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December 11, 1962

SUMMARY EVALUATION OF POTENTIAL LIABILITY FROM ACTIVITIES AT HANFORD

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December 11, 1962

SUMMARY EVALUATION OF POTENTIAL FOREIGN LIABILITY FROM ACTIVITIES AT HANFORD

Methods and Rationale

E. C. Watson

I. CONTAINED INVENTORY OF RADIONUCLIDES

A. Reactor Case

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.(1) The values used are shown in Table 1.

B. Shipment Case

The inventory of a radionuclide in a shipping cask was assumed to be 150,000 curies of Sr^{90} in the form $SrCO_3$.(2) The shipment is assumed to contain 2.5 curies of Sr^{89} per curie of Sr^{90}.

II. RELEASE OF RADIONUCLIDES

A. Reactor Case

The quantity of fission products released to the atmosphere during a major accident(3) depends upon: (a) the amount of uranium melted; (b) the fraction of the affected inventory escaping from the molten uranium; (c) the temperature of the unmelted uranium; (d) the chemical and physical form of the released nuclides; (e) the fraction of the fuel-released fission products depositing

---

(1) Nilson, R., Privileged Communication, October 8, 1962.
(2) Watson, E. C., R. L. Junkins, J. J. Fuquay, L. L. Zahn, HW-69561 Rev., "The Consequences of Accidental Releases During Shipments of Radioactive Cesium and Strontium", June 1961.
(3) A major accident for Hanford Production Reactors is assumed to involve the total loss of cooling water.

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TABLE 1

NORMALIZED FISSION PRODUCT INVENTORY FOR A PRODUCTION REACTOR

FP Category(4)	Quantity Present in Reactor After 24 Hours Decay (Megacuries/1000 Mw-70 days)(5)	
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

(4) Fission Product categories used are those used in the Gatlinburg Treaty, "Memorandum of Meeting of Risk Evaluations Subcouncil", M. C. Leverett, J. W. Healy, Karl Cohen, Gatlinburg, Tennessee, June 16, 1959.

(5) All computed values have been rounded to two significant figures.

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or "plating-out" on the cooler surfaces of core material, shielding, building and piping surfaces; and, (f) 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. Fraction of Uranium Inventory Melted in a Major Accident
   The Gatlinburg treaty value was used.(4) This assumes that the portion of the uranium which melts contains 50 percent of the inventory of fission products. Although there is a possibility of vaporization of some of the fuel, this was not considered here.

2. Fractional Release from Molten Uranium
   Once again, the Gatlinburg treaty values have been assumed, with one exception. In the referenced document ruthenium was placed in the "volatile solids" category.(4) This assignment of category, however, is considered to be in error.(6) This opinion has been verified by the recent work conducted at Hanford by Hilliard and Reid.(7) The release fractions from molten fuel assumed here are:

---

(6) Hilliard, R. K., Privileged Communication, January 1962.
(7) Hilliard, R. K., D. L. Reid, "Fission Product Release from Overheated Uranium - A Laboratory Study", Health Physics, 7, December 1961.

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

3. Fractional Release from Unmelted Uranium at Elevated Temperatures

No release was assumed for fission products contained in the 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 more volatile fission products. Failure to include this release tends to under estimate the total release of fission products.

4. Chemical and Physical Forms of Released Fission Products

It is assumed, conservatively, that the fission products released from the uranium are chemically unadulterated and do not agglomerate into particles large enough to preclude their being transported by air currents either inside the building or in the atmosphere.

5. Plate-Out Correction Factors

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

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given in reference (4), and are:

Noble Gases	1.0
Halogens	0.5
All Remaining Fission Products	0.3

6. Building and Stack Air Filtration Factors

No depletion of fission products was assumed for existing stack filtering systems. This assumption is consistent with present IPD philosophy of considering the existing production reactor buildings as offering little or no confinement capabilities in the event of a major accident.(8)

B. Shipment Case

1. Description of Shipment(2)

Strontium is shipped as $SrCO_3$ in a dry powder form. The particles vary in size from 1 to 4 microns. They tend to agglomerate into larger particles which range in size up to 25 microns, with the majority in the size range of 4 to 12 microns. These agglomerates, however, are very loosely bound, and can be easily fractured into the basic particle sizes.

The shipping system, HAPO II, consists of a product container sealed in a cask which in turn is firmly positioned in a larger buffer. The ensemble is 8 feet in diameter by 12 feet high and weighs about 20-1/2 tons. It is secured to a rail car with tie-down bars of sufficient strength to more than

(8) Greager, O. H., Privileged Communication, October 1962.

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withstand the forces encountered in normal rail transport. The cask, surrounded by its buffer, is capable of withstanding an impact with an unyielding object at a velocity of 30 miles per hour. In addition, it will withstand direct flame impingement (2500 F) for two hours.

2. Release to the Atmosphere

It is assumed that a severe collision occurs followed by fire or explosion. A complete breach of the product container and cask is considered incredible. Further, a multiple ventilation barrier is provided by the cask and buffer. The net result is that one percent of the shipment is assumed to escape to the atmosphere.

III. RELEASED INVENTORY OF RADIONUCLIDES

A. Reactor Case

The several depletion factors discussed in Section II-A are summarized in Table 2.

TABLE 2

SUMMARY OF DEPLETION FACTORS

Fission Product Category	Fraction in Melted U.	Fraction Released From Melt	Fraction Not Plated-Out	Fraction Released to Atmosphere (9)
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

(9) Equal to the product of the factors listed in previous three columns.

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Multiplication of the factors given in the last column of Table 2 by the normalized inventory figures given in Table 1 results in the inventory of fission products released to the atmosphere as shown in Table 3.

B. Shipment Case

The released inventory is:

Sr^{90}	1500 curies
Sr^{89}	3800 curies

IV. 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: (2, 10) ~~(10)~~

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

(10) Experimental evidence indicates that Eq (1) is valid for moderately stable atmospheres, for $h = 0$ to 70 meters.
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.

Earlier ref. for elevated release

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TABLE 3

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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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

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

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

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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[11] are shown in Table 4, page 13. 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:[12]

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

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

---

(11) Fuqua, J. J. and reported by J. W. Healy, "Calculations on Environmental Consequences of Reactor Accidents", HW-54128, December 1957.

(12) Neither Eq (1) nor Eq (3) has been experimentally verified for neutral atmosphere at Hanford ~~climatology~~. 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.

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For this analysis (a release above ground level in a neutral 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:

$$Q = Q_o \exp\left[- \frac{2}{C_z\sqrt{\pi}} \left(\frac{V_\Delta}{\bar{u}_o}\right)\left(\frac{\bar{u}_o}{\bar{u}_h}\right) \int_0^x x^{\frac{n-2}{2}} \exp\left(- \frac{h^2}{C^2_z} x^{(n-2)}\right) dx \right] \qquad (4)$$

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 various parameters are:

$h = 70$ meters

$\bar{u}_h = 5$ 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

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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:

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

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

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

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[13] are available; however, assumptions had to be made particularly for iodine. The values currently in use are:

	f_v
Iodine	1
Strontium	0.4
Cesium	0.2

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

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TABLE 4

DEPOSITION COEFFICIENTS AND WIND SPEED RATIOS

Atmospheric Condition	Deposition Coefficient $\left(\frac{V_\Delta}{\bar{u}_o}\right)$ Particulates	Halogens	Radio of Wind Speed at Ground Level to Wind Speed at Height of Release (70 m) $\left(\frac{\bar{u}_o}{\bar{u}_h}\right)$	$\frac{H}{\bar{u}_h}$ part.	halo.
Very stable	1.5×10^{-4}	2.4×10^{-3}	0.17	2.6×10^{-5}	4.1×10
Moderately stable	2.2×10^{-4}	3.4×10^{-3}	0.35	7.7×10^{-5}	1.2×10
Neutral	3×10^{-4}	4.6×10^{-3}	0.5	1.5×10^{-4}	2.3×10
Unstable	6×10^{-4}	8×10^{-3}	0.7	4.2×10^{-4}	5.6×10

long term $\frac{1 r}{yr}$ @ 5 yr $\Rightarrow$ $d = 925 \frac{\mu c}{m^2}$ @ 1 day

Short Term

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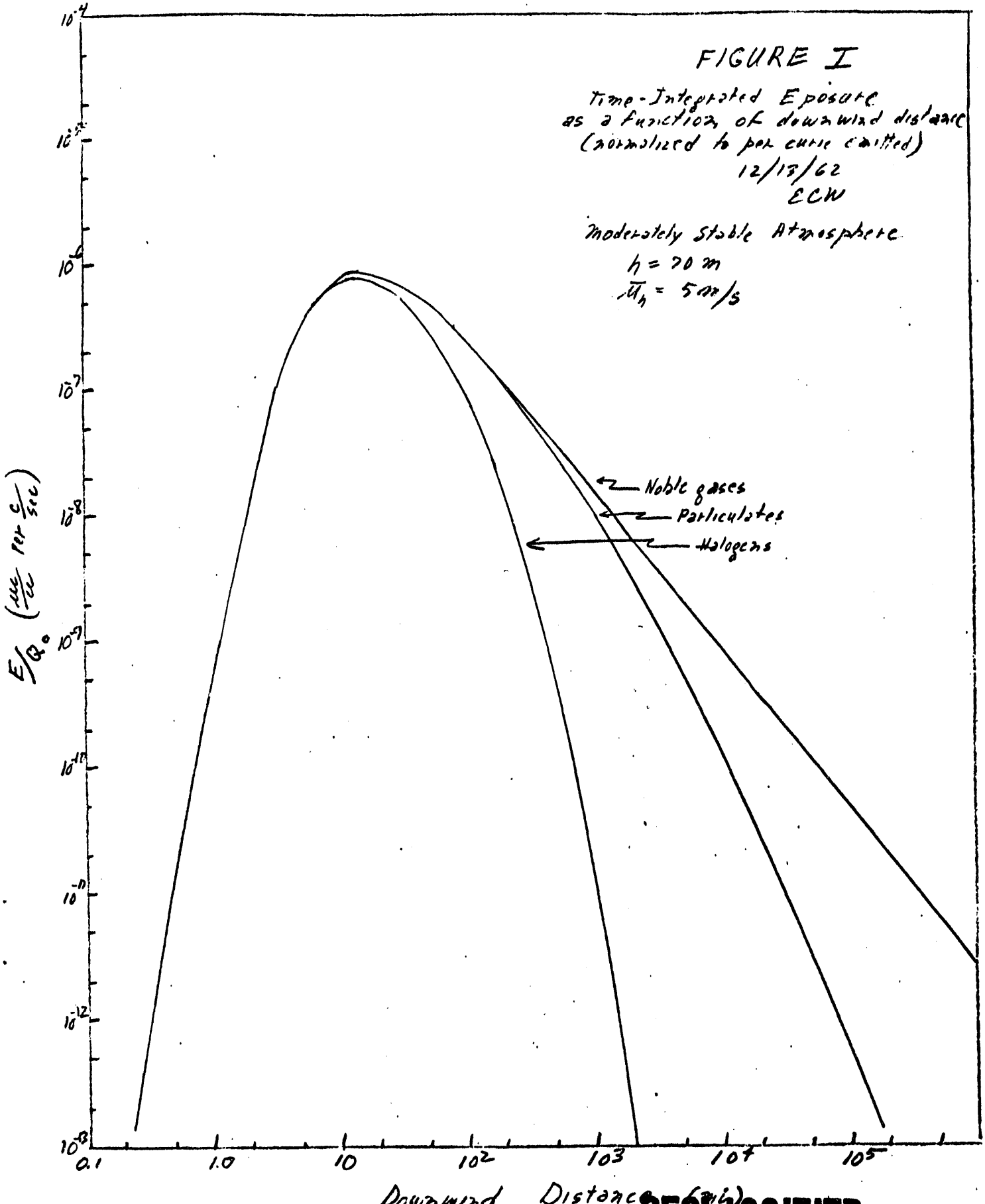

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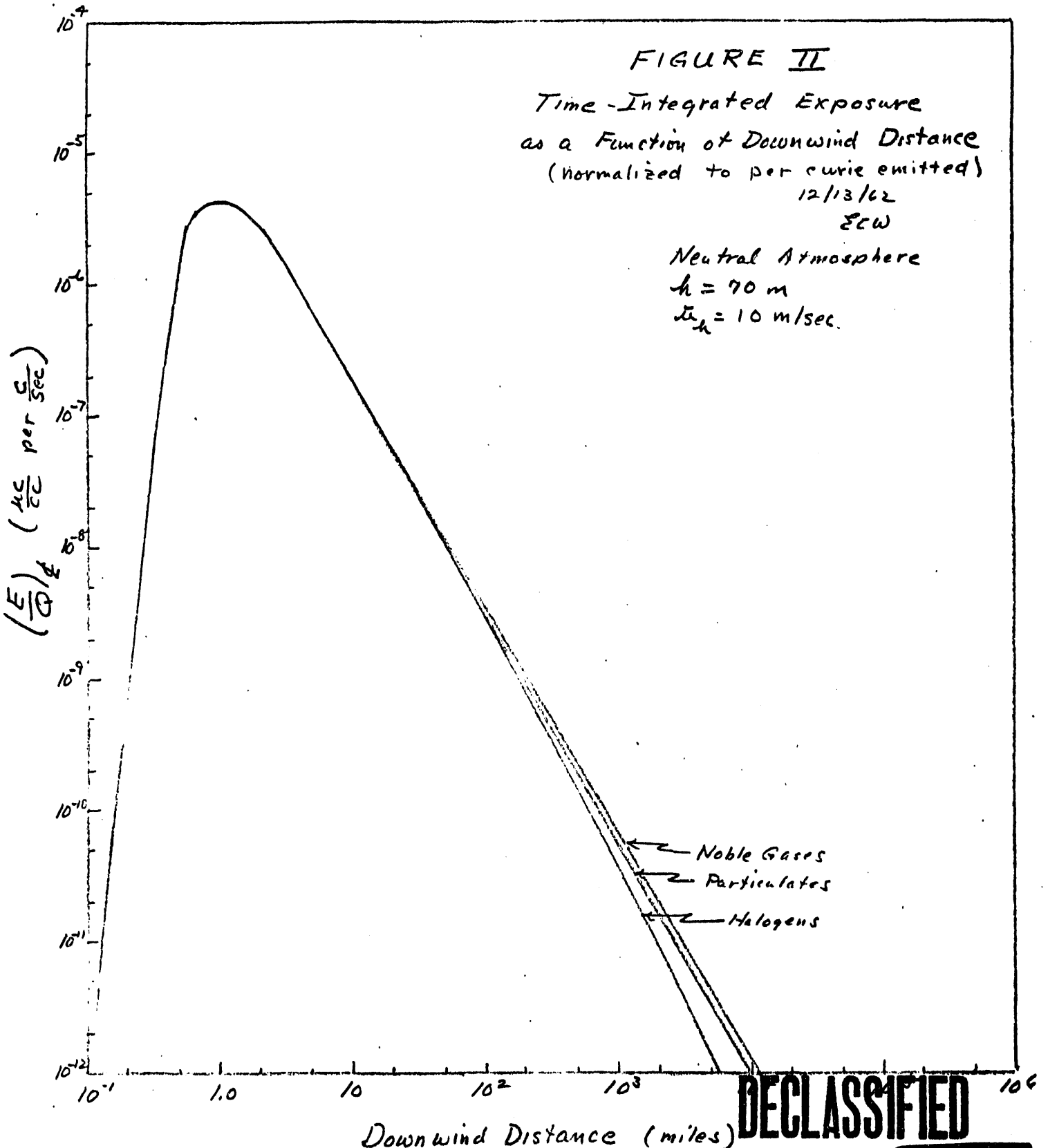

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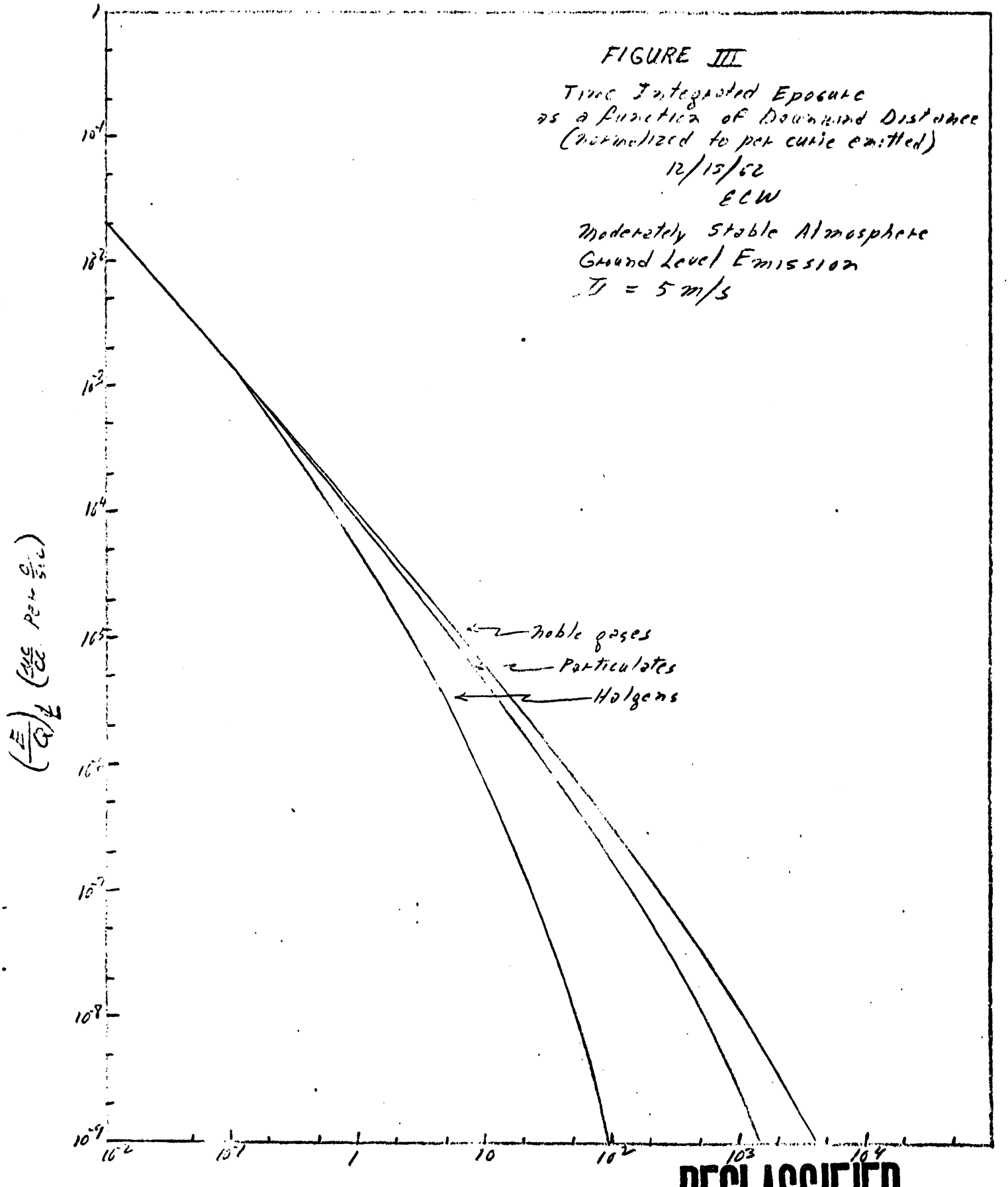

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C. Isopleth Area

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. The area can be estimated very closely by:

$$\text{Area} = 0.114\, \ell^{1.8} \left\{ \ln \left[\frac{(\frac{E}{Q})'_{\ell/2}}{(\frac{E}{Q})'_{\ell}} \right]^2 \right\}^{1/2} \qquad (6)$$

($h = 0$, Moderately Stable Atmosphere)

where:

~~x = maximum downwind distance defined by $(\frac{E}{Q})'_{\ell}$~~

ℓ = the length of the isopleth along its major axis (downwind direction). ~~For $h = 0$, $\ell \propto x^{0.8} = x^{1.8}$~~

$(\frac{E}{Q})'$ = centerline value (y = o) of ~~either~~ Eq (1) ~~and (3)~~

$(\frac{E}{Q})'_{\ell/2}$ = $(\frac{E}{Q})'$ at the midpoint of ℓ

$(\frac{E}{Q})'_{\ell}$ = $(\frac{E}{Q})'$ at the either end of ℓ

Actually, it is equal ~~any~~ to $(\frac{E}{Q})$ at any point on the isopleth

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

For an elevated release ($h \neq 0$), ~~[redacted]~~ the area is estimated by:

$$\text{Area} = 0.114\, \ell (x + x')^{0.8} \left[\ln \psi^2 \right]^{1/2} \qquad \text{Mod. Stable} \quad (6a)$$

Also, for a neutral atmosphere and $u_h = 10$ m/s

$$\text{Area} = 0.0941\, \ell (x + x')^{0.875} \left[\ln \psi^2 \right]^{1/2}$$

where: $\ell = x - x'$

x = maximum downwind distance to $(\frac{E}{Q})'$

x' = minimum " " " "

$\psi = \frac{(\frac{E}{Q})'_{\ell/2}}{(\frac{E}{Q})'_{\ell}}$

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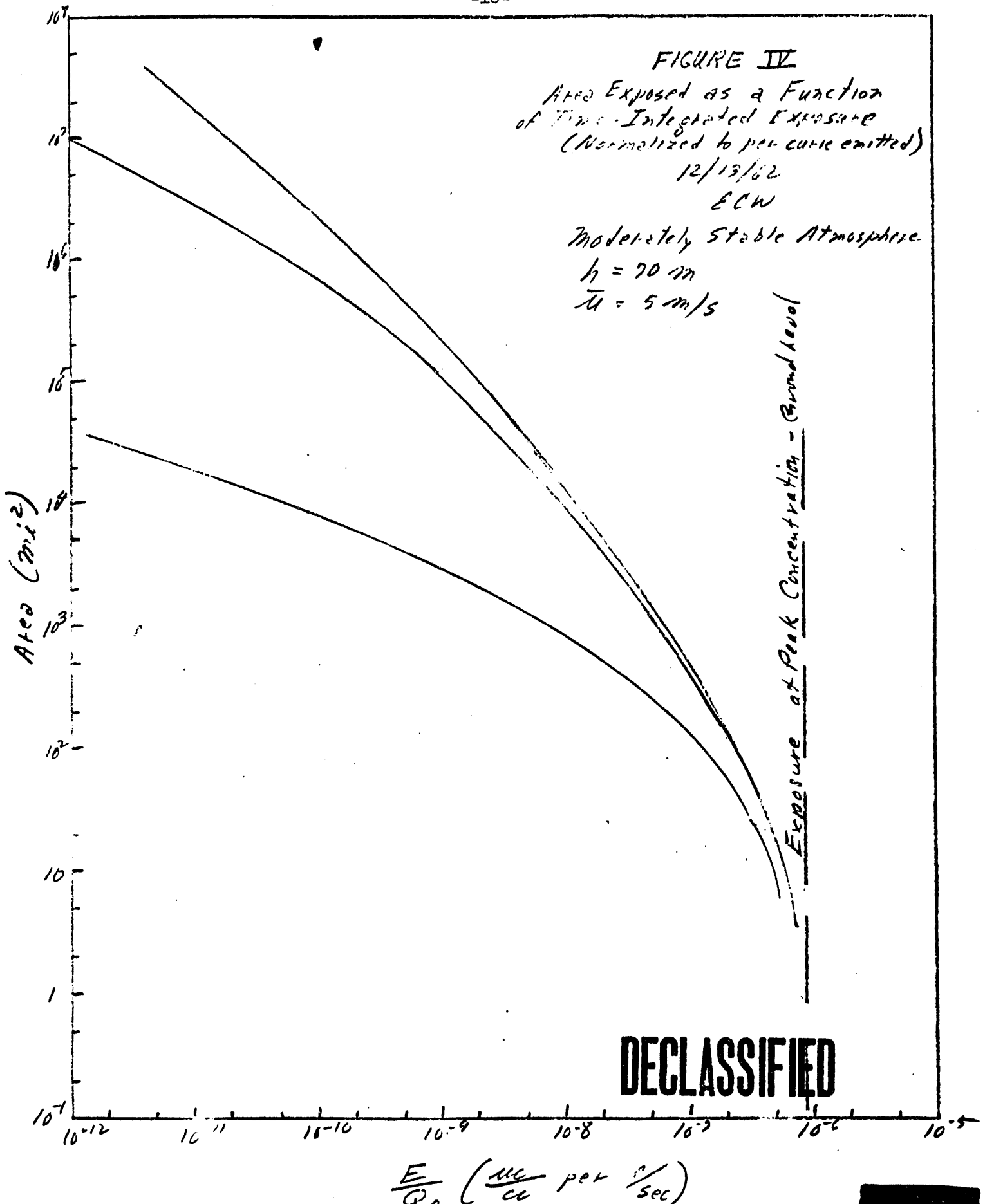

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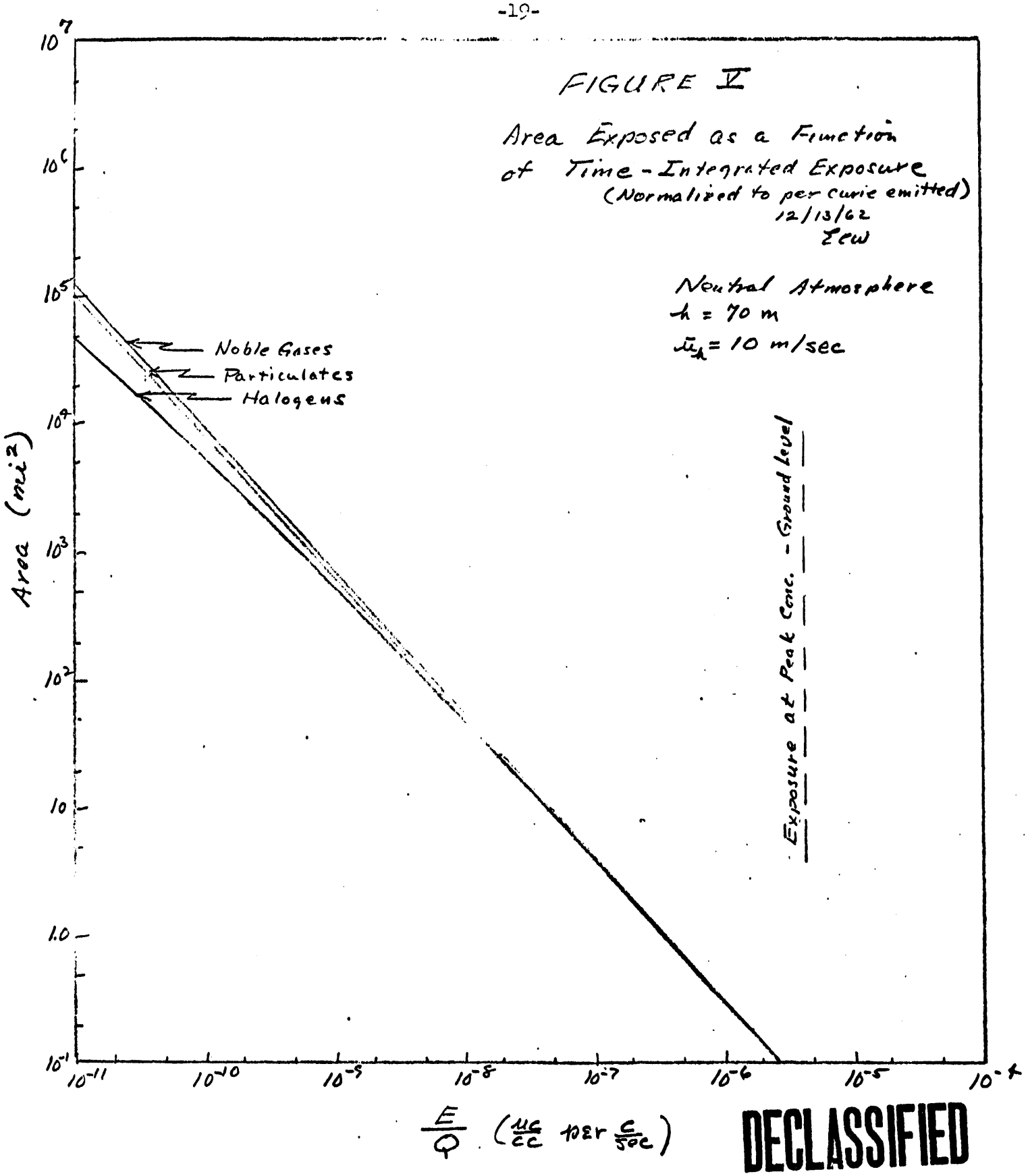

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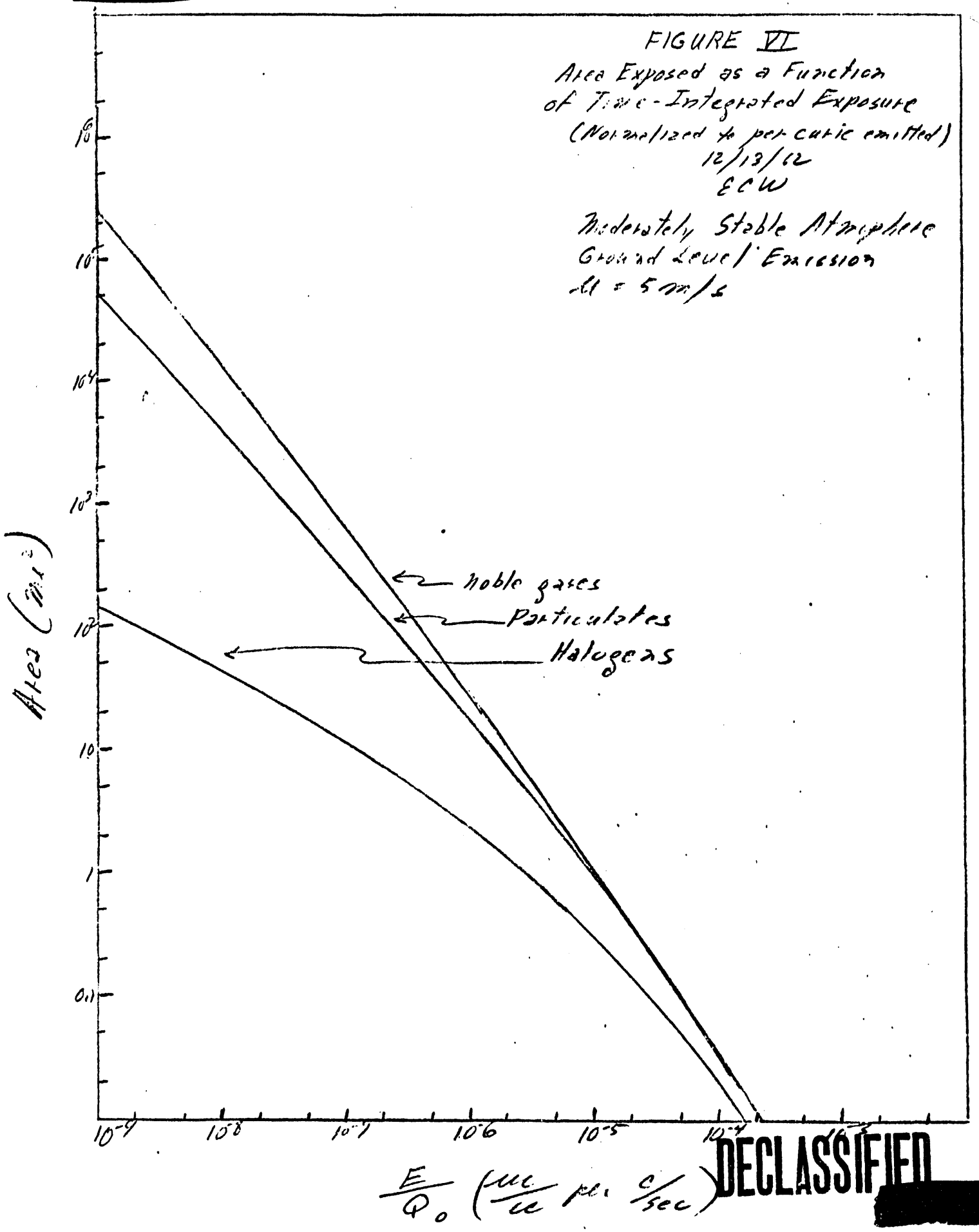

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V. EXPOSURE CRITERIA

A. Reactor Case

1. External Radiation Exposure

The criteria used here are those used generally within the Company. (4)

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

Whole Body Dose	Probable Effect
≥ 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.

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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.
$\geq$ 250 rems to a 2 g thyroid	2.8 $\mu c/m^2$ I^{131}	Confiscate current milk supplies and provide feed for dairy cattle. (Temporary)

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

B. Shipment Case (Strontium)

Exposure criteria for inhalation developed previously (2) were used for this analysis.

1. Internal Deposition

The purity of the product is such that only internal deposition of radiostrontium is of concern. There are several exposure modes, the more important of which are: (a) inhalation during cloud passage; (b) ingestion of strontium-contaminated fresh leafy vegetables and; (c) ingestion of strontium contaminated milk.

a. Exposure to the cloud. Persons exposed to the cloud will, in a manner similar to the reactor case, receive significant doses to the lung, G.I. tract, and whole body. Only the bone dose is considered in this analysis. The criteria selected and expected biological effects are:

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Quantity of $Sr^{89,90}$ Inhaled (μc)	Bone Deposition[15] (μc)		Probable Effects	First Year* Dose to Bone (rems)	
	Sr^{89}	Sr^{90}		Sr^{89}	Sr^{90}
$\geq 3.8 \times 10^4$	$\geq$ 4500	$\geq$ 1800	Some lethalities Extended hospitalization	$\geq$ 6700	$\geq 2.7 \times 10^4$
6.2×10^3 to 3.8×10^4	750 to 4500	300 to 1800	Latent effects Hospitalization at some future time	1100 to 6700	4.5×10^3 to 2.7×10^4
42 to 6200	5 to 750	2 to 300	Some increase in frequency of leukemias and sarcomas	7.4 to 1100	30 to 4500

*If no action can be taken to prevent exposure to cloud.

b. Exposure to Residual Ground Contamination

Exposure criteria for public emergency limits have been recommended by the UK Medical Research Council.[16] These dose criteria were transformed into contamination values and used for ingestion of contaminated foods in reference (2). In this analysis, the contamination levels developed in reference (2) have been retained. The criteria selected and probable action required are:

Exposure Criteria

Ground Contamination (μc Sr^{90}/m^2)	Probable Action Required	Dose after 1st Year[17] of milk consumption (rems/year)
$\geq$ 20	Destructive decontamination	$\geq$ 160
1 to 20	Removal of farm lands from production for several years.	8 to 160
0.15 to 1	Confiscation of current crops. Removal of dairy cattle from contaminated pastures.	1.2 to 8

(15) Based on ICRP values for standard man.

(16) Medical Research Council "The Hazards to Man of Nuclear and Allied Radiations" A Second Report, December, 1960

(17) Assumes 2.5 curies of Sr^{89} per curie of Sr^{90}

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VI. AREAS CONTAMINATED

A. Reactor Case

It is convenient to designate the preceding exposure criteria as zones, the outer boundaries of which correspond to the criteria. This is done in Table 5.

The equations[18] for estimating the dose and for determining the corresponding normalized time-integrated exposure are shown in Table 6. The symbols are as follows:

D = Dose (rems)

D_r = Dose rate (rems/hr)

c = Air concentration of released fission products in μc/cc

c_f = Air concentration of all but the noble gas fission products in μc/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.

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(18) Watson, E. C., Transmitted to N. R. Miller August 9, 1962, for publication in NPR Hazards Analysis, Vol. 2.

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d_o = Initial peak ground contamination

$d_o(Sr^{90})$ = 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 non-volatile 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 7 shows the areas by zone for both stable and neutral atmospheres.

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TABLE 5

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	" " "	100 to 450 rems, whole body
C	" " "	5 to 100 rems, whole body
D	External, Ground Contamination	1 rem/yr after 5 years, whole body
E	" "	1 rem in first year, whole body
F	Ingestion	3 $\mu c/m^2$ on the ground
G	"	0.15 $\mu c/m^2$ on the ground
H	"	250 rems, 2 g thyroid

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TABLE 6

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 $\left(\frac{\mu c\text{-sec}}{cc\text{-curie}}\right)$ $\left(\frac{E}{Q}\right)$ 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	$760\ \frac{D_r(5\ yr)}{[redacted]\ Q_p H_p}$
E	$2.1 \times 10^{-5}\ d_o$ rems	$4.8 \times 10^{-2}\ \frac{D}{[redacted]\ Q_p H_p}$
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	$1.1 \times 10^{-8}\ \frac{D}{H_h Q_{31}}$

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TABLE 7

ZONE AREAS - REACTOR ACCIDENT

(Height of release: 70 meters)

Zone	Atmospheric Condition			
	Stable ($\bar{\mu}_h$ = 5m/sec)		~~Unstable~~ Neutral ($\bar{\mu}_h$ = 10m/sec)	
	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	17	5.4
E	90	20	24	10
F	exposure level not reached			
G	100	90	20	6.8
H	850	12000	1900	50,000

B. Shipment Case

Again, the exposure criteria have been used to define zones, as shown in Table 8.

TABLE 8

EXPOSURE CRITERIA AND CORRESPONDING ZONES

Zone	Exposure Criteria
A	≥1800 μc Sr^{90} in bone
B	300 to 1800 μc Sr^{90} in bone
C	2 to 300 μc Sr^{90} in bone
D	≥20 μc Sr^{90}/m^2
E	1 to 20 μc Sr^{90}/m^2
F	0.1 to 1 μc Sr^{90}/m^2

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The equations[2] for estimating the dose and for determining the corresponding normalized time-integrated exposure are shown in Table 9. The zone areas and distance from point of release for both stable and neutral atmospheres are shown in Table 10.

TABLE 9

EQUATIONS FOR ESTIMATING BONE DOSE AND DETERMINING NORMALIZED TIME-INTEGRATED EXPOSURES

Zone	Dose Rate Equations Dose Equals:	Normalized Time-Integrated Exposure Equals:
A,B,C	4.05×10^{2} ct (Sr-90) $\frac{\text{rems}}{\text{yr}}$ at 1 yr.	$3.62 \times 10^{-2} \frac{q}{Q}$
D,E,F	1.33×10^{2} d_o (Sr-90) $\frac{\text{rems}}{\text{yr}}$	$10^{-6} \frac{d_o}{H_p Q}$

(q is the bone burden in μc. Other symbols have been defined previously)

TABLE 10

ZONE AREAS - SHIPPING ACCIDENT
(Height of Release: Ground Level)

Zone	Atmospheric Condition			
	Stable ($\bar{\mu}_o$ = 5m/sec)		~~Unstable~~ Neutral (μ_o = 10m/sec)	
	Distance (miles)	Area (sq. miles)	Distance (miles)	Area (sq. miles)
A	<0.1	nil	<0.1	nil
B	<0.1	nil	<0.1	nil
C	1.7	0.09	0.27	<0.01
D	5.3	0.68	1.1	0.046
E	47	39	6.2	1.2
F	160	350	17	7.9

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VII. ECONOMIC FACTORS

A. Personnel Injury

The most likely cause of unavoidable injury to people would be exposure during passage of the cloud. Since exposures from the cloud great enough to cause injury would occur within relatively short distances of the accident site, it would be difficult to prevent this. It is assumed, therefore, that no action could be taken in time to prevent such exposures. The conversion factors for estimating the costs are given in Table 11.

TABLE 11

COST ESTIMATES FOR PERSONS IN ZONES A, B, & C

Zone	Reactor Accident $/person	Shipping Accident $/person
A	25,000	50,000
B	50,000	25,000
C	5,000	1,000

For the reactor accident, lethalities would occur in Zone A from the over-exposure in a relatively short period of time and prolonged, expensive medical treatment would not be involved. Thus the cost per person is assumed to be less than for the shipping accident where Sr^{90} deposition in the bone would likely involve more extensive medical care. Similar differences in the length and cost of medical care and examinations result in different cost estimates for Zones B and C.

The conversion factors are more conveniently expressed in dollars per square mile. The factors in these units are given in Table 12.

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TABLE 12

COST ESTIMATES FOR LAND AREAS IN ZONES A, B, & C

Zone	Reactor Accident[19] 10^6 ($/mi (Rural only)	Shipping Accident[20] 10^6 $/mi Urban	Suburban	Rural
A	0.18	330	33	0.36
B	0.36	160	16	0.18
C	0.036	6.6	0.66	0.0072

B. Contamination of Property and Farm Products

The concern here, of course, is that the contamination would ultimately result in exposure of people if no remedial action were taken. However, there should be ample time to take such action because high doses to people would be incurred only after continued exposure. The costs associated with this type of damage, therefore, are based on decontamination costs and market values of foods. Both kinds of costs are more readily determined than the price of a man's health. It should be remembered, however, that the need for such measures is based on preventing the exposure of people. The conversion factors for estimating these costs are given in Table 13.

(19) Based on an Eastern Washington population density of 7.2 people/mi^2.

(20) Based on city of Spokane and surrounding areas. The population densities used are: urban: 6,600 people/mi^2; suburban: 660 people/mi^2.

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TABLE 13

COST ESTIMATES FOR DECONTAMINATION AND CONFISCATION

Zone	Reactor Accident (Rural areas only) 10^6 Dollars/mi^2	Shipping Accident 10^6 Dollars/mi^2 Urban	Suburban	Rural
D(21)	0.0072	420	42	0.3
E	0.3	4.5	0.45	0.2
F	0.2	0.15	0.15	0.15
G	0.15	Not Applicable		
H	0.15	Not Applicable		

C. Estimated Costs of Damages

The zone areas shown in Tables 7 and 10 can now be converted to estimated costs. The results are shown in Tables 14 and 15 for the reactor accident and the shipping accident, respectively.

TABLE 14

ESTIMATED OFF-SITE DAMAGE COSTS - REACTOR ACCIDENT

Zone	Estimated Costs (Millions of Dollars) Stable Atmosphere	Neutral Atmosphere
A	None	None
B	None	0.1
C	14	0.12
D	None	None
E	27	3.0
F	None	None
G	15	2.4
H	1,800	7,500
Total	$2,000	$8,000

(21) The property damage unit costs are based on $1,000/person as suggested in Ref(4) and 7.2 people/mi^2. The remaining unit costs are based on Ref (2).

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It is the uniform opinion at Hanford that the neutral atmosphere case should not be used because the theoretical atmospheric dispersion equation is not, in all probability, strictly applicable to this condition and its use results in over estimation of the damages. More experimental data have been developed for the stable atmospheric case and hence more confidence in the diffusion model. For this reason, the stable case is assumed as a superior basis for prediction.

The costs of damages for the shipping accident are estimated for two situations. The first assumes the accident occurs in a rural area and all costs are based on rural dollar conversion factors. This situation is called the "rural release". The second assumes the accident occurs in an urban area, surrounded by a well developed suburban area. It further assumes that the accident occurs at a place in the city such that the largest exposures are encountered in the heavily populated areas. This situation is referred to as the "urban release". Estimating the costs for a zone in which the area is greater than the area of the city and its suburbs would, therefore, involve using three cost conversion factors. For this analysis, the area of the city is estimated to be 27 square miles and the suburban area to be 100 square miles, most of which is located in the northeast quadrant from the city.

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TABLE 15

ESTIMATED DAMAGE COSTS[22] - SHIPPING ACCIDENT
(For a Stable Atmospheric Condition)

Zone	Estimated Costs (millions of dollars)	
	Rural Release	Urban Release
A	nil	<0.1
B	nil	<0.1
C	nil	0.6
D	0.18	290
E	7.8	120
F	52	1100
Total	60	1500

(22) Excludes ordinary costs directly involved in the accident and the immediate area.

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VIII. APPORTIONMENT OF DAMAGE COSTS IN CANADA

In estimating costs occurring in Canada, it was assumed that the released contaminants travelled invariantly in the Northeast direction during the course of the incident. The only zone extending into Canada in either the Reactor or Shipping Accident is the zone with the lowest criteria.

A. Reactor Case

The Zone H criterion is based upon the dose to a 2 g-thyroid resulting from ingestion of milk which contains I^{131}. Although the thyroid dose in this case is controlling, there are other considerations in estimating the costs. Such considerations include the external exposure from other fission products deposited on the ground and the dose to other organs of the body resulting from their ingestion. This latter mode of exposure will not be discussed in detail because of its complexity.

1. External Exposure

   The ground contamination of fission products deposited at the isopleth defining Zone H is initially 120 $\mu c/m^2$. A year later, this level would have decayed to about 0.25 $\mu c/m^2$; the radioiodine would, of course, be gone. The initial dose rate at three feet above ground would be greater than 25 mrem/day.

2. The unit cost figure for Zone H assumes the entire area is agricultural. Unit costs of decontaminating large urban areas, such as Spokane, Washington, and Calgary, Alberta, would be greater. This influence would be offset by large areas of improductive land, however. Forest areas would

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probably not require remedial action if the only contaminant was radioiodine. The dose rates from deposited fission products other than I^{131} are assumed to require remedial action similar to those required for I^{131}. The unit costs, therefore, for Zone H were assumed to be $150,000/mi^2.

The distance to the Canadian border, as measured from K Area through Spokane, Washington, was used to apportion the zone areas between the U. S. and Canada.

B. Shipment Case

The accident was assumed to occur in Spokane, Washington. It should be noted, however, that shipments could travel through a larger urban area such as Seattle, Washington. This routing is not intended, but a mix-up of trains or shipping papers could result in the accident site being in a larger urban area than considered here.

As in the reactor accident, the wind velocity was assumed invariant with a constant wind speed in a Northerly direction. The distance from Spokane to the border was used to apportion the zone areas.

The rural release case was assumed to occur near Cut Bank, Montana, at a distance of 25 miles from the Canadian-U.S. border.

C. Assignment of Costs

The portion of the lowest criteria zone areas occurring in Canada are shown in Table 1Ø. The estimated costs are again based on a

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dollar conversion factor of $150,000/mi^2 in lieu of factual data on land and crop values and costs of remedial action.

TABLE 16

AFFECTED AREAS IN CANADA AND ASSOCIATED COST
(Moderately Stable Atmosphere)

Reactor Accident			Shipping Accident					
			Rural			Urban		
Canadian Area (mi^2)	Costs (millions of $) Canada	Costs (millions of $) Total	Canadian Area (mi^2)	Costs (millions of $) Canada	Costs (millions of $) Total	Canadian Area (mi^2)	Costs (millions of $) Canada	Costs (millions of $) Total
8000	1,000	2,000	320	50	60	170	30	1,000

DISTRIBUTION

1-3 - WE Johnson
4 - HM Parker
5 - RL Junkins
6 - JJ Fuquay
7 - AR Keene
8 - EC Watson
9-10 - Extras

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DATE
FILMED
8/10/94

END