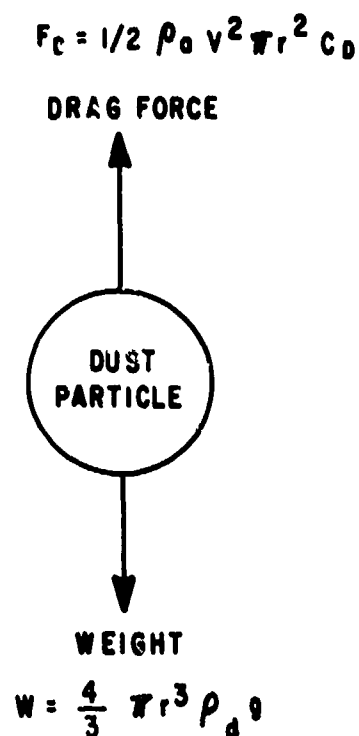**WEIGHT**

$$W = \frac{4}{3} \, \pi r^3 \, \rho_d \, g$$

Figure 2. Vertical Forces Acting on a Dust Particle in the Dust Cloud

where g is the gravitational constant, ρ_d is the density of the particle, ρ_a is the density of the air, r is the particle radius, and C_D is the drag coefficient of the sphere. This drag coefficient has been experimentally measured, and its behavior as a function of Reynolds Number* is depicted in figure 3, which is adapted from Binder (ref. 12). This curve was approximated over the various Reynolds Number ranges depicted in the figure by the following expressions. (The approximations are the dashed lines.)

$$C_D = 24/Re \quad 0.1\mu < r < 60\mu \tag{8}$$

*The Reynolds Number, Re, is a nondimensional parameter and is

$$Re = \frac{\rho_a \, V \, d}{\mu_a}$$

where d is the diameter of the sphere and μ_a the dynamic viscosity of air.
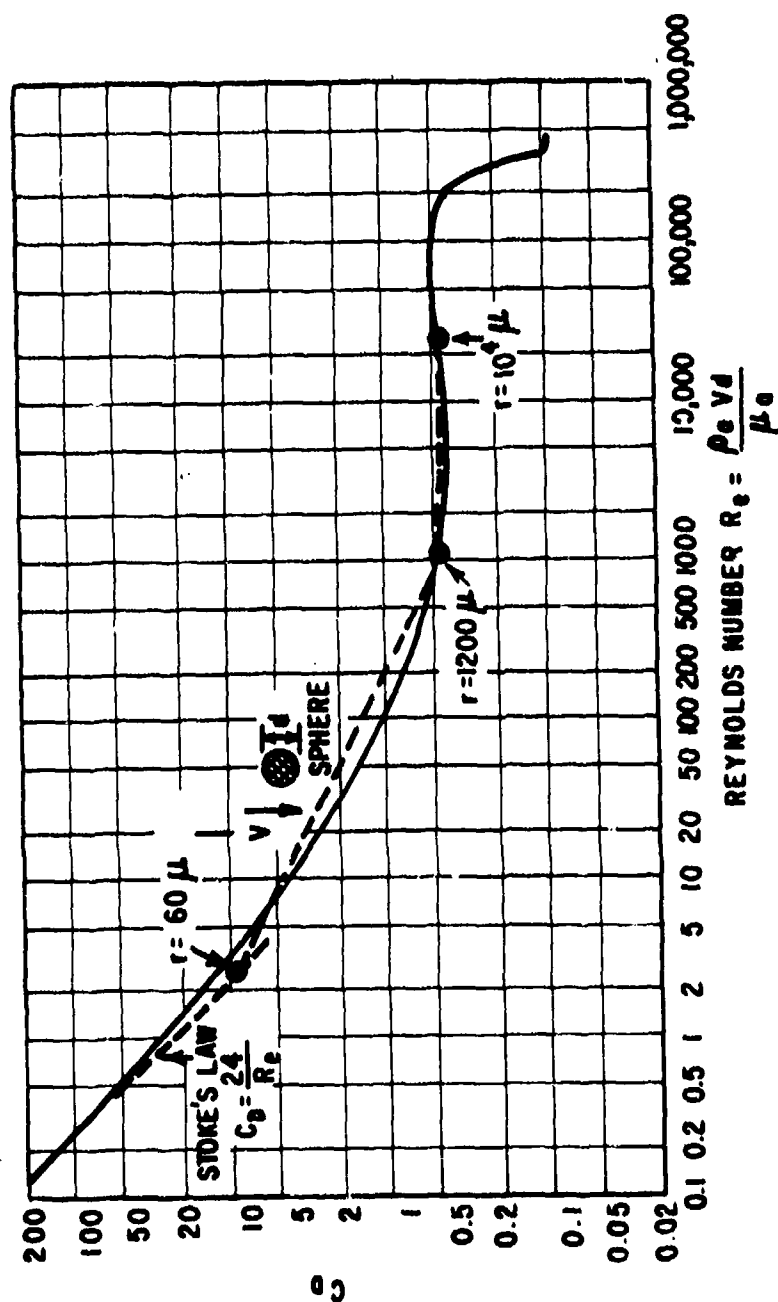
Figure 3.   Drag Coefficient of Dust Particles in the Dust Cloud.
(Adapted from Binder ref. 15)

$$C_D = 14.79/Re^{0.5} \qquad 60\mu < r < 1200\mu \qquad (9)$$

$$C_D = 0.4557 \qquad 1200\mu < r < 10^4\mu \qquad (10)$$

These expressions in conjunction with the previous equation define the particle settling velocity as a function of particle size. Note that large particles have larger velocities and hence accumulate faster on the surface.

Now consider a portion of the cloud over a square centimeter of the surface. The particles in this volume at various times are depicted in particle size-altitude space in figure 4. At 10 minutes, particles are uniformly distributed over all altitudes. Since the larger particles fall faster, the higher altitude
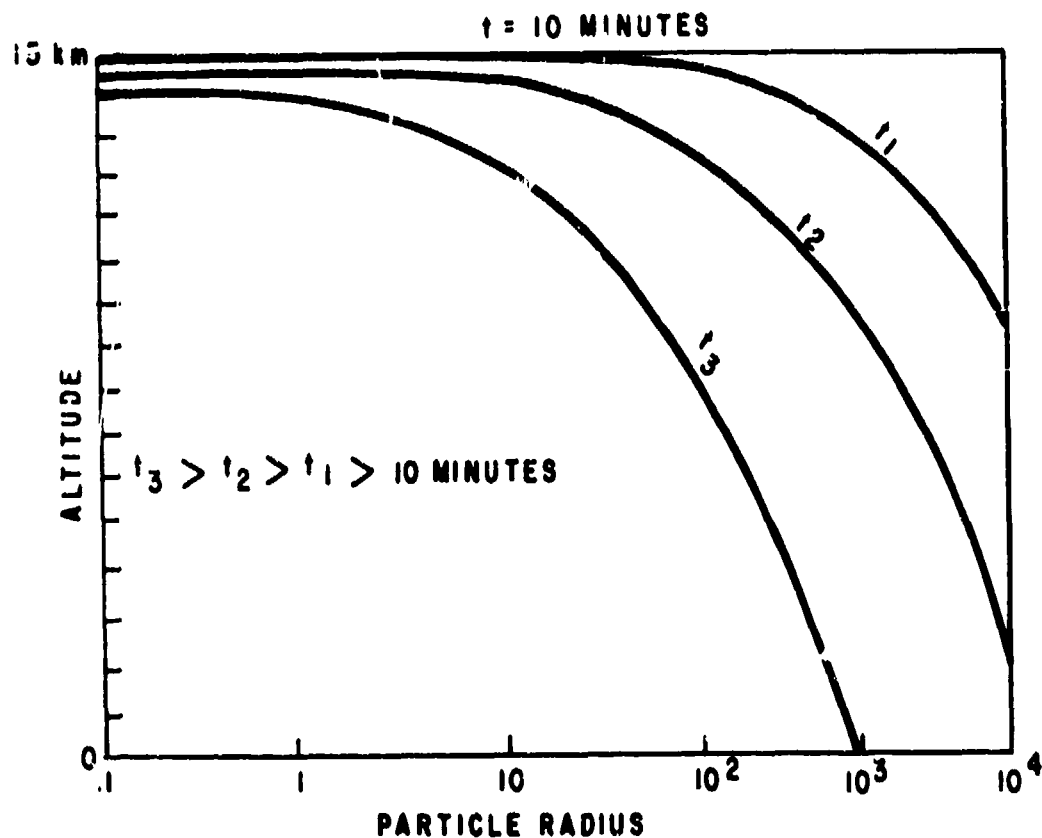

Figure 4. Particle Size Distribution with Altitude and Time
for Radioactive Dust Clouds

dust cloud strata will be depleted of these particles at late times. The total mass of particles in the depleted regions can be calculated because the vertical velocity of each particle size is known. The dust mass multiplied by the specific activity (both are functions of particle size) and then integrated over the depleted region in the depleted space indicated in figure 4, results in the surface fallout activity, $A_{s_2}(t)$.

$$A_{s_2}(t) = \int_{0.1\mu}^{60\mu} \int_{h_3(r,t)}^{h_o} \rho_d(r,t_o) A(r,t) \, dh dr$$

$$+ \int_{60\mu}^{1200\mu} \int_{h_2(r,t)}^{h_o} \rho_d(r,t_o) A(r,t) \, dh dr$$

$$+ \int_{1200\mu}^{10,000\mu} \int_{h_1(r,t)}^{h_o} \rho_d(r,t_o) A(r,t) \, dh dr \qquad (11)$$

where t_o is 10 minutes after detonation and is constant, h_o is the cloud height (assumed to be 15,000 meters), and from the particle velocity relations

$$h_1(r,t) = h_o - 1797.6 \, r^{0.5}(t-t_o) \qquad 1200\mu < r < 10^4\mu$$

$$h_2(r,t) = h_o - 51.9 \, r \, (t-t_o) \qquad 60\mu < r < 1200\mu$$

$$h_3(r,t) = h_o - 0.86 \, r^2 \, (t-t_o) \qquad 0.1\mu < r < 60\mu$$

Performing the indicated operations yields the analytical expression

$$\frac{A_{s_2}(t)}{K_B} = 1.0694 \, t^{-0.2} - 1.787 \, t^{-1.2} \qquad (12)$$

The integrations were performed on the Air Force Weapons Laboratory CDC 6600 computer. The results are depicted in figures 5 and 6. Figure 5 shows the generalized results in terms of K_B, and figure 6 shows the specific results for a 4-megaton surface detonation. The results for a specific threat provide
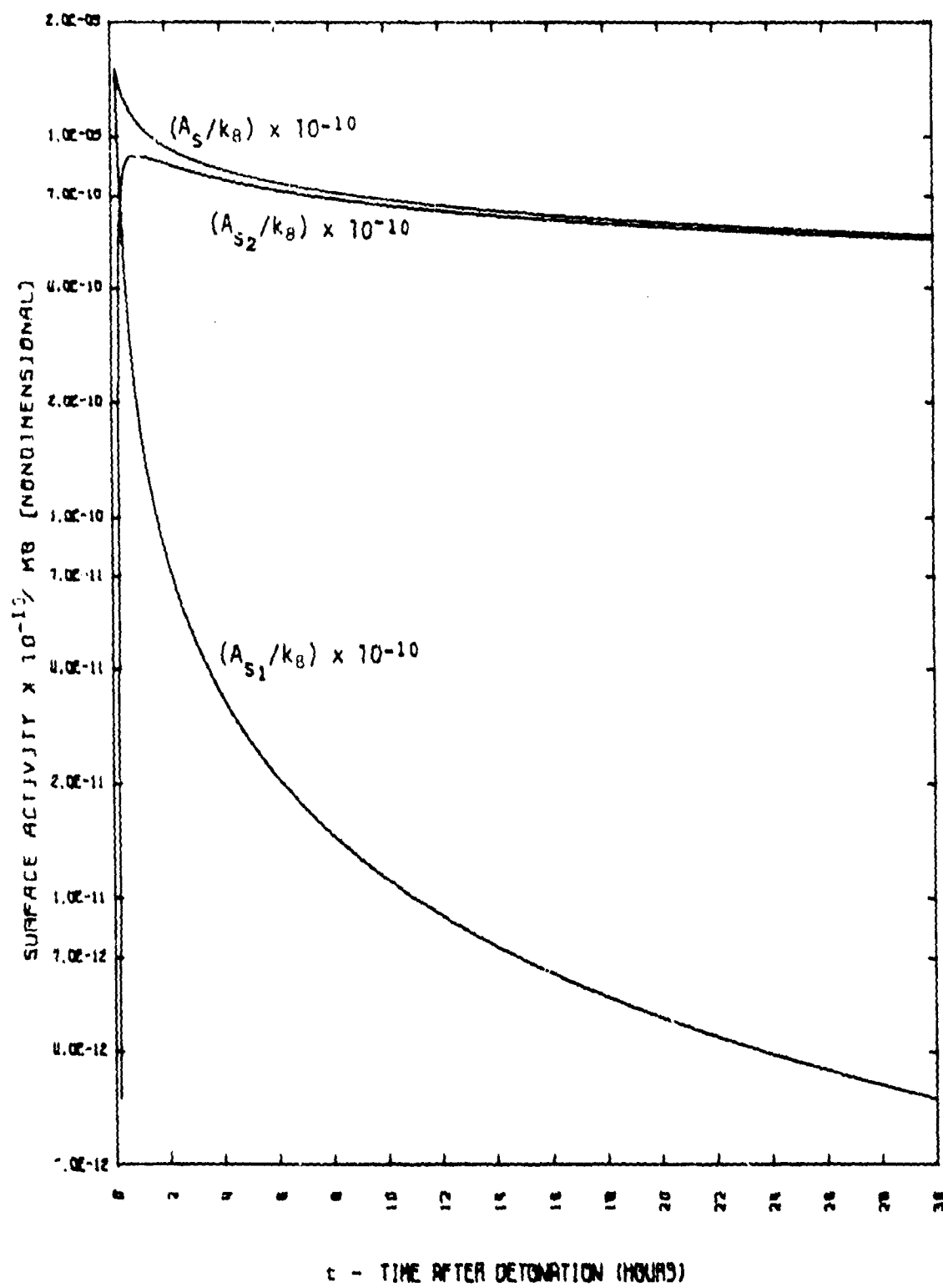
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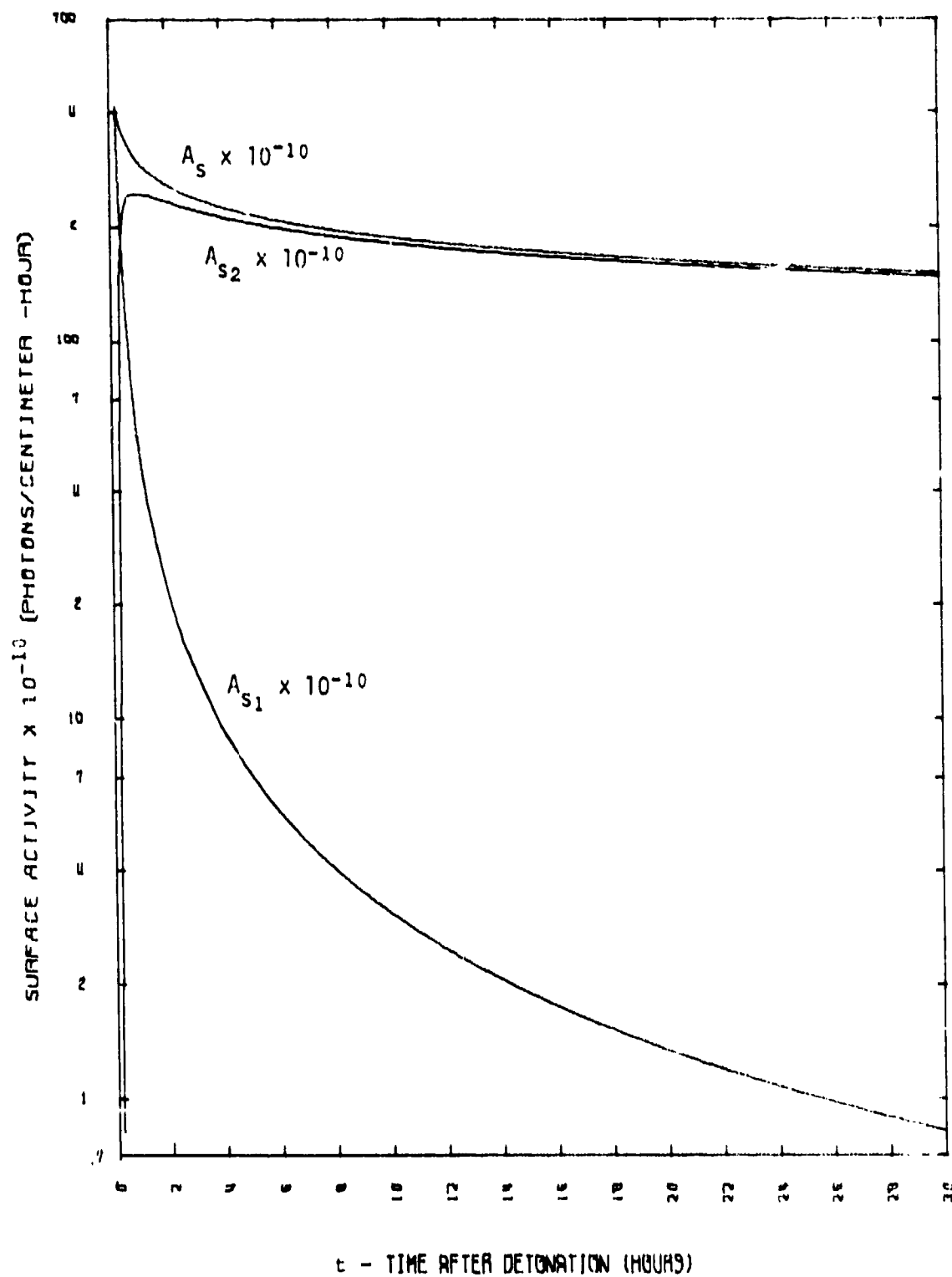Figure 5. Generalized Surface Activities

Figure 6. Surface Activities (4 MT Threat)

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physical insight into the levels of activity that may be observed from a typical detonation. Note that for times less than 1 hour after detonation the 10 minute surface activity is the dominant factor. However, at late times it becomes less significant, and the fallout surface activity becomes dominant (figs. 5 & 6).

Note that in case the cloud is relocated by the wind, only the fallout surface activity would be used to calculate doses and dose rates for flyovers of the new surface where $A_{s_1}(t) = 0$. The dose rate and dose at an aircraft at altitude h would be determined using equations (1) and (2) with $A_s(t) = A_{s_2}(t)$.

FLYOVER DOSE AND DOSE RATE CALCULATIONS

The calculations of the ionizing dose accumulated by an aircraft flying over the contaminated surface at an altitude h and of the ionizing dose rate as a function of time after detonation can now be made. The governing equations are equations (1) and (2), introduced in the previous section, with the surface activity, A_s, in these equations being defined by equations (3), (4), and (11). Performing the indicated operations for a baseline aircraft altitude of 100 meters above the contaminated surface (assumed to be 1000 meters above sea level) yields a dose rate, $\dot{D}_f(t)$ in $\frac{\text{rads (tissue)}}{\text{hour}}$ at the aircraft defined

by the equation

$$\frac{\dot{D}_f(t)}{K_9} = 2.1\ t^{-0.2} - 6.7 \times 10^{-3}\ t^{-1.2} \tag{13}$$

where $K_9 = C\ K_8$ and $C = 4.88 \times 10^{-10}$ rads (tissue)/photon/cm^2
(for the assumed 1 MeV photons).
The dose $D_f(t)$ in rads (tissue) accumulated by the crew of the aircraft from some contaminated area entry time t_i and to some exit time t (where both times are in units of hours after detonation) is defined by the equation

$$\frac{D_f(t)}{K_9} = 2.61\ (t^{0.8} - t_i^{0.8}) + 3.36 \times 10^{-2}\ (t^{-0.2} - t_i^{-0.2}) \tag{14}$$

The dose rate results are presented in figures 7 to 10 and the dose results in figures 11 to 14. The generalized results in figures 7, 8, 11, and 12 are presented in terms of the constant, K_9 rads (tissue)/hour. This constant is used to generalize the results. For a given threat this constant is fixed,
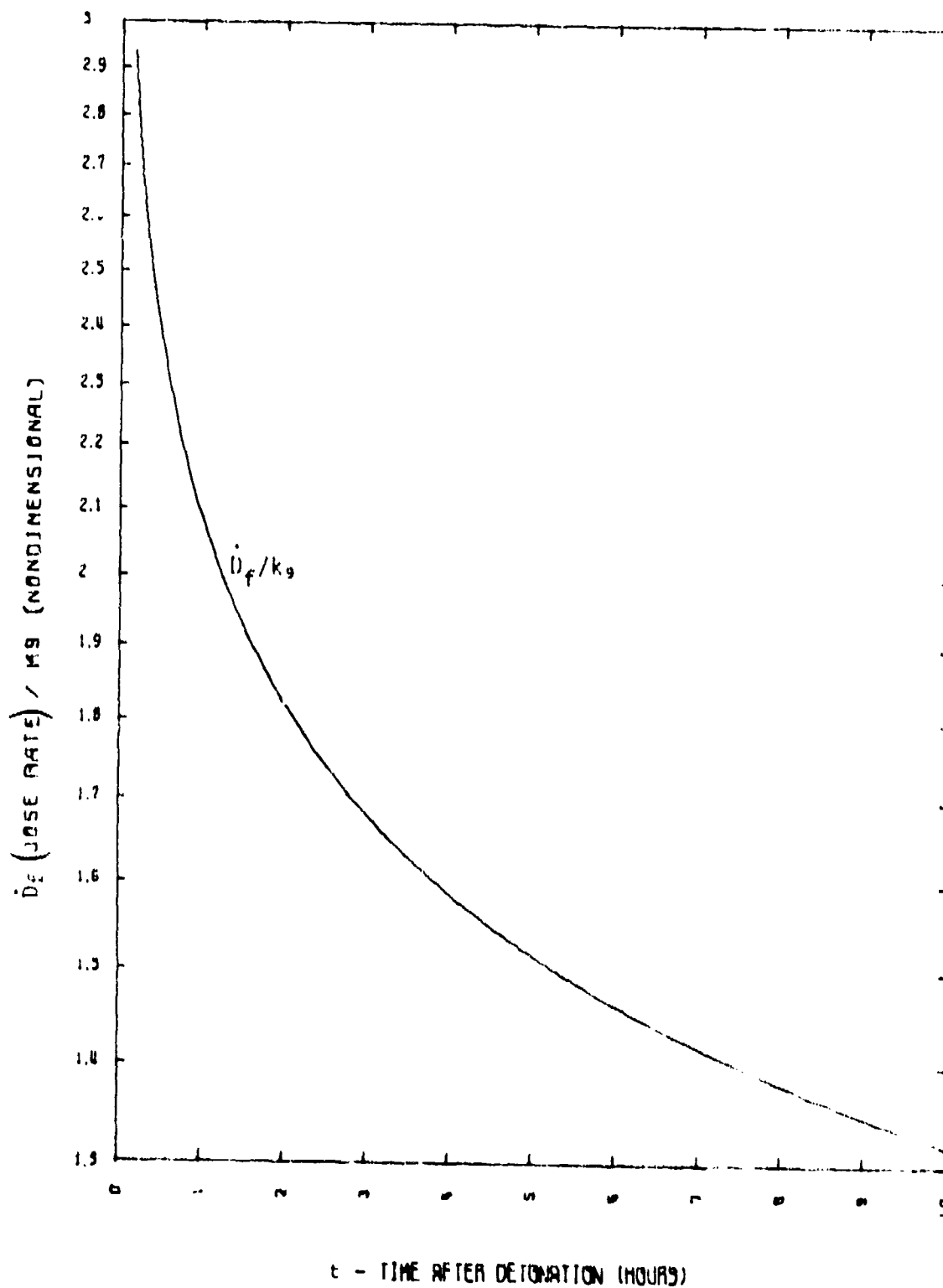
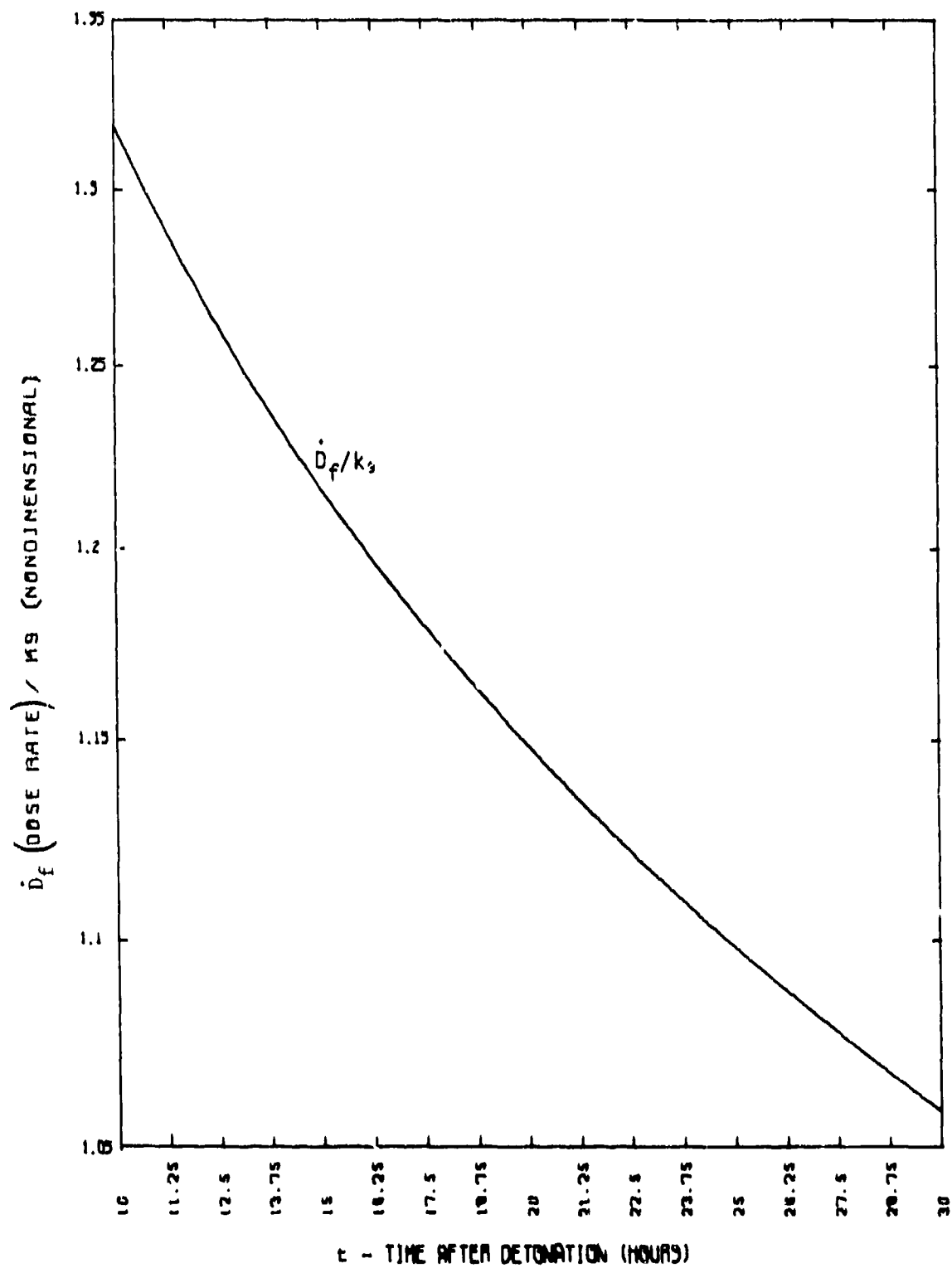Figure 7. Generalized Flyover Dose Rate (Altitude = 100 Meters)

Figure 8. Generalized Flyover Dose Rate (Altitude = 100 Meters)
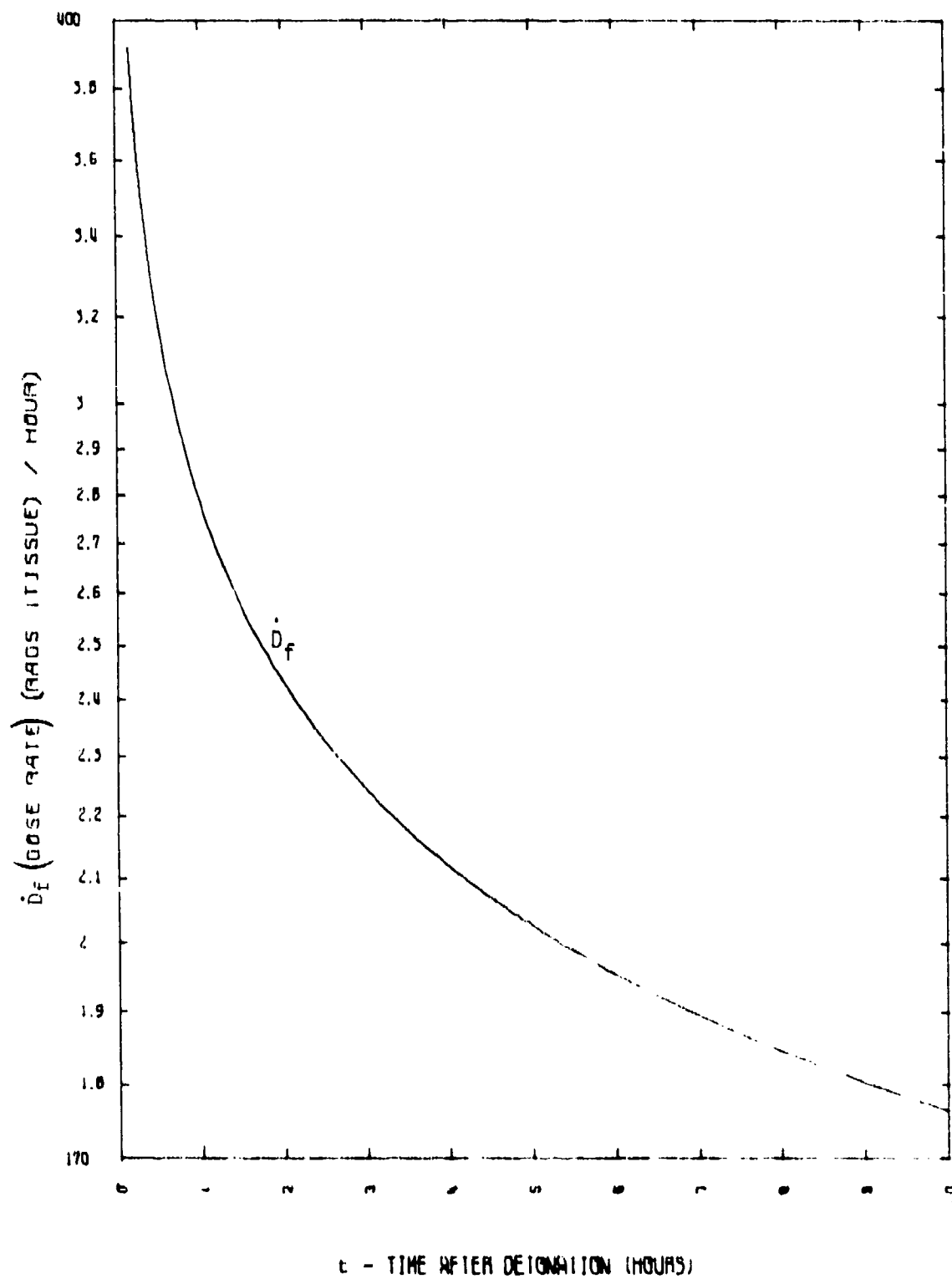
Figure 9. 4 MT Flyover Dose Rate (Altitude = 100 Meters)
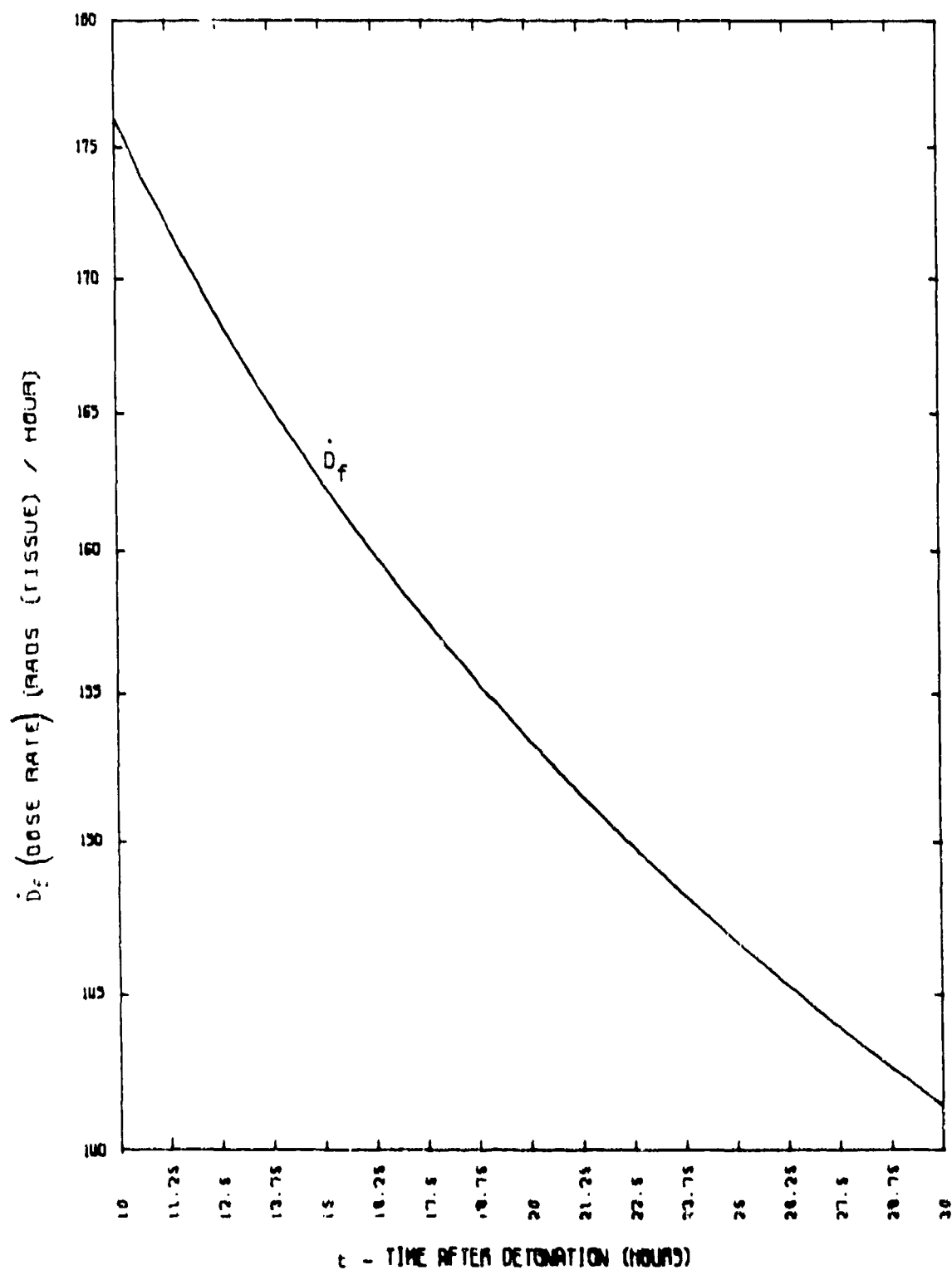
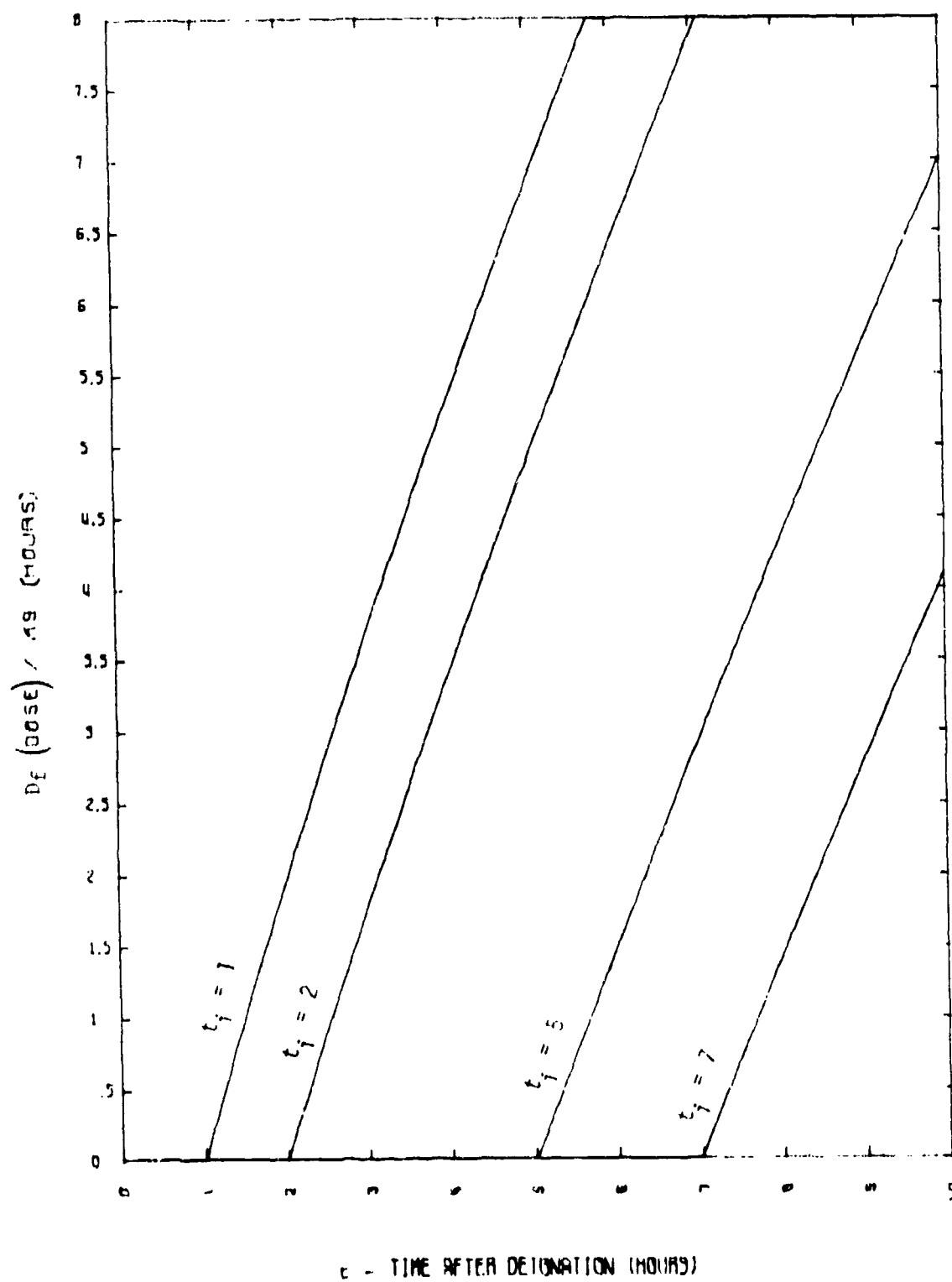Figure 10. 4 MT Flyover Dose Rate (Altitude = 100 Meters)

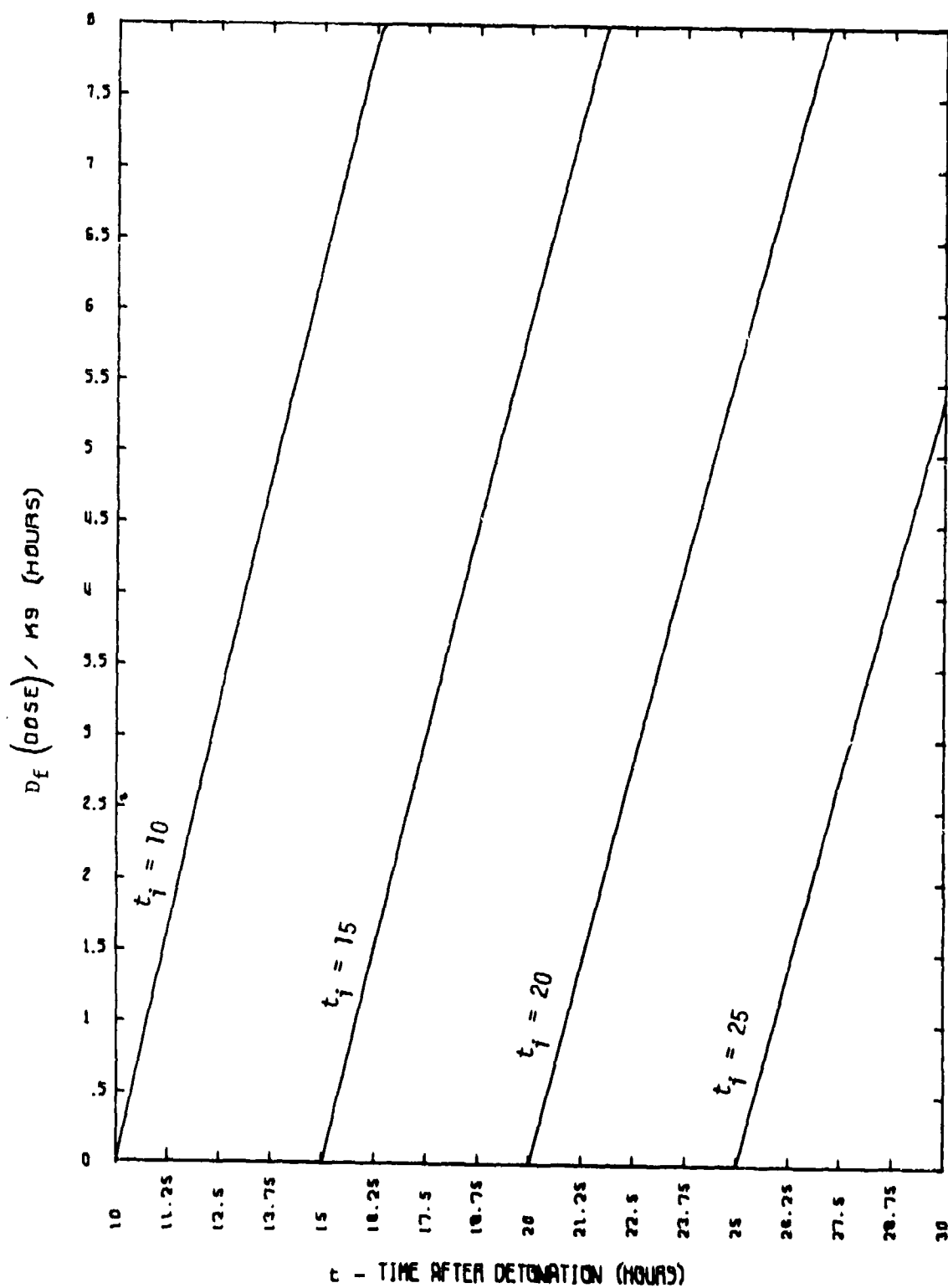Figure 11. Generalized Flyover Dose (Altitude = 100 Meters)

Figure 12. Generalized Flyover Dose (Altitude = 100 Meters)

and specific dose rates and doses can be obtained. Figures 9, 10, 13, and 14 correspond to a specific threat and are presented to give the user a "feel" for the type of results he may encounter. These figures are based on a 4 megaton (MT) surface detonation, i.e., $L_f = 0.0129$ MT/km².

All of these results are for a baseline aircraft altitude of 100 meters. Scaling factors to make these results applicable to other altitudes are presented in figure 15. To use this scaling factor, first determine the altitude of interest, then determine the pertinent scaling factor from figure 15. (For example, if the aircraft altitude is 200 meters, the scaling factor is 0.34.) The scaling factor is applied to the ordinates of figures 7 to 14 by simple multiplication.

Note that the dose results are presented as families of curves, one curve for each contaminated area entry time. Therefore, for each flyover, the threat, the aircraft altitude, the entry time, and the contaminated area exit time must be known in order to "fix" the ionizing dose accumulated by the aircraft. The instantaneous ionizing dose rate for any time during flyover can also be "fixed." Note that the dose and dose rate results are presented in rads (tissue) which are directly applicable to the aircrew. If the results are desired in terms of rads (silicon) for application to electronic equipment, then the conversion factor to use (for the assumed 1 MeV photons) is

$$\text{rads (silicon)} = 0.922 \text{ rads (tissue)} \tag{15}$$

It is noted that during the flyover of the contaminated area, the aircraft may also be penetrating the radioactive cloud above this area. Therefore, the total ionizing dose accumulated would be the sum of the doses from (1) the contaminated surface and (2) the radioactive cloud. The first dose can be estimated using the methods and results presented in this paper. The second dose can be estimated by using the techniques and methods presented in reference 8.

To illustrate the technique of using these results, an example will be presented. Assume that a 4 megaton weapon had detonated on the surface

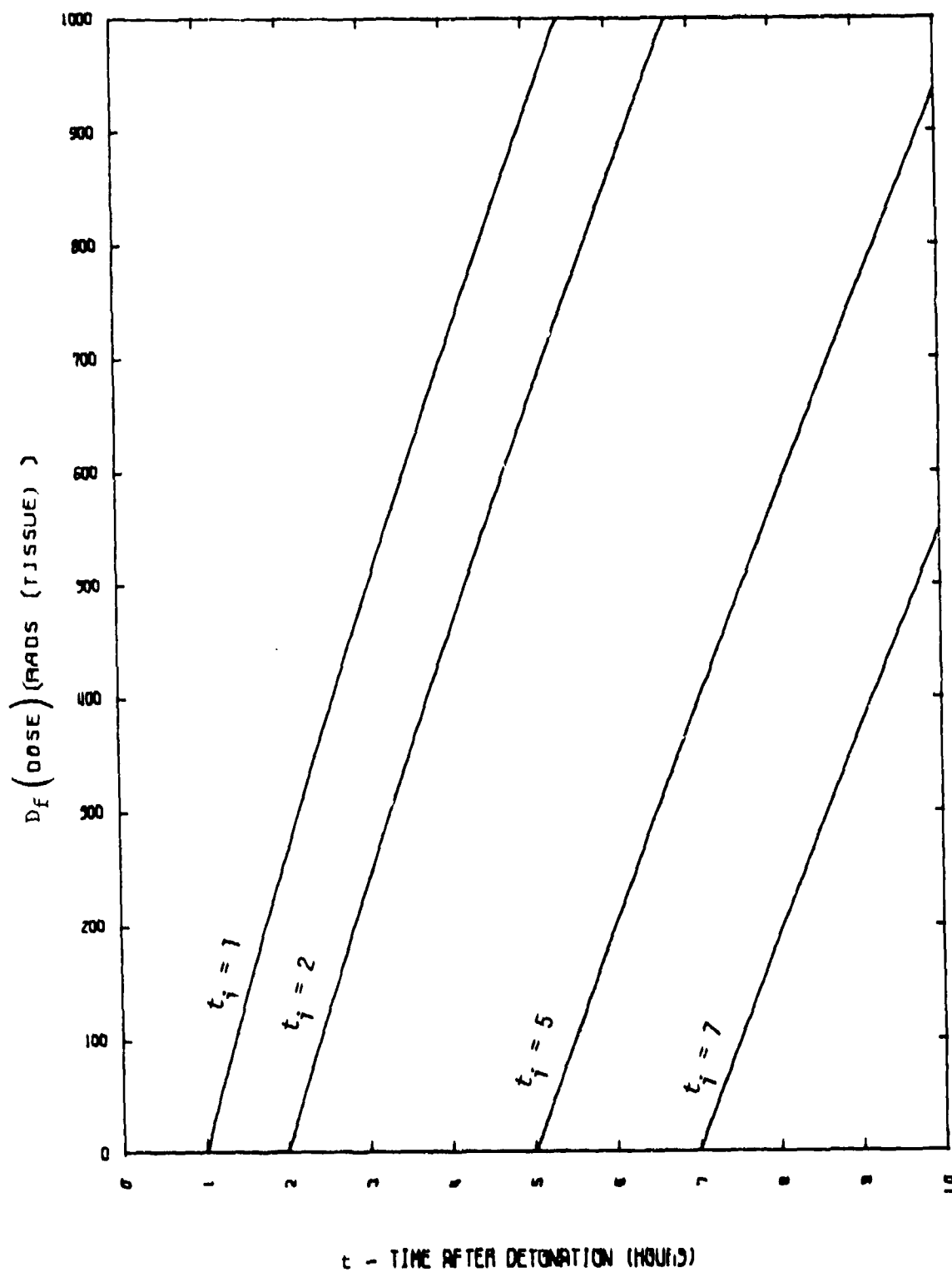$$R = 5.7(4)^{0.4}$$

$$R = 9.92 \text{ kilometers}$$

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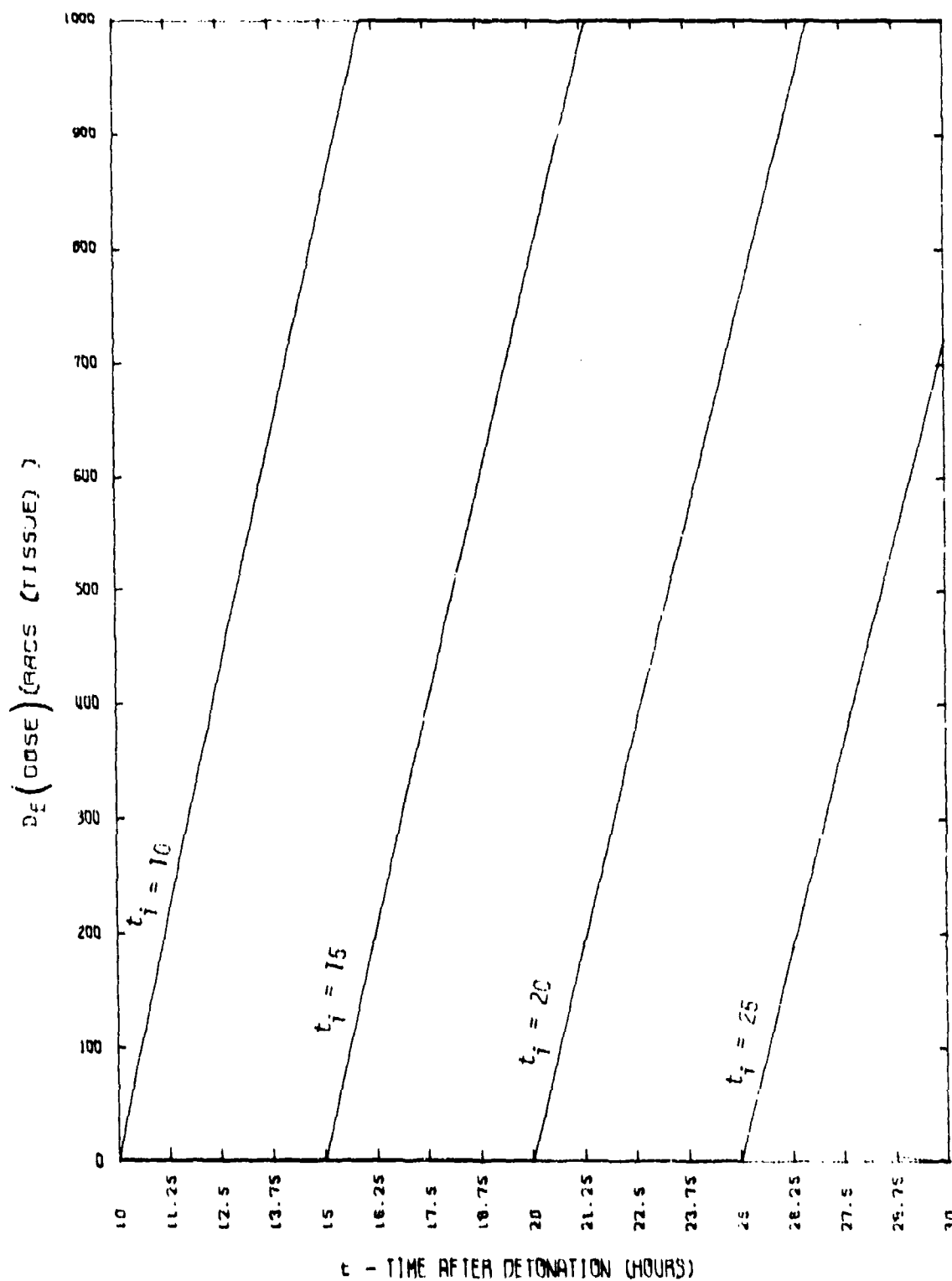Figure 13. 4 MT Flyover Dose (Altitude = 100 Meters)
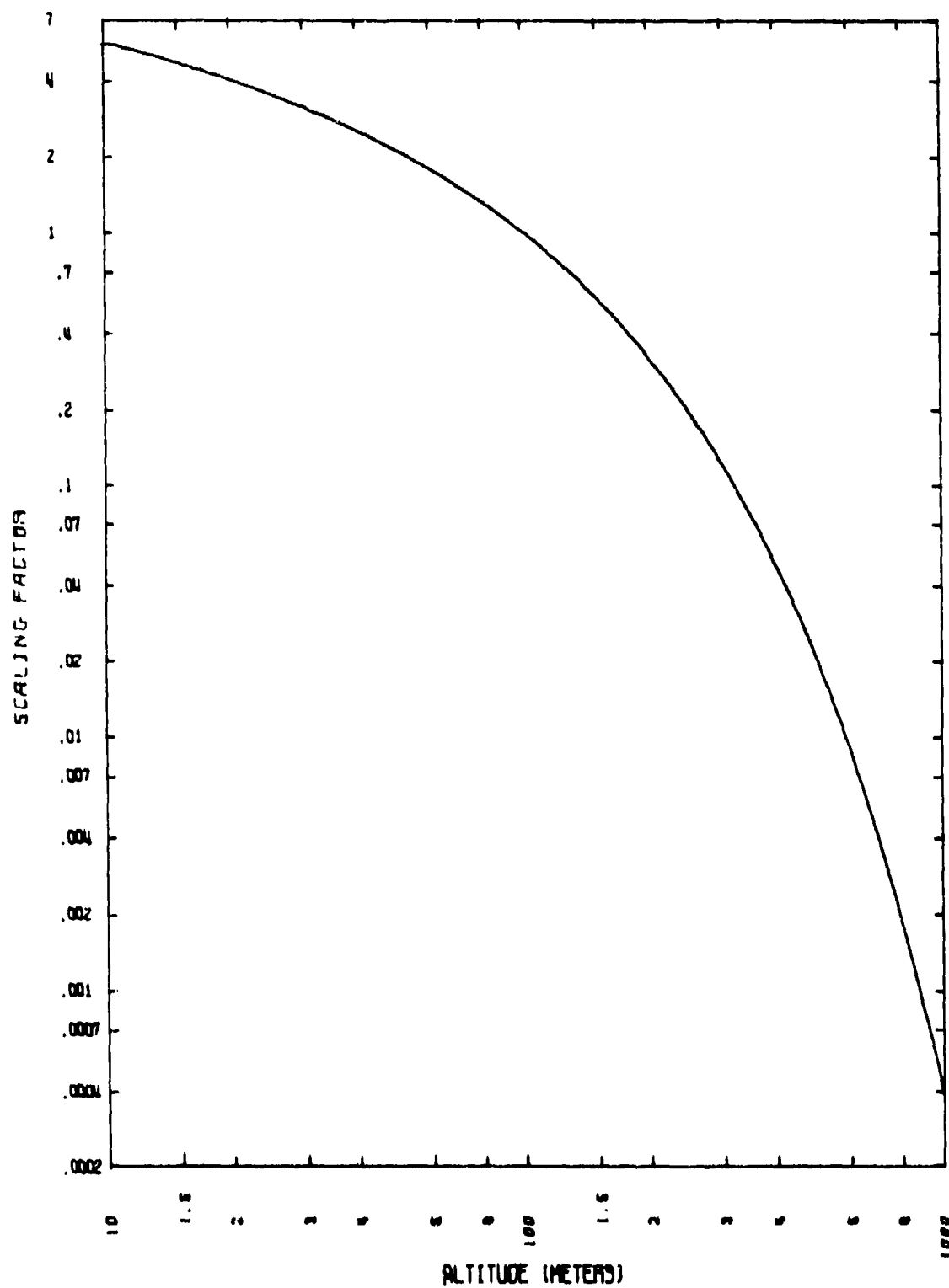
Figure 14. 4 MT Flyover Dose (Altitude = 100 Meters)

Figure 15. Altitude Scaling Factor

and

$$L_f = \frac{4 \text{ megatons}}{\pi(9.92)^2 \text{ km}^2} = 0.0129 \frac{MT}{km^2}$$

Assume that an aircraft is flying over the radioactive surface at an altitude of 150 meters at a velocity of 200 meters/second. At 2 hours after detonation the aircraft enters the contaminated area to conduct a damage assessment survey. Since its velocity is 200 meters/second and the diameter of the contaminated area is about 2×10^4 meters, the aircraft exits the radioactive area 1.7 minutes after entry.

With a contaminated area entry time, t_i, and exit time, t_f, the generalized dose results of figures 11 and 12 could be used. And for relatively long flyovers, i.e., $(t_f - t_i) > 10$ minutes, reasonably accurate results could be obtained. However, for short flyovers, the resolution is poor, and the results obtained from the dose curves are questionable. Better estimates for short flyovers can be approximated by using the dose rate results of figures 9 and 10. The dose is simply

$$D \sim \dot{D} (t_f - t_i) \tag{16}$$

where $\dot{D}$ is the dose rate at the time $(t_f + t_i)/2$ and the times are in hours. Using this technique, the flyover dose accumulated by the aircraft for the situation in the previous paragraph is (244×0.55) rads(tissue)/hour $(1.7/60)$ hours, or 3.8 rads(tissue), where 0.55 is the scaling factor obtained from figure 15, and 244 is the dose rate at 2 hours after detonation obtained from figure 9.

IONIZING DOSE RATE AT VARIOUS HORIZONTAL DISTANCES FROM RADIOACTIVE SURFACE AREAS AND RADIOACTIVE DUST CLOUDS

An aircraft engaging in conducting damage assessment surveys of targets previously attacked may be required to fly over radioactive surface areas to accomplish its mission. However, to keep the ionizing dose accumulation to acceptable levels, avoidance of radioactive clouds and radioactive surface areas not specifically designated as its responsibility may be desirable. A prerequisite to avoidance is detection. An important consideration in the design and development of hardware to accomplish detection of radioactive dust clouds and/or surface areas is the determination of ionizing dose rates as a

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function of horizontal distance from the boundary of these radioactive clouds/
surface areas. Sensors should be developed sensitive enough to allow detection
and avoidance maneuvers prior to penetration of the cloud and/or flyover of
the surface area if this technique is to be of optimum utility.

Consider first the radioactive cloud. It is assumed that the cloud boundary
is well defined, that all the airborne radioactive material is uniformly dis-
tributed throughout the cloud, and that the cloud boundary is a vertical plane
perpendicular to the aircraft flightpath. This situation is schematically
depicted in figure 16. This figure shows the aircraft at some distance, d,
from the cloud boundary and the ring volume element of the cloud. The ionizing
dose rate at the aircraft due to the radioactive dust particles in this
element is

$$\dot{D}_c(t) = \int_{0.1\mu}^{R'(t)} \rho_d(r,t) \, A(r,t) \, dr \tag{17}$$

The dose rate at the aircraft due to all of the particles in the cloud then is

$$\dot{D}_c(t) = \int_0^{\Pi/2} \int_{d\sec\Theta}^{\infty} \int_{0.1\mu}^{R'(t)} \rho_d(r,t) \, A(r,t) \, Ce^{-\mu'R} \sin\theta \, dr dR d\theta$$

The integration was performed numerically, and the dose rates as a function
of the time after detonation are shown in figures 17 and 18 for a baseline
distance of 4000 meters between the aircraft and the cloud boundary. Figure
19 provides scaling factors if the dose rate corresponding to another distance
is required. Note that this scaling factor is 1.0 for a distance of 4000
meters. If the distance is less, the scaling factor is larger and vice versa.
This scaling factor is used to scale the ordinate of the dose rate graph of
figures 17 and 18.

The radioactive surface area situation is depicted in figure 20. The air-
craft is flying at an altitude of h meters and is a distance d_s meters from
the boundary of the radioactive surface area. The dose rate at the aircraft
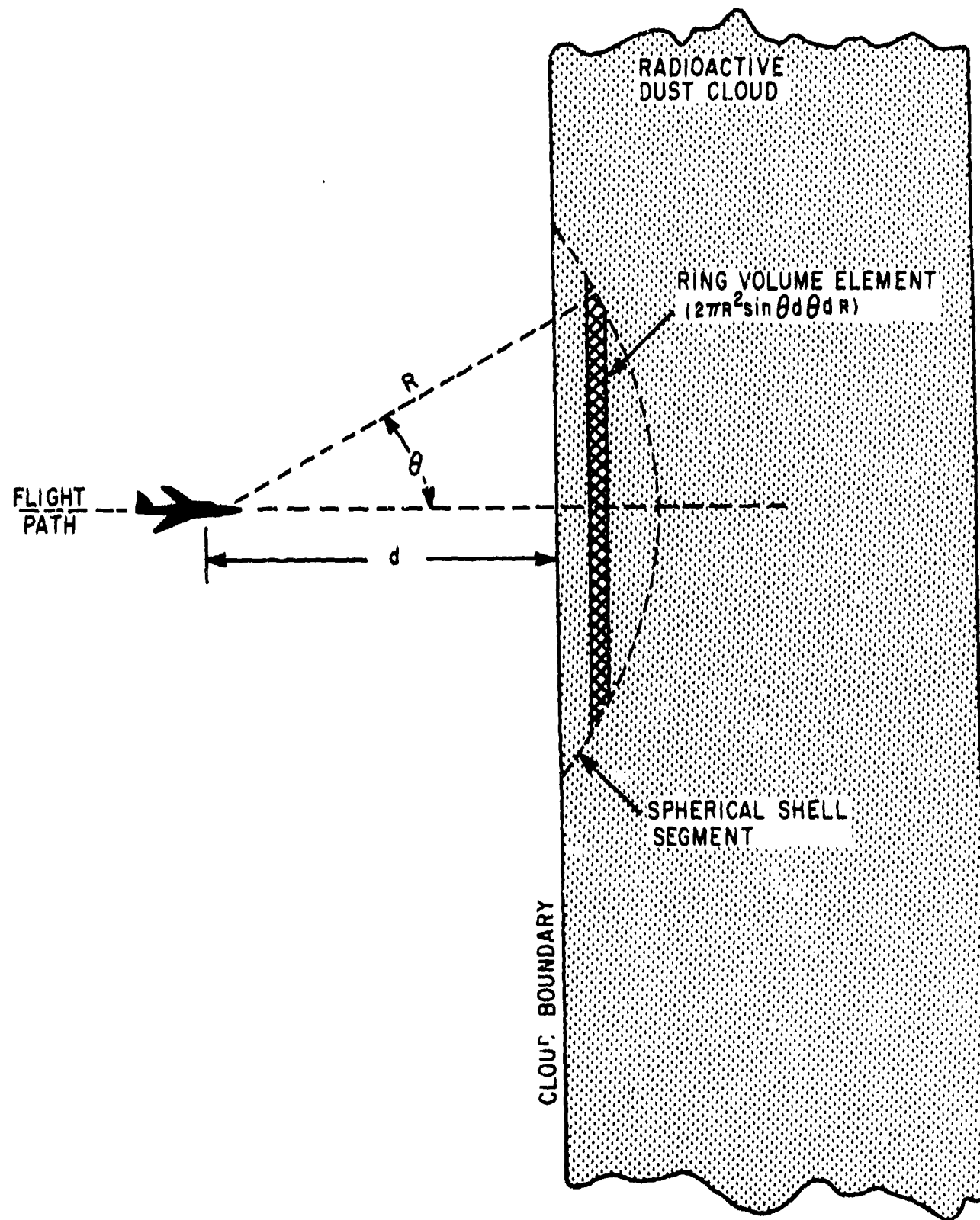from the radioactive material in the surface area element is

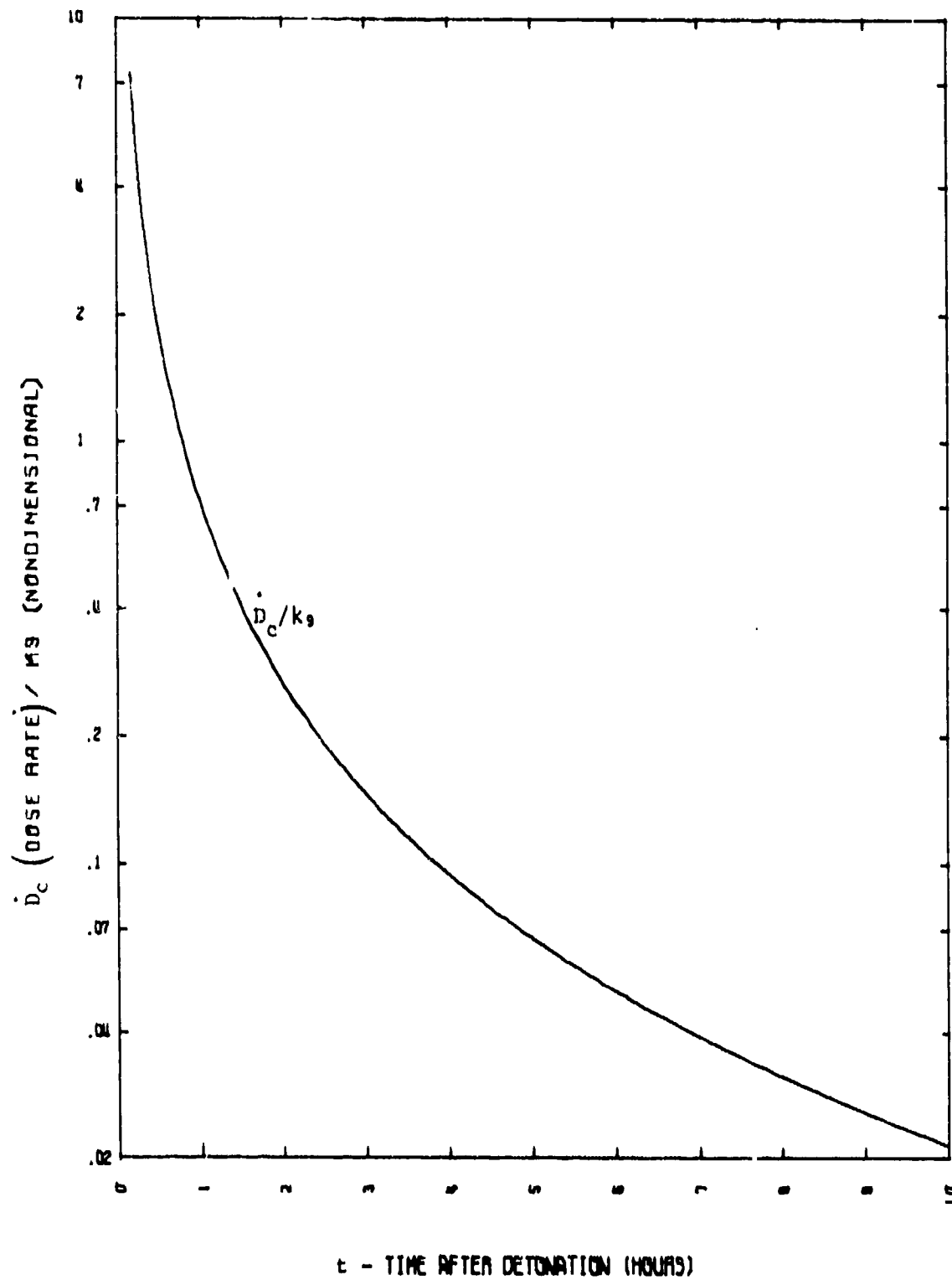Figure 16. Aircraft Approaching an Infinite Radioactive Cloud

Figure 17. Generalized Dose Rate 4000 M from Cloud Boundary
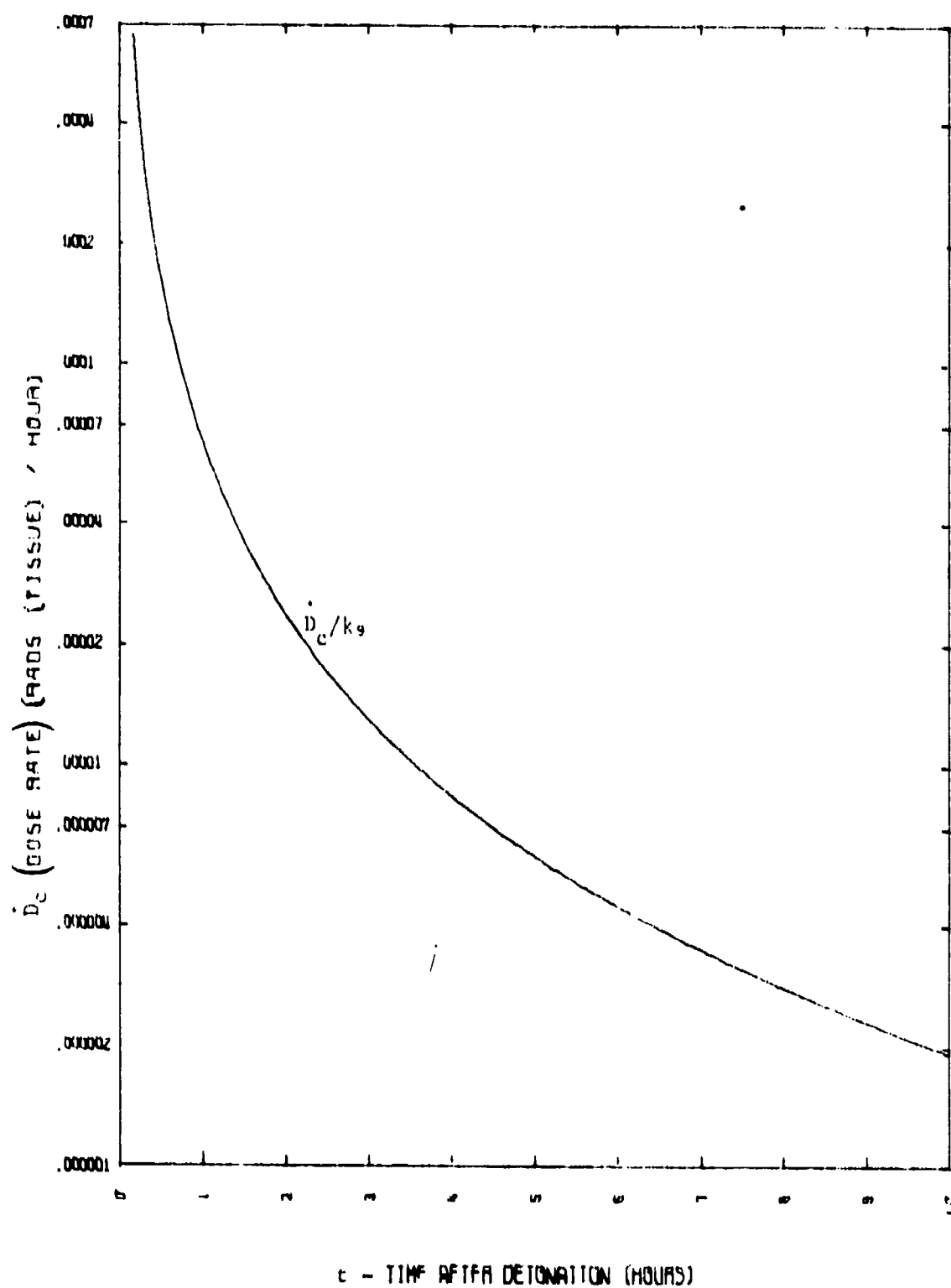
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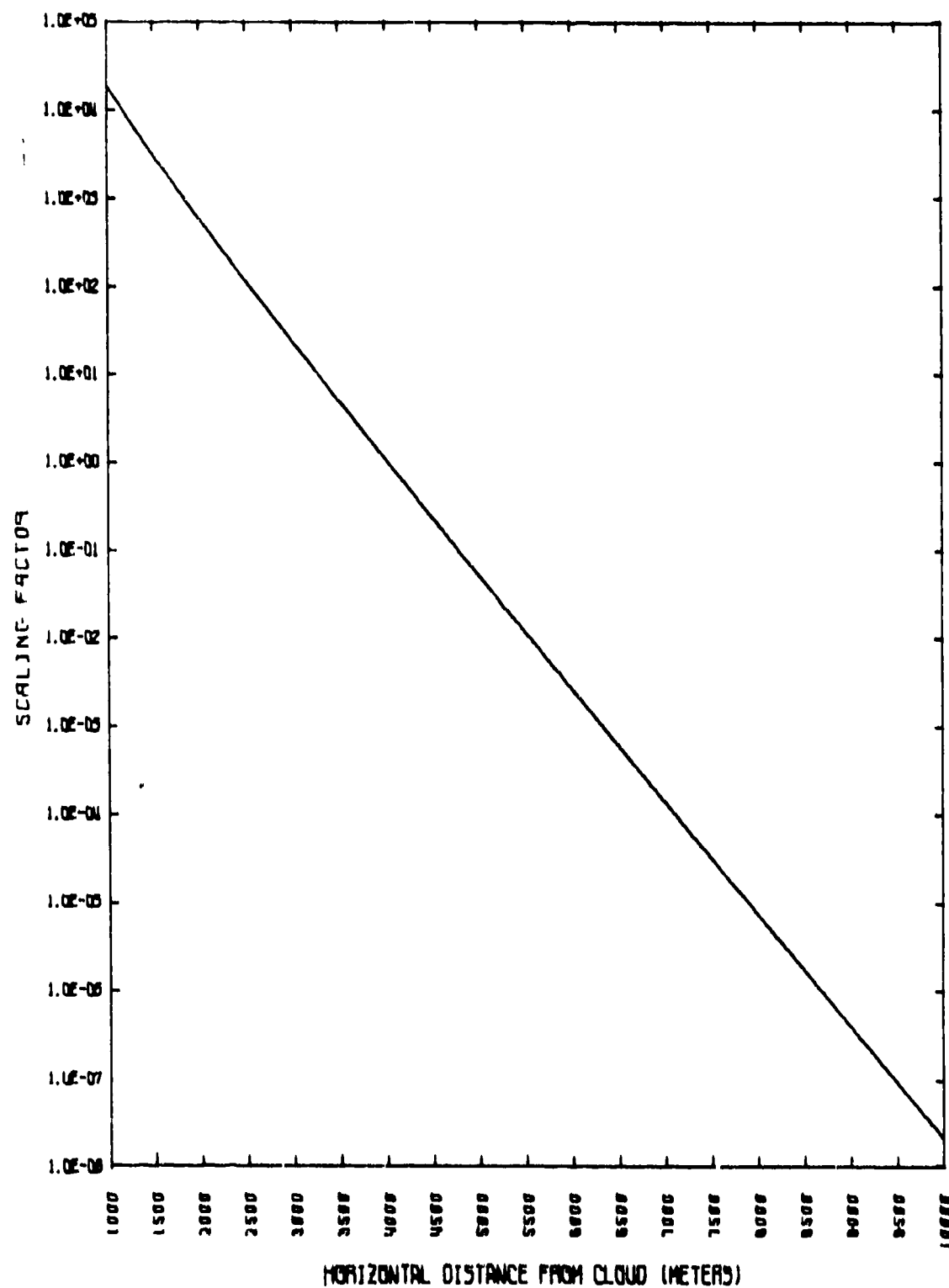Figure 18. Dose Rate 4000 Meters from 4 MT Cloud Boundary

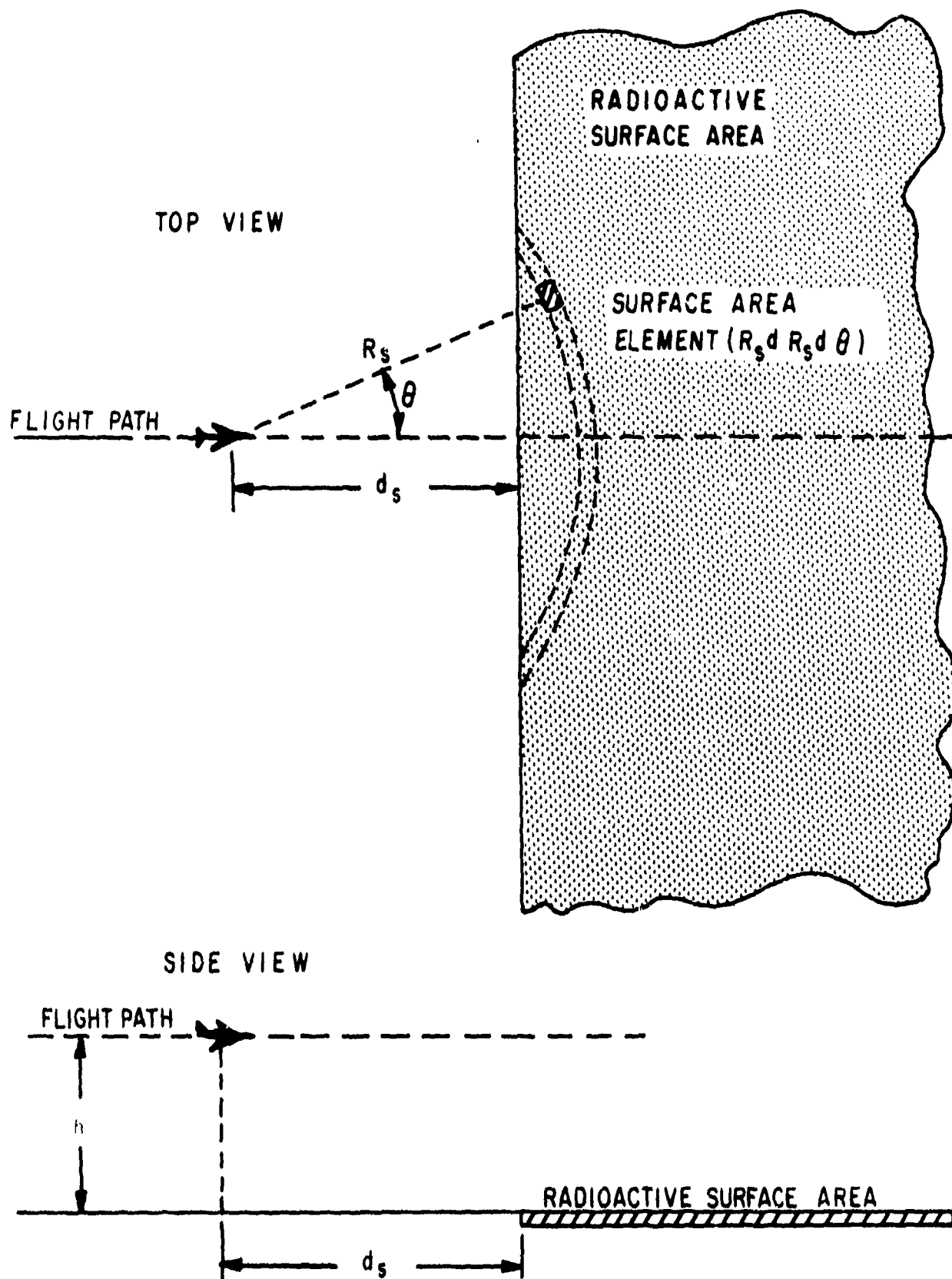Figure 19. Scaling Factor for Distance from Cloud Boundary

Figure 20. Aircraft Approaching an Infinite Radioactive Surface Area

$$\dot{D}_s(t) = \frac{CA_s(t)\ e^{-\mu'\ (R_s^2 + h^2)^{1/2}}\ R_s}{4\Pi(R_s^2 + h^2)}\ dR_s\ d\Theta \tag{19}$$

The dose rate at the aircraft due to all of the radioactive material on the surface is

$$\dot{D}_s(t) = \int_0^{\Pi/2} \int_{ds\ \sec\ \Theta}^{\infty} \frac{CA_s(t)\ e^{-\mu'\ (R_s^2 + h^2)^{1/2}}R_s}{4\Pi\ (R_s^2 + h^2)}\ dR_s d\Theta \tag{20}$$

Performing the indicated operations, the following expression is obtained.

$$\frac{\dot{D}_s(t)}{K_9} = \frac{9.76 \times 10^{-6}\ A_s(t)}{K_8} \tag{21}$$

For a baseline altitude of 100 meters and a horizontal distance of 1000 meters, the dose rate is shown in figures 21 to 24 as a function of time after detonation. For other altitudes and horizontal distances, scaling factors from figure 25 must be used to scale the ordinate of figures 21 to 24.

A specific aircraft being analyzed has well defined performance characteristics. Therefore, a horizontal distance can be defined which corresponds to successful avoidance of the cloud and/or surface area. For this distance, an ionizing dose rate can be defined from the results above. An onboard radiation sensor must be capable of detecting an instantaneous dose rate of that magnitude for the avoidance technique to be feasible.
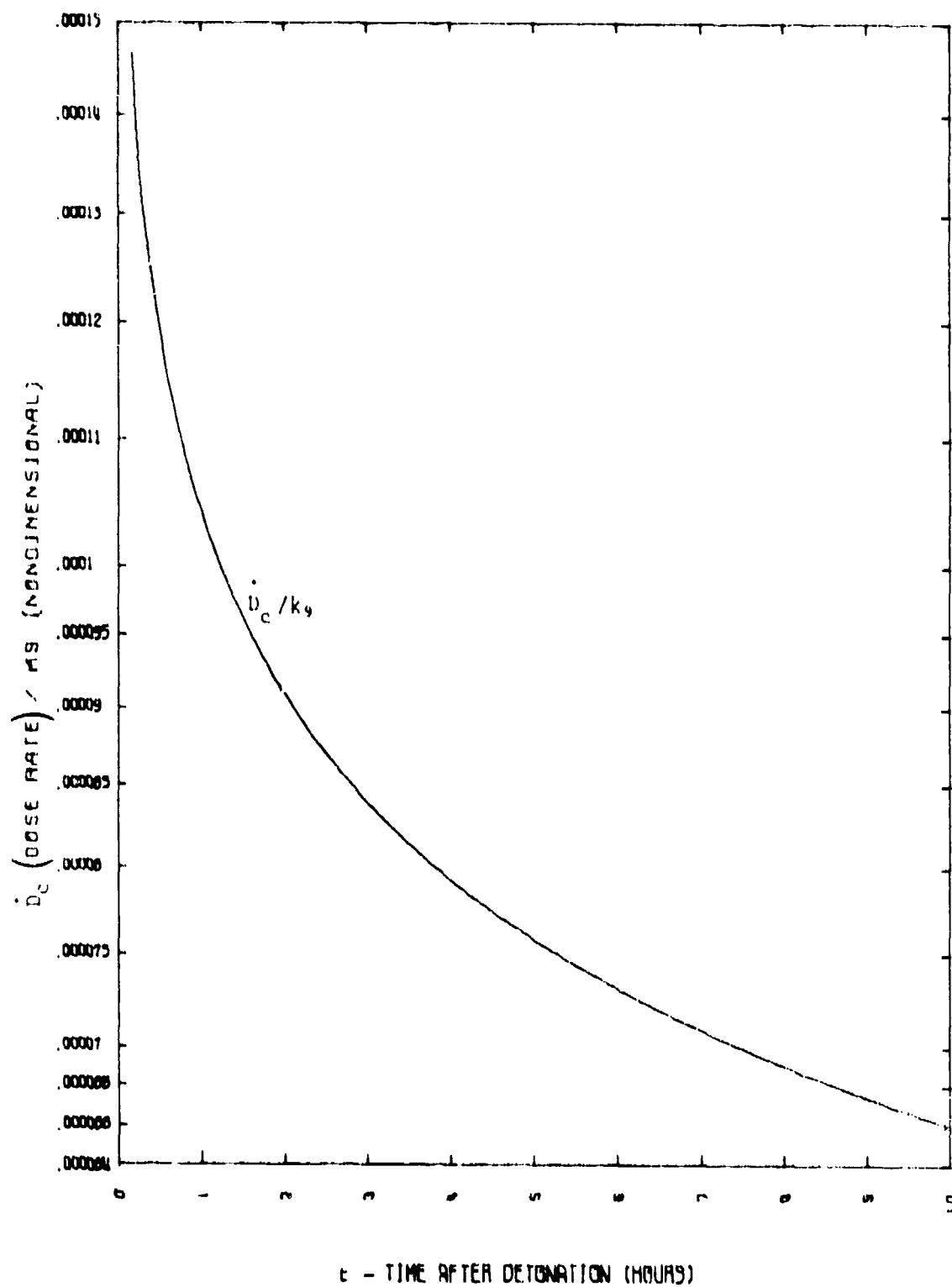
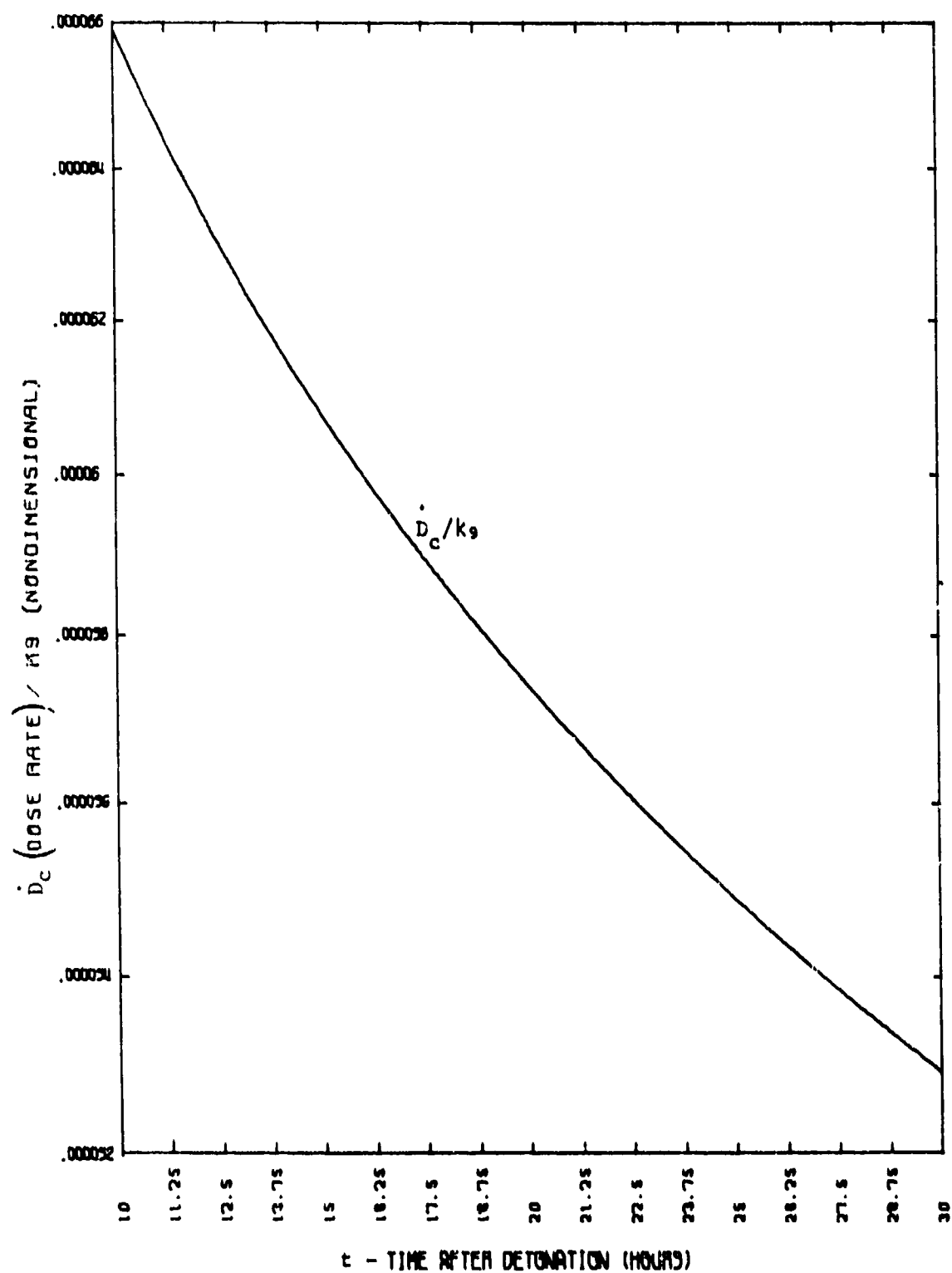Figure 21. Generalized Dose Rate, 1000 m. Distance, 100 m. Alt

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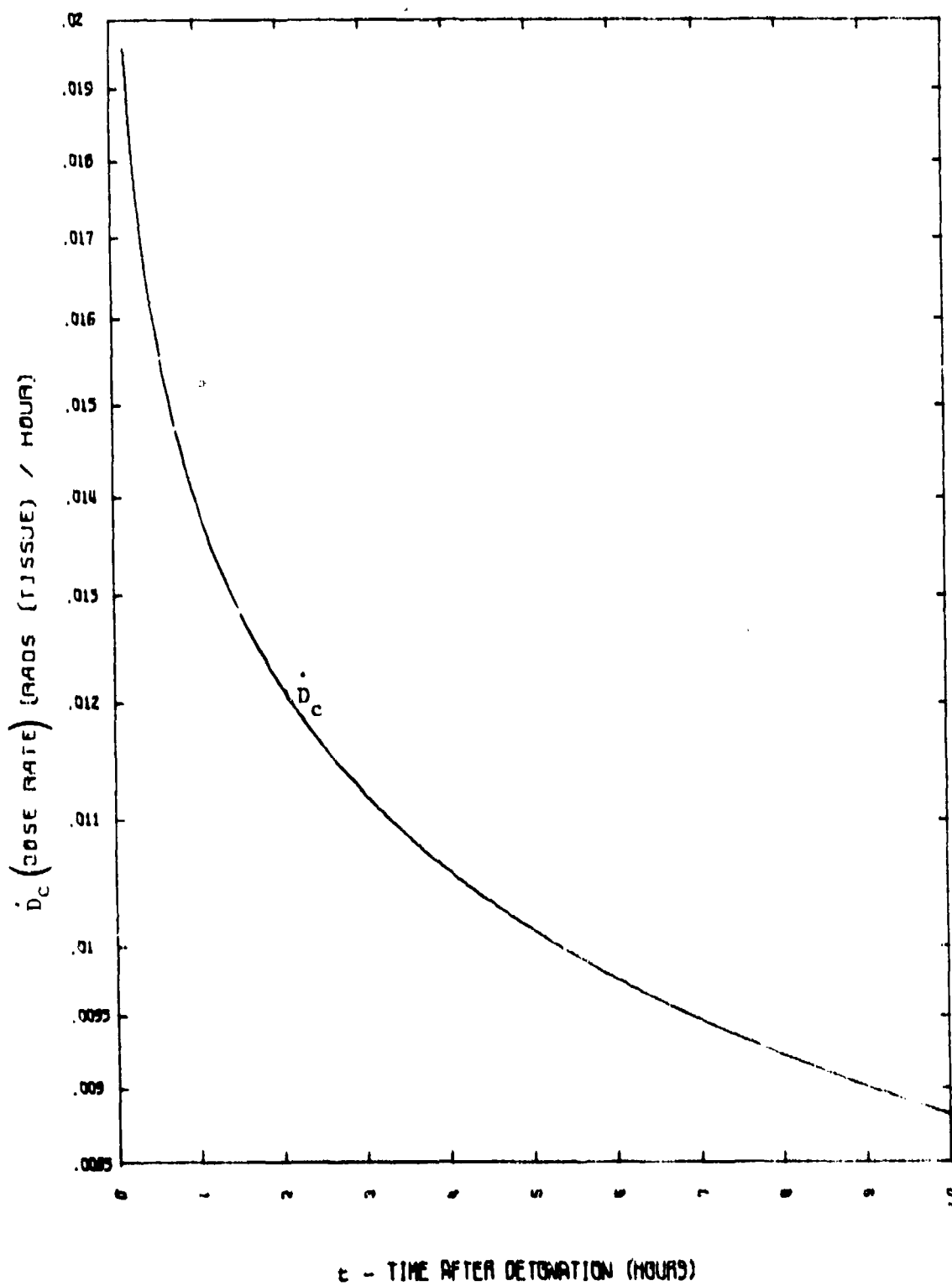Figure 22. Generalized Dose Rate, 1000 m. Distance, 100 m. Alt

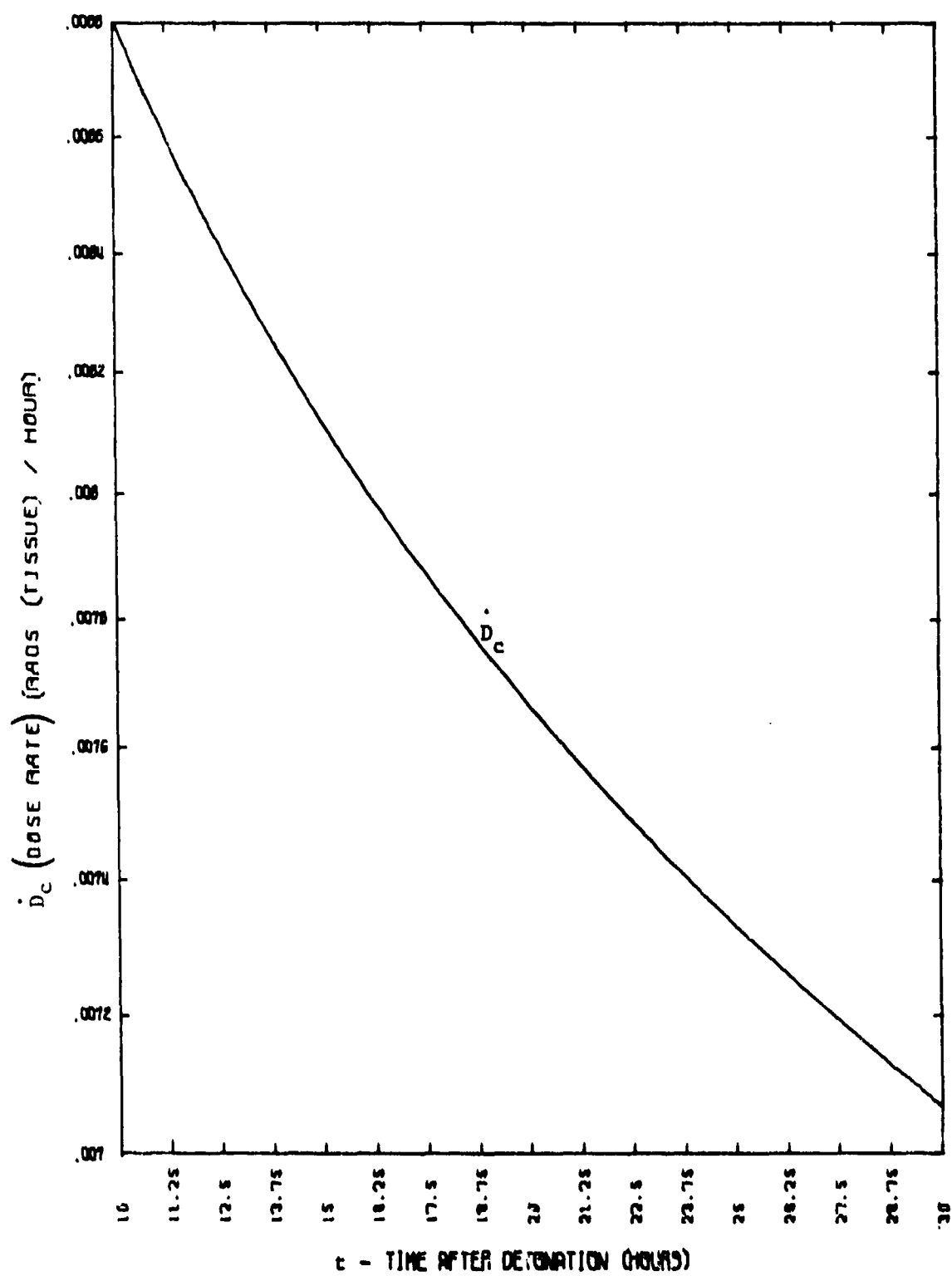Figure 23. 4 MT Dose Rate, 1000 m. Distance, 100 m. Altitude

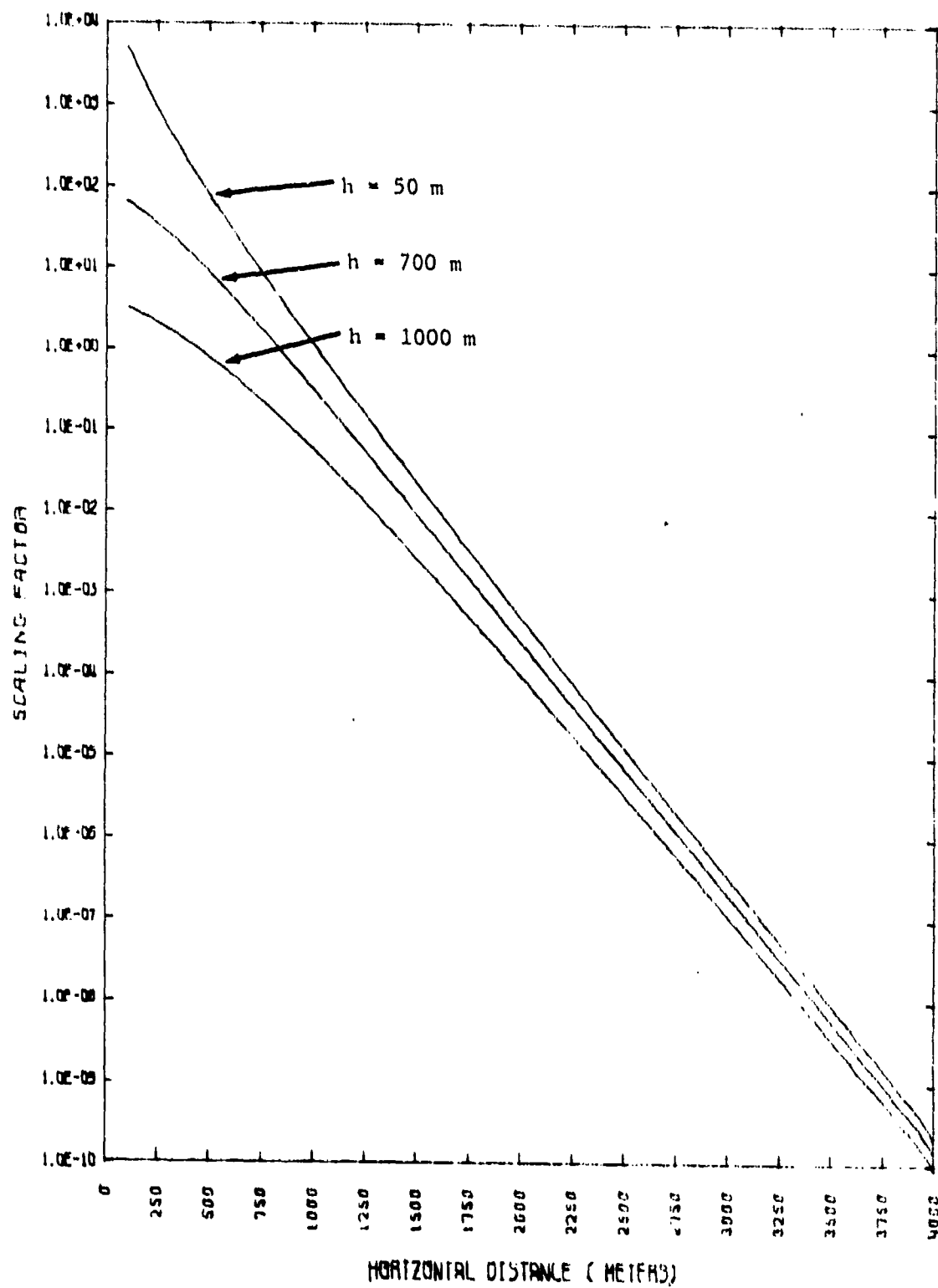Figure 24. 4 MT Dose Rate, 1000 m. Distance, 100 m. Altitude

Figure 25. Horizontal Distance and Altitude Scaling Factors

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