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CONSEQUENCES OF A PRODUCTION REACTOR ACCIDENT

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CONSEQUENCES OF A PRODUCTION REACTOR ACCIDENT

by

R. L. Junkins and E. C. Watson

Hanford Laboratories

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March 8, 1963

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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CONSEQUENCES OF A PRODUCTION REACTOR ACCIDENT

INTRODUCTION

The purpose of this report is to estimate the consequences of a Hanford reactor accident with emphasis on the effects at distant points. The potential effects in Canada are estimated as well as the consequences within the United States.

SUMMARY

Calculations indicate that a total area of about 16,000 square miles may be contaminated to an extent which requires remedial measures. Of this area, about 70% may be in Canada. Other meteorological conditions, notably rainout or a neutral atmosphere, could increase the area contaminated.

The accident evaluated assumes a partial meltdown of one of the 100-K production reactors. The methods used and the assumptions involved are consistent with those reported in previous hazards analyses. Meteorological conditions were chosen which transport the contaminants to distant points.

RELEASE OF RADIONUCLIDES

The inventory of fission product isotopes per 1000 Mw for 70 days irradiation was computed from the fission product program ACTICAY by R. Nilson of IPD. The values used are shown in Table I.

The quantity of fission products released to the atmosphere during a major accident involving the loss of coolant depends upon: the amount of uranium melted; the fraction of the affected inventory escaping from the molten uranium; the temperature of the unmelted uranium; the chemical and physical form of the released nuclides; the fraction of the fuel-released fission

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TABLE I

NORMALIZED FISSION PRODUCT INVENTORY FOR A PRODUCTION REACTOR

FP Category	Quantity Present in Reactor After 24 Hours Decay (Megacuries/1000 Mw-70 Days)	
Noble Gases:		
Xe^{133}	52	
Xe^{135m}	1.3	
Xe^{135}	9.1	
All Noble Gases		64
Halogens:		
I^{131}	22	
I^{132}	31	
I^{133}	25	
I^{135}	4.1	
All Halogens		82
Volatile Solids:		
Te^{127}	1.6	
Te^{129m}	2.3	
Te^{129}	2.4	
Te^{132}	30	
Cs^{137}	0.23	
All Volatile Solids		38
Remaining Fission Products:		
Sr^{89}	24	
Sr^{90}	0.23	
Zr^{95}	28	
Ba^{140}	49	
Ce^{144}	7.9	
All Remaining Fission Products		550
TOTAL ALL FISSION PRODUCTS		740

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products depositing or "plating-out" on the cooler surfaces of core material, shielding, building, and piping surfaces; and the fraction removed by the stack filtering system. Each of these depletion mechanisms has been considered.

The maximum consequences in the environment would result if the postulated accident occurred at one of the K reactors and this case is used. Such considerations have led to the following assumptions:

1. The portion of the uranium which melts contains 50% of the inventory of fission products. Although there is a possibility of vaporization of some of the fuel, this was not considered.

2. The release fractions from molten fuel assumed are:

Noble Gases	1.0
Halogens and Volatile Solids (Br, I, Cs, Te, Se)	0.5
All Remaining Fission Products (including ruthenium)	0.01

3. No release of fission products was assumed from unmelted uranium in tubes adjacent to the tubes containing molten uranium. There would undoubtedly be some release, especially of the noble gases and of some of the other volatile fission products. Failure to include this release tends to underestimate the total release of fission products.

4. Some of the fission products released from the uranium deposit on cooler surfaces at the accident site. When the quantities of fission products released from the uranium are multiplied by the plate-out correction factors, the

reduced amounts which may actually escape to the environment are obtained. The values used here are consistent with those in other hazards analyses.

Noble Gases	1.0
Halogens	0.5
All Remaining Fission Products	0.3

5. No depletion of fission products was assumed for existing stack filtering systems. This assumption considers the existing production reactor buildings as offering little or no confinement capabilities in the event of a major accident.

The several depletion factors are summarized in Table II.

TABLE II

SUMMARY OF DEPLETION FACTORS

Fission Product Category	Fraction in Melted U	Fraction Released From Melt	Fraction Not Plated-Out	Fraction Released to Atmosphere*
Noble Gases	0.5	1.0	1.0	0.5
Halogens	0.5	0.5	0.5	0.125
Volatile-Solids	0.5	0.5	0.3	0.075
Remaining FP	0.5	0.01	0.3	0.0015

* Equal to the product of the factors listed in previous three columns.

Multiplication of the factors given in the last column of Table II by the normalized inventory figures given in Table I results in the inventory of fission products released to the atmosphere as shown in Table III.

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TABLE III

NORMALIZED FISSION PRODUCT INVENTORY
RELEASED TO THE ATMOSPHERE

Fission Product Category	Quantity Released After 24 Hours Decay (Megacuries/1000 Mw-70 days)	
Noble Gases:		
Xe^{133}	26	
Xe^{135m}	0.65	
Xe^{135}	4.6	
All Noble Gases		32
Halogens:		
I^{131}	2.8	
I^{132}	3.9	
I^{133}	3.1	
I^{135}	0.51	
All Halogens		10
Volatile Solids:		
Te^{127}	0.12	
Te^{129m}	0.17	
Te^{129}	0.18	
Te^{132}	2.2	
Cs^{137}	0.017	
All Volatile Solids		2.8
Remaining Fission Products:		
Sr^{89}	3.6×10^{-2}	
Sr^{90}	3.4×10^{-4}	
Zr^{95}	4.2×10^{-2}	
Ba^{140}	7.4×10^{-2}	
Ce^{144}	1.2×10^{-2}	
All Remaining Fission Products		0.82
TOTAL ALL FISSION PRODUCTS		46

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METEOROLOGICAL DISPERSION AND DEPOSITION

A. Downwind Dispersal of Emitted Radionuclides

1. Moderately Stable Atmosphere

This atmosphere is characterized by an increase in temperature with increased altitude of 1 F between 100' and 300'.

a. Dispersion

The downwind time-integrated exposure (E) at ground level from a quantity of radionuclides (Q) released at a stated height above ground level (h in meters) is best described by the diffusion equations*:

$$E = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}_h} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma^2_y} + \frac{h^2}{\sigma^2_z}\right)\right] \qquad (1)$$

---

* Experimental evidence indicates that Eq (1) is valid for moderately stable atmospheres.

Barad, M. L. (Ed), "Project Prairie Grass, A Field Program in Diffusion", Geophysical Research Paper No. 59, Vol. 1 and 2. U. S. Air Force, Cambridge Research Center, 1958.

Barad, M. L. and J. J. Fuquay (Ed), "The Green Glow Diffusion Program", Vol. 1 and 2. HW-71400, April 1962.

where the remaining symbols are:

σ^2_y = the cross-wind dispersion variance

$\sigma^2_y = 0.016\ x^{1.6}$ (meters^2)

σ^2_z = the vertical wind dispersion variance

$$\sigma^2_z = 97\ \left[1 - \exp(-2.5\times10^{-4}\ \frac{x^2}{\bar{u}_h^2})\right] + 0.33\ \frac{x}{\bar{u}_h}\ (\text{meters}^2)$$

x = downwind distance from point of release (meters)

$\bar{u}_h$ = average wind speed at height of release (meters/second)

y = cross-wind distance at ground level normal to the line between any point x and the point of release (meters)

The units of E are curie-seconds per meter^3, if Q is in units of curies.

b. Depletion

As the cloud moves downwind, it contacts the ground. A fraction of all but the noble gas radionuclides are deposited on vegetation and soil, thereby being removed from the cloud. The rate of radionuclide removal from the cloud with distance x is:

$$\frac{\partial Q}{\partial X} = -\int_{-\infty}^{\infty} \left(\frac{V_\Delta}{\bar{u}_o}\right) \left(\frac{\bar{u}_o}{\bar{u}_h}\right) \bar{u}_h\ E_s\ dy \qquad (2a)$$

where additional symbols are:

Q = quantity of radionuclide remaining in cloud at x distance from point of release

$\left(\frac{V_\Delta}{\bar{u}_h}\right)$ = the deposition coefficient

$\bar{u}_o$ = wind speed at ground level (meters/sec)

E_s = the cross-wind time-integrated exposure found from Eq (1) with x as a parameter

From eq (2a), it can be shown that the quantity of contaminant remaining in the cloud at any downwind distance x is:

$$Q = Q_o \exp\left[-\sqrt{\frac{2}{\pi}}\left(\frac{V\Delta}{\bar{u}_o}\right)\left(\frac{\bar{u}_o}{\bar{u}_h}\right)\int_0^x \frac{\exp\left(-\frac{h^2}{2\sigma^2_z}\right)}{\sigma_z}\,dx\right] \qquad (2b)$$

Typical values of the deposition coefficients and wind speed ratios* are shown in Table IV. The integral has been evaluated numerically.

2. Neutral Atmosphere

This atmosphere is characterized by a temperature change with increased altitude ranging from a slight decrease to no change within the first few hundred feet of the ground's surface.

a. Dispersion

The downwind time-integrated exposure (E) at ground level from a quantity of radionuclides (Q) released at a stated height above ground level (h in meters) is given by Sutton's Equation: **

$$E = \frac{2Q}{\pi\, C_y\, C_z\, \bar{u}_h\, x^{(2-n)}} \exp\left[-x^{(n-2)}\left(\frac{y^2}{C^2_y} + \frac{h^2}{C^2_z}\right)\right] \qquad (3)$$

where C_y, C_z, and n are empirically determined parameters.

---

* Fuquay, J. J. and reported by J. W. Healy, "Calculations on Environmental Consequences of Reactor Accidents", HW-54128, December 1957.

** Neither Eq (1) nor Eq (3) has been experimentally verified for neutral atmospheric conditions at Hanford. The dispersion variances used in Eq (1), therefore, are unknown. On the other hand, a number of workers elsewhere have measured and reported values for C_y and C_z. Eq (3) is used as a matter of necessity.

For this analysis (a release above ground level in a neutron atmosphere), $C_y = C_z = C$ and $n = 0.25$. The value of C further depends upon the wind speed at the height of release and decreases from 0.15 for $\bar{u}_h = 1$ m/s to 0.11 for $\bar{u}_h = 10$ m/s.

As previously stated, if Q is expressed in units of curies, E has units of curie-seconds per cubic meter.

b. Depletion

The correction for cloud depletion is found in the same manner as discussed previously. The quantity of contaminants remaining in the cloud at any downwind distance x is given by:

$$Q = Q_o \exp\left[-\frac{2}{C_z\sqrt{\pi}}\left(\frac{V_\Delta}{\bar{u}_o}\right)\left(\frac{\bar{u}_o}{\bar{u}_h}\right)\int_o^x x^{(n-2)/2}\exp\left(-\frac{h^2}{C^2_z}x^{(n-2)}\right)dx\right] \quad (4)$$

Figures I, II and III are centerline plots (y = o) of Eq (1) and (3) normalized to unit quantity of radionuclide emitted. The values assumed for the release heights and wind speeds are:

$h = 70$ meters and ground level

$\bar{u}_h = 5$ m/s (stable)

$\bar{u}_h = 10$ m/s (neutral)

It is assumed the deposition coefficient for noble gases is zero. Eq (1) and (3), therefore, represent the downwind dispersion of the noble gases. The equations have been corrected for cloud depletion by appropriate

substitution of Eq (2b) and (4) using appropriate values for the deposition coefficient. The resulting curves appear also in Figures I, II, and III.

B. Ground Deposition

The quantity of radionuclides per unit area (d) deposited on the ground following an accident can be estimated by:

$$d = Q \left(\frac{E}{Q}\right) \left(\frac{V\Delta}{\bar{u}_o}\right) \left(\frac{\bar{u}_o}{\bar{u}_h}\right) \times 10^6 \frac{\mu c}{m^2} \qquad (5a)$$

One is also interested in the deposition occurring on leafy vegetables and pasture grass (d_v). Such estimate results by modifying Eq (5a).

$$d_v = \frac{f_v}{\rho_v} \, d \qquad \frac{\mu c}{g} \qquad (5b)$$

where

f_v = fraction of ground deposition deposited on vegetation

ρ_v = the mass of vegetation per unit area assumed to be 10^3 g/m^2 for Eastern Washington

Values of f_v for all but a few radionuclides are unknown. Some reported values * are available; however, assumptions had to be made particularly for iodine. The values currently used are:

	f_v
Iodine	1
Strontium	0.4
Cesium	0.2

* Morgan, A. "The Direct Uptake of Fission Products on Rye Grass". AERE-R-3181, 1959.

TABLE IV

DEPOSITION COEFFICIENTS AND WIND SPEED RATIOS

Atmospheric Condition	Deposition Coefficient $(\frac{V_\Delta}{\bar{u}_o})$ Particulates	Deposition Coefficient $(\frac{V_\Delta}{\bar{u}_o})$ Halogens	Radio of Wind Speed at Ground Level to Wind Speed at Height of Release (70 m) $(\frac{\bar{u}_o}{\bar{u}_h})$
Very stable	1.5×10^{-4}	2.4×10^{-3}	0.17
Moderately stable	2.2×10^{-4}	3.4×10^{-3}	0.35
Neutral	3×10^{-4}	4.6×10^{-3}	0.5
Unstable	6×10^{-4}	8×10^{-3}	0.7

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FIGURE I

TIME-INTEGRATED EXPOSURE AS A FUNCTION OF DOWNWIND DISTANCE
(Normalized to per Curie Emitted)

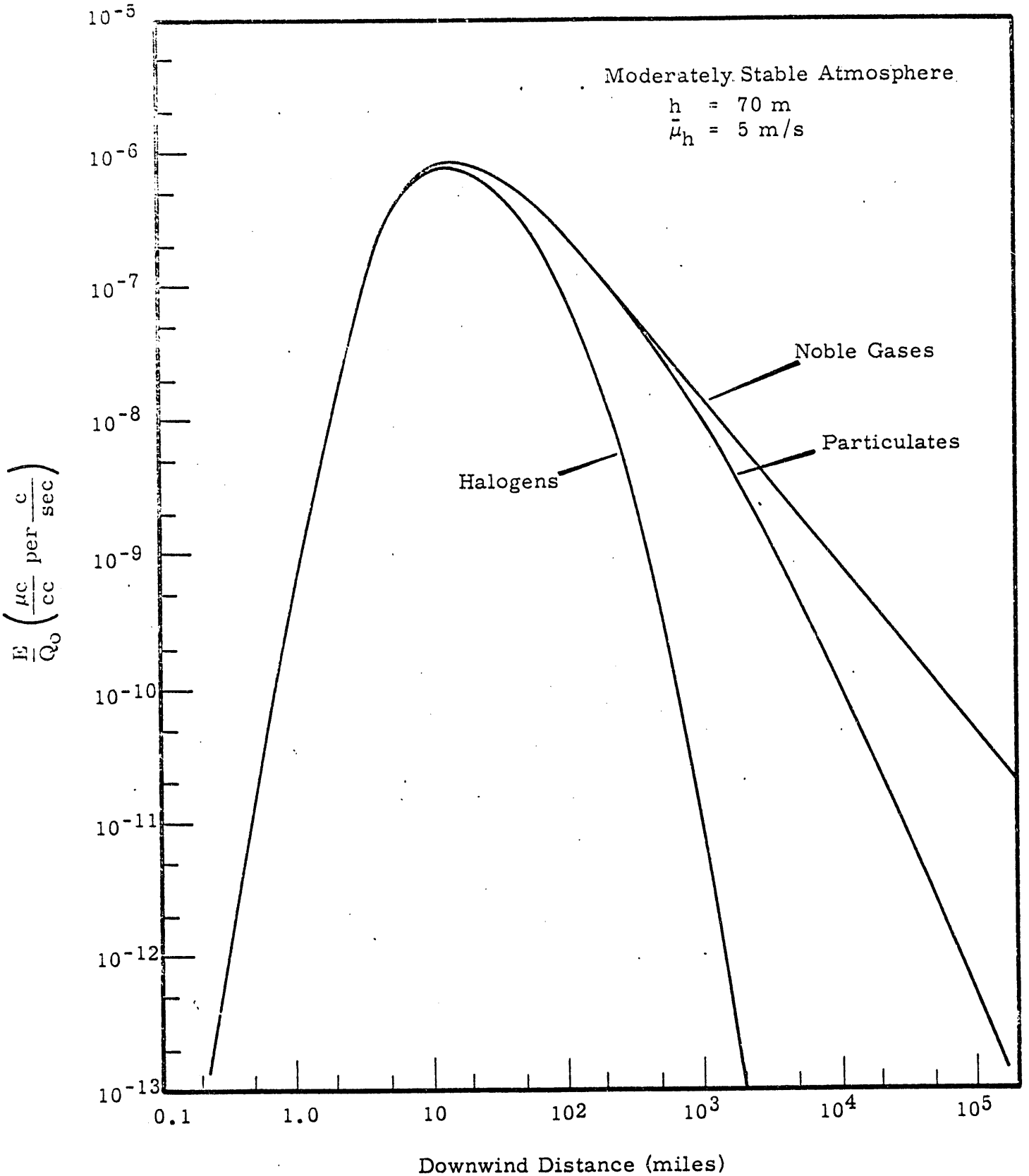

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FIGURE II

TIME-INTEGRATED EXPOSURE AS A FUNCTION OF DOWNWIND DISTANCE
(Normalized to per Curie Emitted)

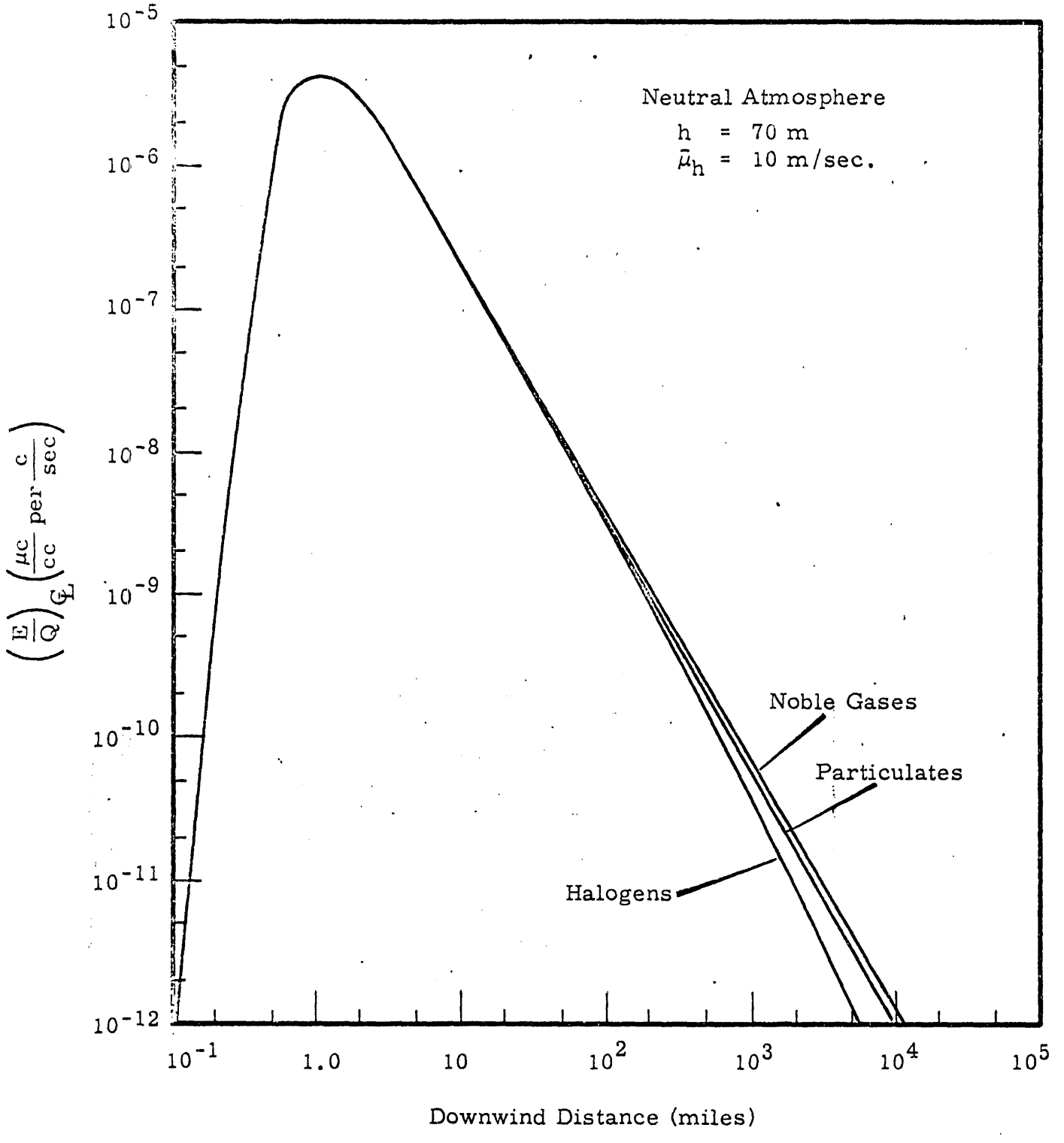

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FIGURE III

TIME-INTEGRATED EXPOSURE AS A FUNCTION OF DOWNWIND DISTANCE
(Normalized to per Curie Emitted)

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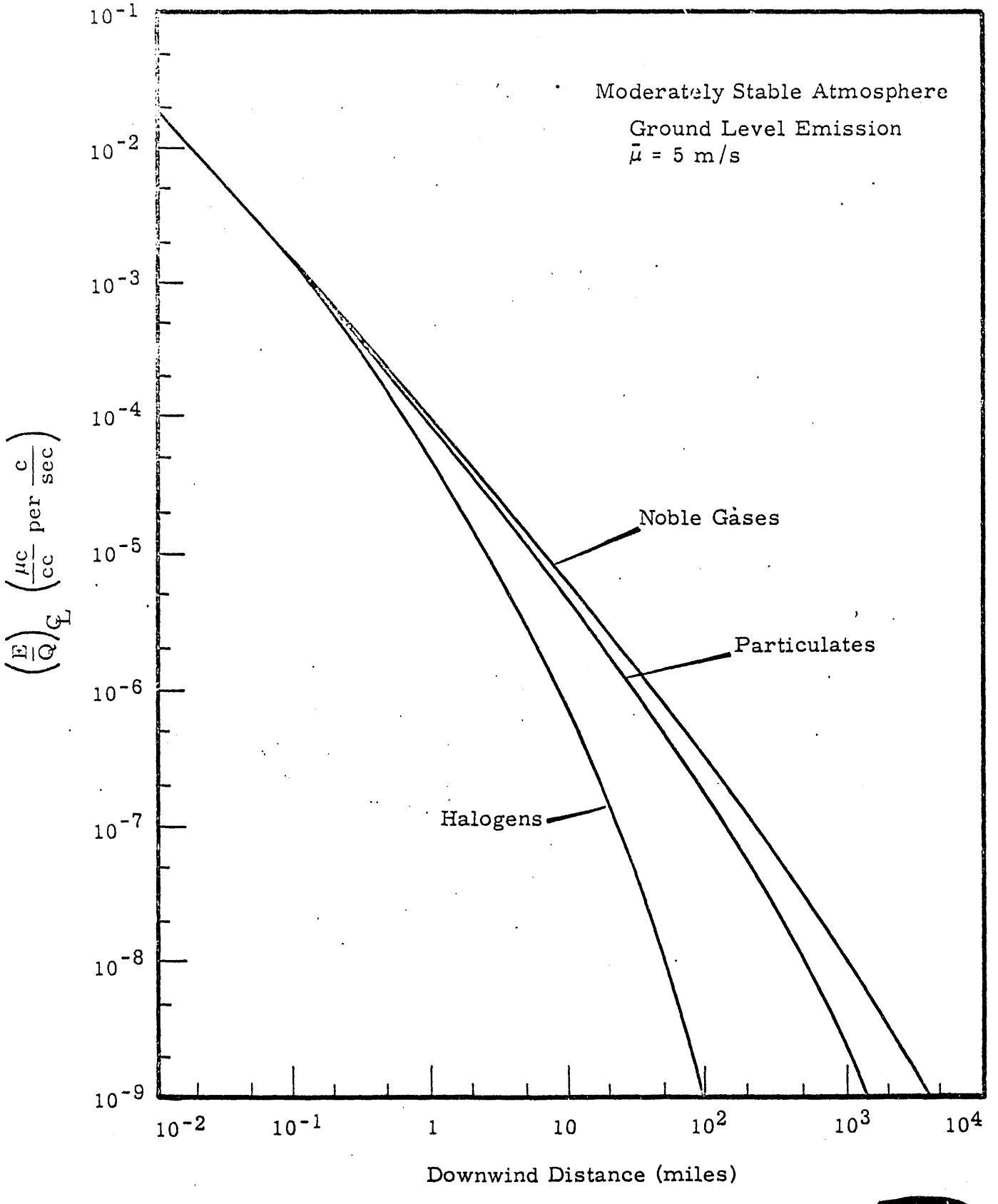

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C. Isopleth Area

The selection of a particular value for the normalized time integrated exposure results in an isopleth of the downwind distance x and the cross-wind distance y. For each value of $(\frac{E}{Q})$ there is a corresponding area enclosed by the isopleth so defined. Depending upon the atmospheric temperature profile and height of release, the areas within a given isopleth can be estimated by one of the following equations:

1. Moderately Stable Atmosphere, $h \neq o$

$$\text{Area} = 0.114\,\ell\,(x_o + x')^{0.8}\,\psi \qquad (6a)$$

2. Moderately Stable Atmosphere, $h = o$

$$\text{Area} = 0.114\,x_o^{1.8}\,\psi \qquad (6b)$$

3. Neutral Atmosphere, $h \neq o$

$$\text{Area} = 0.0941\,\ell\,(x_o + x')^{0.875}\,\psi \qquad (6c)$$

where:

ℓ = centerline length of isopleth

$\ell = x_o - x'$

x_o = maximum downwind distance

x' = minimum downwind distance = 0 for h = 0

$$\psi = \left\{ \ln\left[\left(\frac{E}{Q}\right)'_{\frac{\ell}{2}}\right]^2 - \ln\left[\left(\frac{E}{Q}\right)'_{\ell}\right]^2 \right\}^{1/2}$$

$\left(\frac{E}{Q}\right)'$ = value of $\left(\frac{E}{Q}\right)$ with y = 0

$\left(\frac{E}{Q}\right)'_{\ell} = \left(\frac{E}{Q}\right)'$ at x_o

$\left(\frac{E}{Q}\right)'_{\frac{\ell}{2}} = \left(\frac{E}{Q}\right)'$ at $(x_o + x')/2$

Figures IV, V, and VI are plots of Eq (6a), (6b), and (6c). Again each figure contains curves for noble gases, halogens and particulates.

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FIGURE IV

AREA EXPOSED AS A FUNCTION OF TIME-INTEGRATED EXPOSURE
(Normalized to per Curie Emitted)

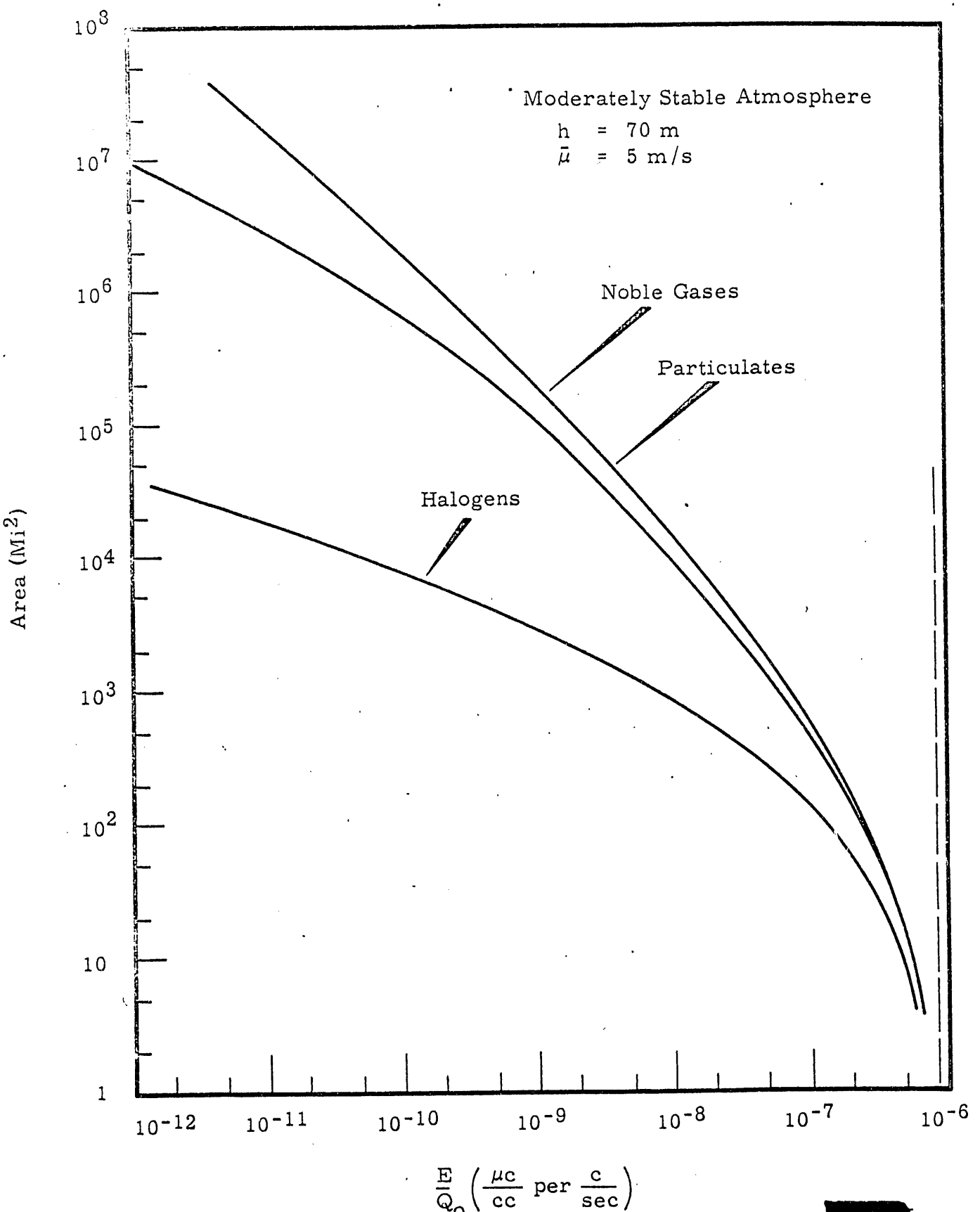

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FIGURE V

AREA EXPOSED AS A FUNCTION OF TIME-INTEGRATED EXPOSURE
(Normalized to per Curie Emitted)

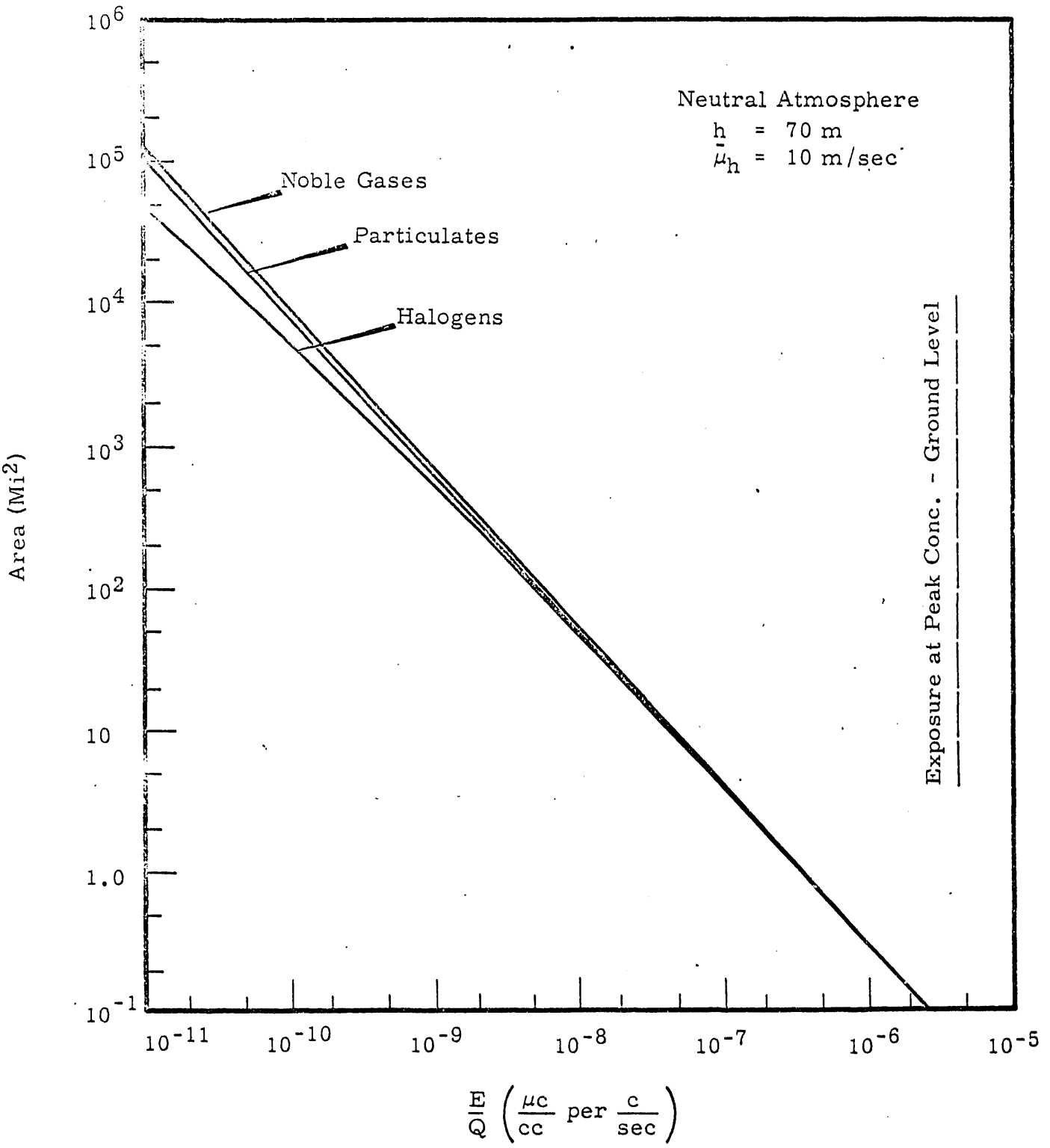

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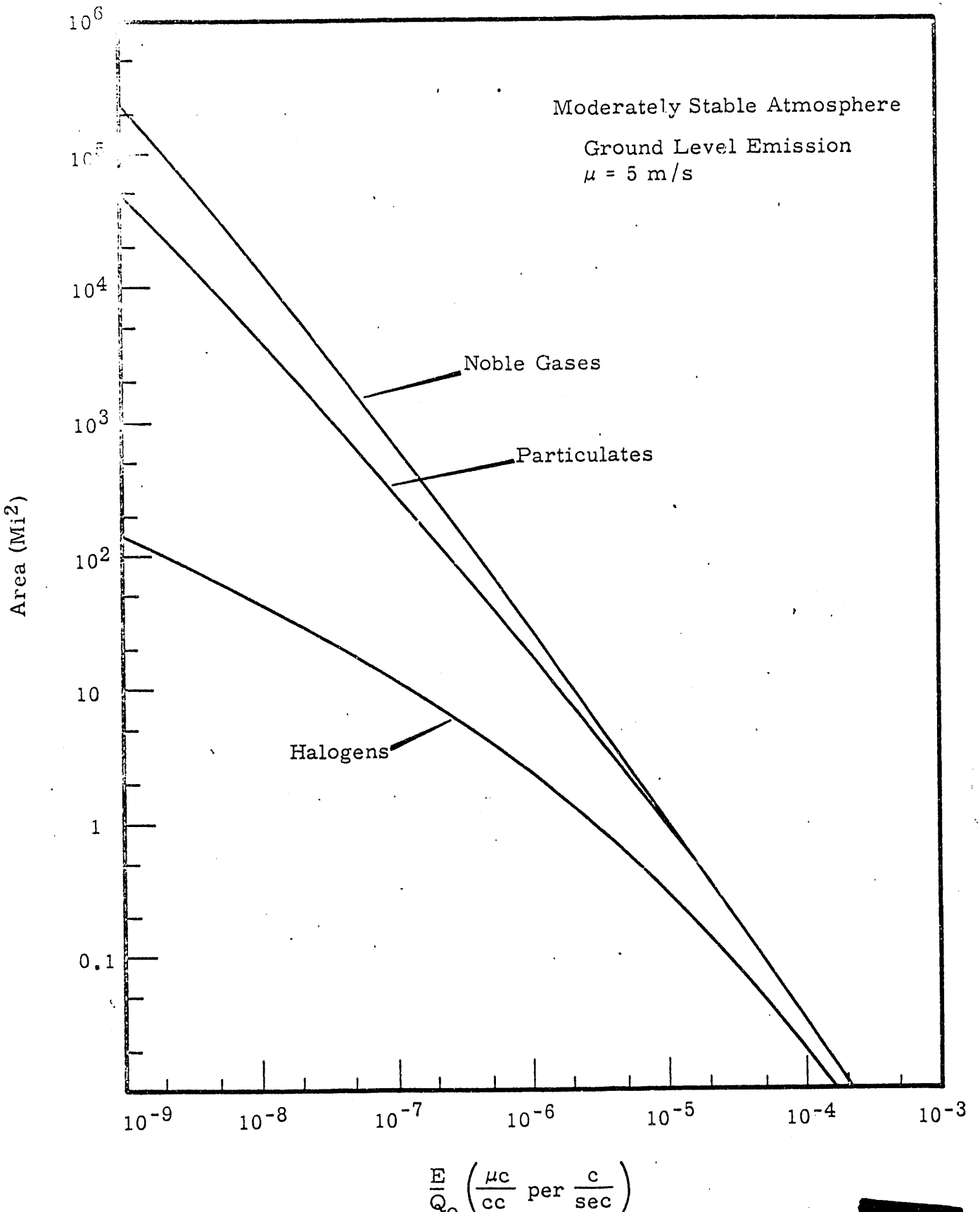
FIGURE VI

AREA EXPOSED AS A FUNCTION OF TIME-INTEGRATED EXPOSURE
(Normalized to per Curie Emitted)



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EXPOSURE CRITERIA

1. External Radiation Exposure

The criteria used here are those used generally in reactor hazards analyses.

a. From the Cloud - The exposure criteria used and the expected biological effects to man are:

Whole Body Dose	Probable Effect
$\geq$ 450 rems	Lethal
100 to 450 rems	Injury
5 to 100 rems	Medical Attention

b. From Residual Ground Contamination - The criteria used here and the action visualized are:

Whole Body Dose if no Action is Taken	Probable Action Required
1 rem/yr at the end of 5 years	Long-term evacuation and extensive decontamination of property.
1 rem in first year	Temporary evacuation; some decontamination of property.

2. Internal Deposition of Radionuclides

a. From the Cloud - The inhalation of mixed fission products will result in a complex dosimetry problem. The dose to lungs, GI tract, and bone will undoubtedly be significant, but only the whole body has been considered in this analysis. The criteria listed for external radiation exposure from the cloud are assumed to apply to the whole body from either mode of exposure.

b. From Residual Ground Deposition - The dose criteria selected, equivalent ground contamination, and expected action are:

Dose if No Action is Taken	Ground Contamination	Probable Action
$\geq$ 130 rems/yr (to bone)*	1 $\mu c/m^2$ Sr^{90}	Confiscates crops for several years; extensive decontamination. Provide feed for dairy cattle for several years.
20 to 130 rems/yr (to bone)*	0.15 $\mu c/m^2$ Sr^{90}	Confiscate current crops and milk supplies. Moderate decontamination.
	1 $\mu c/m^2$ I^{131}	Confiscate current milk supplies and provide feed for dairy cattle. (Temporary) Other actions may be necessary depending upon the presence of other long-lived nuclides and the nature of the crops.

* To newly formed mineral bone from both Sr^{90} and Sr^{89}.

AREAS CONTAMINATED

It is convenient to designate the preceding exposure critera as zones, the outer boundaries of which correspond to the criteria. This is done in Table V.

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TABLE V

EXPOSURE CRITERIA AND CORRESPONDING ZONES

Zone	Source of Exposure	Exposure Criteria Defining Outer Boundary if No Action can be Taken
A	Internal and external, Cloud	$\geq$ 450 rems, whole body
B	Internal and external, Cloud	100 to 450 rems, whole body
C	Internal and external, Cloud	5 to 100 rems, whole body
D	External, Ground Contamination	1 rem/yr after 5 years, whole body
E	External, Ground Contamination	1 rem in first year, whole body
F	Ingestion	1 $\mu c/m^2$ on the ground
G	Ingestion	0.15 $\mu c/m^2$ on the ground
H	Ingestion	1 μc I^{131}/m^2 on vegetation

The equations for estimating the dose and for determining the corresponding normalized time-integrated exposure are shown in Table VI. The symbols are as follows:

D = Dose (rems)

D_r = Dose rate (rems/hr)

c = Air concentration of released fission products in $\mu c/cc$

c_f = Air concentration of all but the noble gas fission products in $\mu c/cc$

t = Time of exposure

$(f_a k)$ = Effective dose per unit of the released mixture of fission products inhaled (excluding noble gases) = 5.1×10^{-5} rem/μc in this analysis

d_0 = Initial peak ground contamination

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$d_o(Sr^{90})$ = Initial peak Sr^{90} ground contamination

$d_o(I^{131})$ = Initial peak I^{131} ground contamination

$(\frac{E}{Q})$ = Normalized time - integrated exposure

Q = Quantity of all released fission products

Q_h = Quantity of all released halogens

Q_p = Quantity of all released volatile and nonvolatile solids

Q_{90} = Quantity of all released Sr^{90}

Q_{31} = Quantity of all released I^{131}

H = Deposition velocity

$$H = \left(\frac{V_\Delta}{\bar{\mu}_o}\right)\left(\frac{\bar{\mu}_o}{\bar{\mu}_h}\right) \bar{\mu}_h \text{ in meter/sec}$$

subscripts having same meaning (e.g., H_h is deposition velocity of halogens).

TABLE VI

EQUATIONS FOR ESTIMATING DOSE AND DETERMINING NORMALIZED TIME-INTEGRATED EXPOSURE

Zone	Dose (Rate) Equations (rems or rems/hr) D (or D_r) equals:	Normalized Time-Integrated Exposure $(\frac{\mu c\text{-sec}}{cc\text{-curie}})$ $(\frac{E}{Q})$ equals:
A,B,C	0.195 ct (external) rems 230 $(f_a k)$ $c_f t$ (internal) rems	$5.1 \frac{D}{Q}$
D	$1.2 \times 10^{-5}\ d_o t^{-1.2}$ rems/hr	$760 \frac{D_r\ (5\ yr)}{Q_h H_h + Q_p H_p}$
E	$2.1 \times 10^{-5}\ d_o$ rems	$4.8 \times 10^{-2} \frac{D}{Q_h H_h + Q_p H_p}$
F,G	$1.33 \times 10^2\ d_o\ (Sr^{90})$ rems (milk path only)	$10^{-6} \frac{d_o}{H_p Q_{90}}$
H	$98.4\ d_o\ (I^{131})$ rems	$1.1 \times 10^{-8} \frac{D}{H_h Q_{31}}$

[redacted]

Table VII shows the areas by zone for both stable and neutral atmospheres.

TABLE VII

ZONE AREAS - REACTOR ACCIDENT

(Height of release: 70 meters)

	Atmospheric Condition			
	Moderately Stable ($\bar{u}_h$ = 5 m/sec)		Neutral ($\bar{u}_h$ = 10 m/sec)	
Zone	Max. Distance (miles)	Area (sq. miles)	Max. Distance (miles)	Area (sq. miles)
A	exposure level not reached			
B	exposure level not reached			
C	210	400	2.4	<0.1
D	80	6.1	17	5.4
E	90	200	24	10
F	exposure level not reached			
G	100	90	20	6.8
H	1000	16,000	2000	70,000

The estimated distances along the center line of the contaminated area were used to apportion the area between the United States and Canada. An illustrative example (Figure VII) shows a contamination pattern in a northeasterly direction. Under these conditions about 70% of the contaminated area (Zone H, ≥ 1 μc I^{131}/m^2) or about 11,000 miles^2 would be in Canada. Cloud meander would tend to alter the fraction of contaminated land in Canada.

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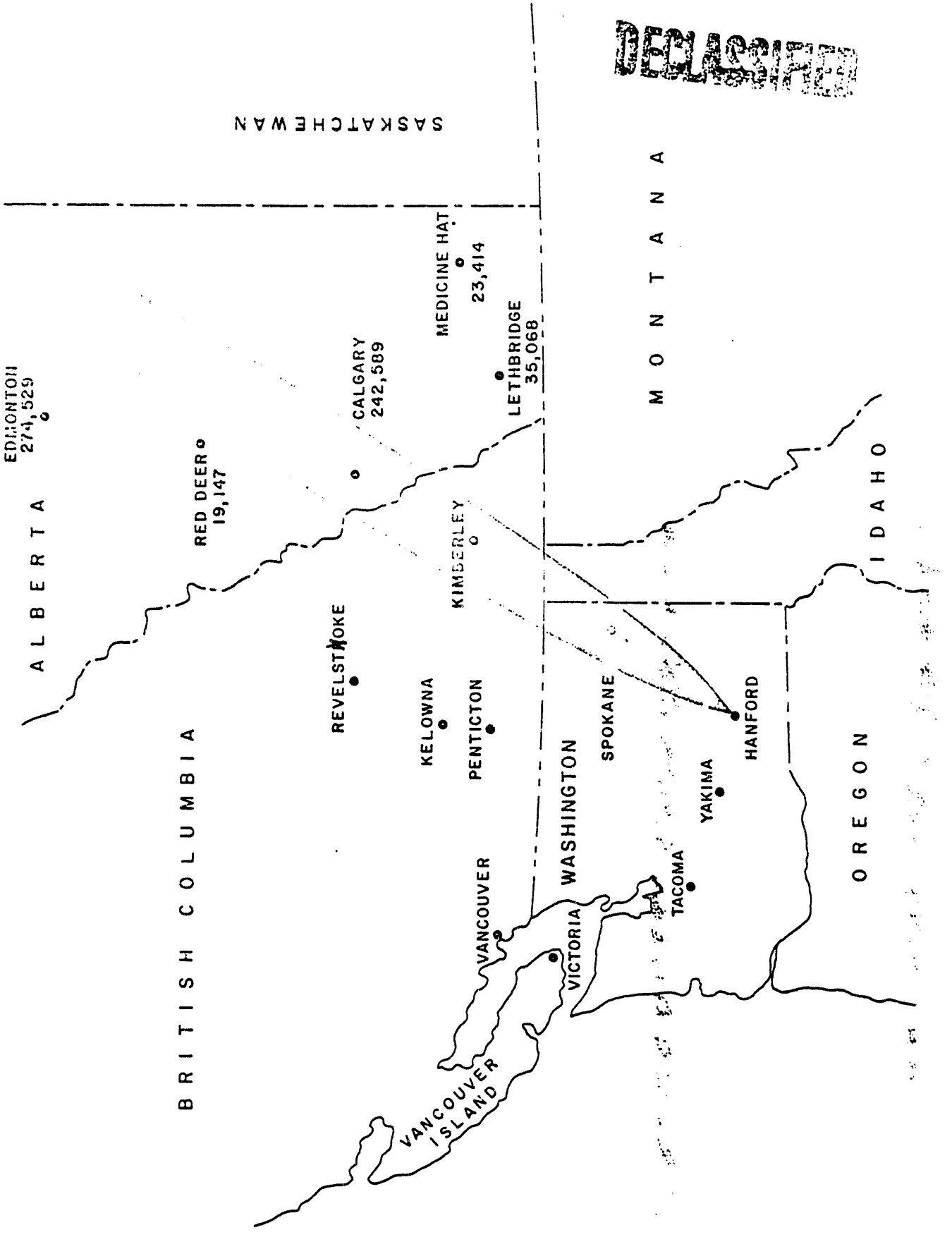
FIGURE VII

ILLUSTRATIVE EXAMPLE



The appropriate corrective actions in Zone H are not entirely determined by I^{131} contamination. Other fission products would be present to a greater extent in terms of contamination per unit area. I^{131} is more rapidly depleted from the cloud than particulates because of its higher deposition velocity. This effect is apparent in Figures I-III. At a distance of 400 miles, corresponding to Calgary, Alberta, in the illustrative example (Figure VII), 30 μc FP/m^2 would be deposited at the isopleth representing 1 μc I^{131}/m^2. The subsequent decay of the halogens and other fission products is illustrated in Figure VIII.

The distribution of the contamination along a perpendicular to the center line of the contaminated area is "bell-shaped" or Gaussian. The contamination level decreases with distance along the center line and also decreases outward from the maximum at the center line so that contamination levels within a criteria isopleth are higher than the isopleth value. To continue the illustrative example, at 400 miles (Calgary, Alberta), the contamination level of I^{131} varies from 1 μc/m^2 at the isopleth to about 20 μc/m^2 near the center line. At 170 miles (Canadian border) a more pronounced variation is estimated for I^{131}; from 1 μc/m^2 at the isopleth to about 400 μc/m^2 at the center line.

Because of greater confidence in the mathematical model for the moderately stable atmosphere, this case is preferred for evaluations. It cannot be categorically stated as the most unfavorable atmospheric condition, however, because of the possible applicability of the model for a neutral atmosphere. Also if "rainout" occurs at the larger travel distances, the contamination levels and the areas affected in Canada could be much larger.

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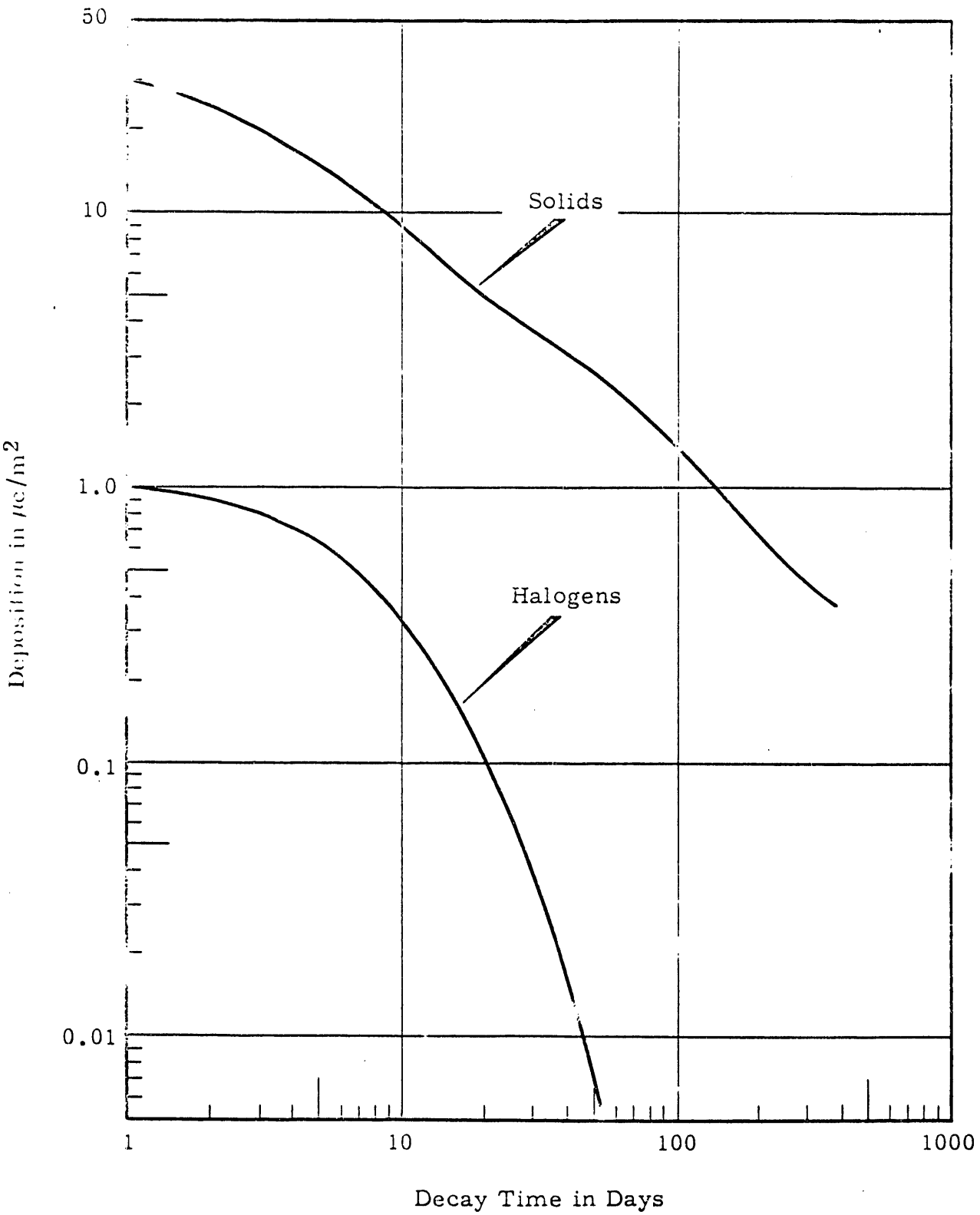
FIGURE VIII

RELATIVE ABUNDANCE OF FISSION PRODUCTS DEPOSITED



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RL Junkins:jm

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