

## Dosimetric Concepts

HPHY 6605  
2012

## Biological Dosimetry

- The first dosimetry method was biological, the erythema dose.
  - An erythema dose is 2 to more than 5 Gy, depending on the individual.
- This dose range has no application in routine environmental dosimetry, but has been pertinent in a few major accidents.

## Introduction

- The concept of radiation dose is fundamental to describing risk from ionizing radiation
- Radiation dose can be determined for any type or energy of ionizing radiation
- Once the amount of the appropriate dose quantity is known, risk can be estimated
- This is different from chemical risk, which has to be established for each chemical

## Biological & Instrumental Dosimetry

- Today there are biological dosimetry methods that are well established and research is being done on others
- Examples include
  - blood cell count
  - various radiation syndromes
  - chromosome damage in peripheral lymphocytes
  - electron spin resonance in teeth.

## Biological & Instrumental Dosimetry

- These methods, all of which are more sensitive than erythema dose, still have no application in normal environmental situations
- Consequently we rely on instrumental methods and modeling for assessing doses in the environment

## Absorbed Dose

- Absorbed dose, "D", is the fundamental quantity  $\varepsilon = \text{energy imparted}$
- The SI unit of absorbed dose is gray (= 1 joule/kg)  $\varepsilon = R_{in} - R_{out} + \sum Q$
- The traditional unit is rad  $\bar{\varepsilon} = \text{mean energy imparted}$
- One gray = 100 rads
- Depends on absorbing material **and** radiation field
- Just plain "dose" is a generic term for any dose quantity, but only if meaning is clear  $Dose = D = \frac{d\bar{\varepsilon}}{dm}$

## Exposure

$$Exposure = X = \frac{dQ}{dm}$$

- Exposure is an early quantity that is related to the ionization of air
  - Property of the radiation field
- Unit of exposure is the roentgen (R)
- One R is ionization of one sign in dry air of:  $2.58 \times 10^{-4} \text{ C kg}^{-1}$  or 1 esu per  $\text{cm}^3$

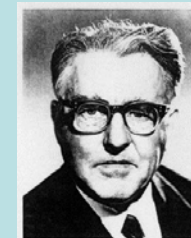


Wilhelm Roentgen, discoverer of x rays

## Gray

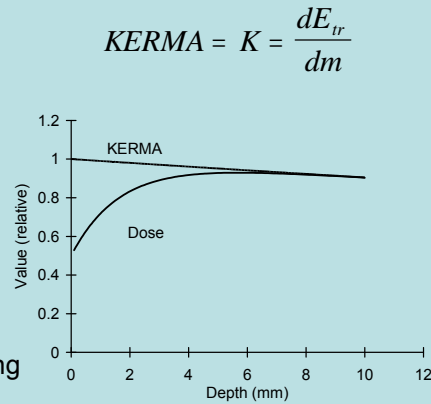


- Louis Harold Gray, English radiobiologist whose name is honored by using it for the unit of absorbed dose



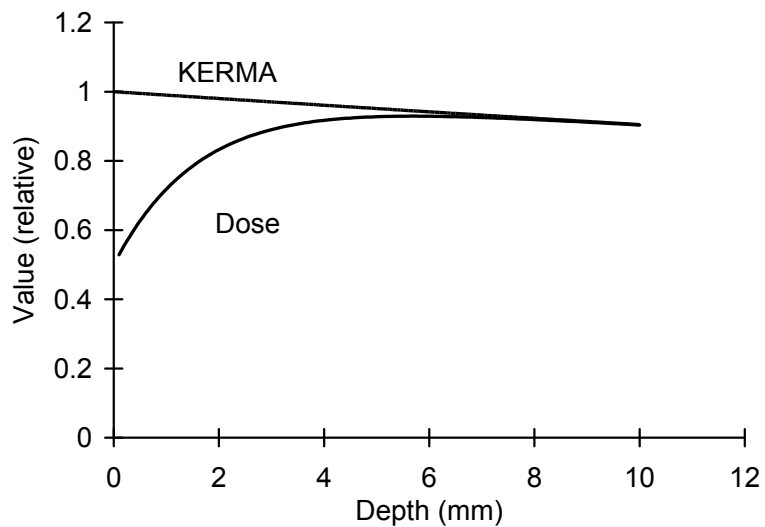
## Kerma

- $E_{tr}$  = initial kinetic energies of all charged particles liberated by uncharged ionizing particles
- $K$  approaches  $D$  as charged particle equilibrium is approached, assuming negligible bremsstrahlung
- Units are the same as dose



## Averaging Dose

- Dosimetric quantities (dose, KERMA) can be specified at a point but in radiation protection are usually taken as an average over a tissue or organ
- The concept of averaging over a tissue or organ has severe limitations for deterministic effects, i.e. hot particles
  - Deterministic effects can occur even though the average dose to an organ or tissue falls within regulatory limits



## RBE

- Relative biological effectiveness

$$RBE = \frac{\text{Dose of 250 kVp x rays to produce an effect}}{\text{Dose of another kind of radiation to produce same effect}}$$

## Dose Equivalent

- Dose equivalent =  $H = QD$ 
  - $Q$  is the quality factor, a rough appraisal of biological effectiveness defined as a function of LET. Over a range of radiation qualities,

$$\bar{Q} = \text{mean value of } Q$$

- for a range of radiation qualities

$$H = \bar{Q}D$$

- $H$  is a point quantity
- Quantity of  $H$  is dose equivalent; Unit is rem or Sievert

## Effective Q as a Function of Photon Energy

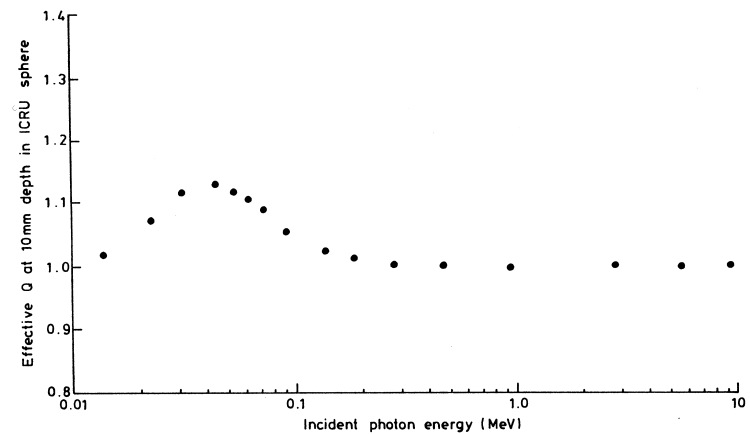
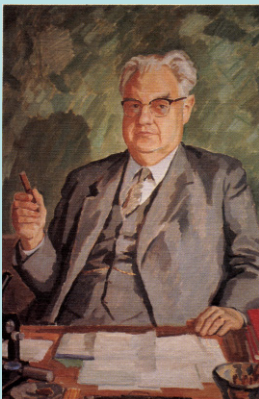


Fig. A-2. Effective  $Q$ , ( $\bar{Q}$ ) as a function of photon energy. Reference: Drexler *et al.* (1990).

ICRP 60

## Sievert



- Rolf Sievert, a Swedish medical physics professor and pioneer dosimetrist, whose name is honored by using it for the units of the quantities equivalent and effective dose

## Effective Q as a Function of Neutron Energy

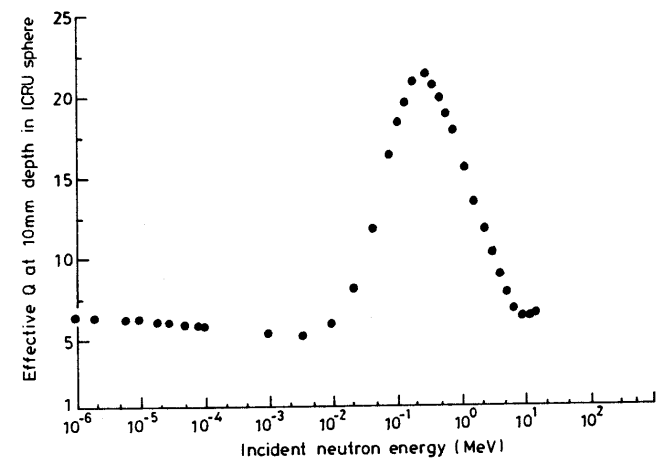


Fig. A-3. Effective  $Q$ , ( $\bar{Q}$ ) as a function of neutron energy. Reference: Leuthold (1990).

ICRP 60

### Average quality factors recommended in ICRP 26

Type of radiation	Average Q
X rays, gamma rays, electrons	1
Neutrons, protons, singly charged particles	10
Alpha particles, multiply charged particles	20

### Radiation weighting factors in ICRP 103

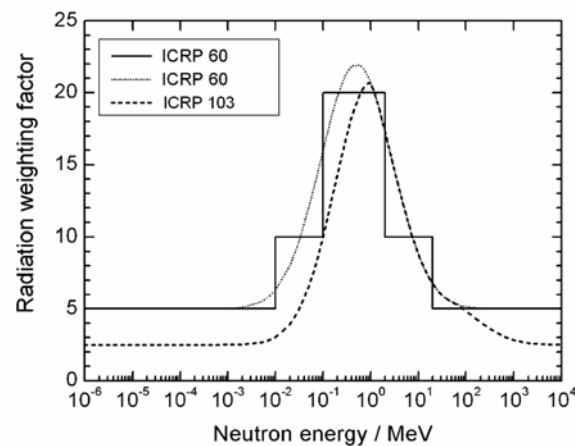
Radiation type	Radiation weighting factor, $w_R$
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy (see Fig. B.4 and Eqn. B.3.16)

### Radiation weighting factors recommended in ICRP 60

Type of radiation	$W_r$
Photons	1
Electrons	1
Neutrons < 10 keV	5
Neutrons 10 - 100 keV	10
Neutrons 100 keV - 2 MeV	20
Neutrons 2 MeV - 20 MeV	10
Neutrons > 20 MeV	5
Protons > 2 MeV	5
Alpha and heavier particles	20

### Radiation weighting factor, $w_R$ , for neutrons versus energy

(ICRP 103, ANNEX B)



### Radiation weighting factor equations for neutrons as a function of neutron energy

$$w_R = \begin{cases} 2.5 + 18.2 e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0 e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\ 2.5 + 3.25 e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$

### Effective Dose

$$E = \sum_{T=1}^n \sum_{R=1}^n W_T H_{T,R}$$

- Effective dose, E, (formerly effective dose equivalent) accounts for differing risks to different organs and tissues from different qualities of radiations and is an average
- $W_T$  = the tissue weighting factor
- $H_{T,R}$  = mean equivalent dose in organ or tissue, T, delivered by radiation, R

### Equivalent Dose

- $H_t$  = equivalent dose = average H over a tissue or organ
- $H_t = W_r D_t$
- $W_r$  = radiation weighting factor
- $D_t$  = mean absorbed dose in tissue/organ

### Effective Dose (cont.)

- For simplicity,  $W_t$  and  $W_r$  are taken as independent so

$$E = \sum_{T=1}^n W_T \sum_{R=1}^n W_R D_{T,R}$$

- The old definition of H included "N" -- "other modifying factors" "N" was never used and has been dropped

## ICRP Tissue Weighting Factors

Organ/tissue	Publication 26 1977	Publication 60 1990	Publication 103 2007
Bladder		0.05	0.04
Bone surfaces	0.03	0.01	0.01
Brain			0.01
Breast	0.15	0.05	0.12
Colon		0.12	0.12
Esophagus		0.05	0.04
Gonads	0.25	0.20	0.08
Liver		0.05	0.04
Lungs	0.12	0.12	0.12
Red bone marrow	0.12	0.12	0.12
Salivary glands			0.01
Skin		0.01	0.01
Stomach		0.12	0.12
Thyroid	0.03	0.05	0.04
Remainder	0.30	0.05	0.12

## Collective and Committed Quantities

- Committed effective dose is given by

$$E_r = \int_{t_0}^{(t_0+r)} \dot{E}(t) dt$$

## Collective and Committed Quantities

- Collective effective dose is given by

$$S = n \bar{E} \quad \text{or} \quad \sum_{i=1}^m n_i \bar{E}_i$$

- Committed equivalent dose is given by

$$H_r = \int_{t_0}^{(t_0+r)} \dot{H}(t) dt$$

## Ambient Dose Equivalent

- $H^*(d)$  is the ambient dose equivalent
  - $d$  is usually taken as 10 mm
- $H^*(d)$  is the product of  $W_r$  and  $D$  that would be created in the 30 cm ICRU sphere at a depth,  $d$ , by an expanded and aligned field on a radius opposite the direction of the aligned field
- $H^*(d)$  can be measured by an isotropic instrument calibrated in terms of  $H^*(d)$
- $H^*(d)$  is used for penetrating radiation

Ambient Dose Equivalent per Unit Fluence  
 $[H^*(10)/\Phi]$

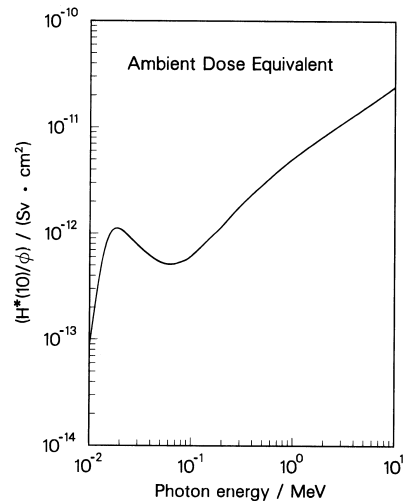


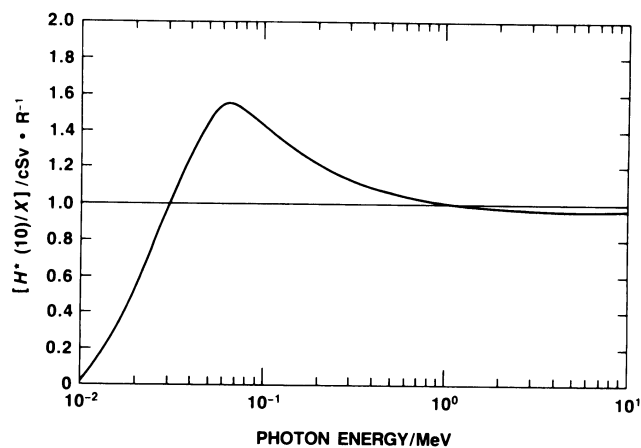
Fig. B.2. Ambient dose equivalent,  $H^*(10)$ , per unit fluence,  $\Phi$ , as a function of photon energy.

ICRU 43

## Directional Dose Equivalent

- $H'(d, \omega)$  is the directional dose equivalent
  - $H'(d, \omega)$  is the product of  $W_r$  and  $D$  produced at a depth,  $d$ , in an ICRU sphere by an expanded field at a specified direction,  $\omega$ ;
  - $d$  is usually 0.07 mm for skin or 3 mm for lens of the eye
- $H'(0.07)$  is the quantity measured by a typical survey meter set up to measure skin dose

Ambient DE per unit of Exposure (cSv/R)



ICRU 39

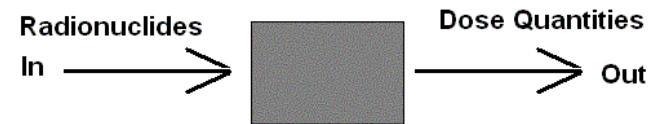
## Traditional Dosimetric Quantities

- For personal dosimetry, particularly in the US, the following quantities are used
  - $H_p(d)$ , usually  $H_p(10)$  is the individual dose equivalent for strongly penetrating radiation
  - $H_s(d)$ , usually  $H_s(0.07)$  or  $H_s(3)$  is the individual dose equivalent for weakly penetrating radiation
- These quantities are essentially equivalent to the  $H_s$  and  $H_d$  used by NVLAP and DOELAP to test dosimeters

## External and Internal Dose

- For external fields, computation or measurement is relatively simple
  - determination is done by direct measurement, measurement plus calculation or calculation from known radionuclide distributions

## Black Box Internal Dosimetry



- One Curie is equal to  $3.7 \times 10^{10}$  decays per second, approximately the decay rate of a gram of radium-226
- One Becquerel is equal to 1 decay per second

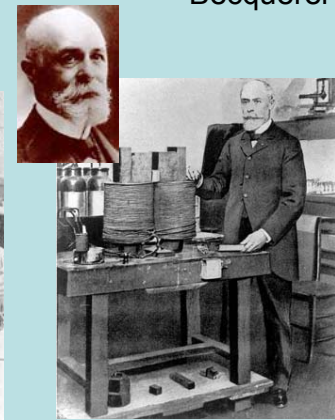
## External and Internal Dose

- For internal dose the black box approach can be taken, using published tables to relate intakes to internal dose
  - for internally deposited radionuclides, measurement, computation and assessment is extremely complex
  - if intakes are unknown and internal dosimetry has to be done from bioassay or whole body counter data, situation becomes even more complex

Marie and  
Pierre Curie



Henri  
Becquerel

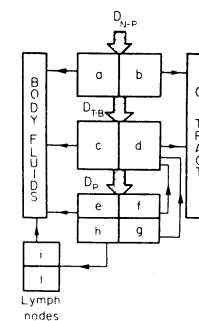


## Models

- Biokinetic models are used to calculate the movement of radionuclides within the body
- Dosimetry models are used to calculate the dose to organs from radionuclides within the organ and from radionuclides within neighboring organs

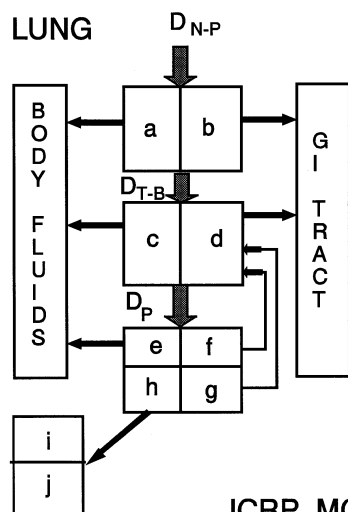
## Coefficients for Biokinetic Lung Model

Region	Compartment	Class					
		D		W		Y	
		T day	F	T day	F	T day	F
N-P ( $D_{N-P} = 0.30$ )	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.40	0.99
T-B ( $D_{T-B} = 0.08$ )	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P ( $D_P = 0.25$ )	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1.0	0.4	1.0	0.4
	g	n.a.	n.a.	50	0.4	500	0.4
L	h	0.5	0.2	50	0.05	500	0.15
	i	0.5	1.0	50	1.0	1000	0.9
	j	n.a.	n.a.	n.a.	n.a.	$\infty$	0.1

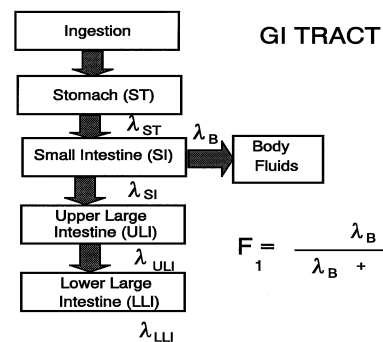


ICRP 30

## Biokinetic Model for Lung



ICRP MODELS



## ICRP GI Biokinetic Model

$$F = \frac{\lambda_B}{\lambda_B + \lambda_{SI}}$$

Section of GI tract	Mass of walls* (g)	Mass of contents* (g)	Mean residence time (day)	$\lambda$ day <sup>-1</sup>
Stomach (ST)	150	250	1/24	24
Small Intestine (SI)	640	400	4/24	6
Upper Large Intestine (ULI)	210	220	13/24	1.8
Lower Large Intestine (LLI)	160	135	24/24	1

\*From ICRP Publication 23 (1975).

Dosimetric model for the gastrointestinal system. ICRP Publ.30, Part I, p. 33



Excerpt from Inhalation dose Coefficients for Iodine

FGR 11

Nuclide	Class/ $f_1$	Committed Dose Equivalent per Unit Intake (Sv/Bq)	
		Thyroid	Effective
I-120	D 1.0	<b>1.55</b> $10^{-9}$	<b>1.20</b> $10^{-10}$
I-120m	D 1.0	<b>5.84</b> $10^{-10}$	<b>7.15</b> $10^{-11}$
I-121	D 1.0	<b>7.54</b> $10^{-10}$	<b>3.21</b> $10^{-11}$
I-123	D 1.0	<b>2.25</b> $10^{-9}$	<b>8.01</b> $10^{-11}$
I-124	D 1.0	<b>1.69</b> $10^{-7}$	<b>5.23</b> $10^{-9}$
I-125	D 1.0	<b>2.16</b> $10^{-7}$	<b>6.53</b> $10^{-9}$
I-126	D 1.0	<b>3.94</b> $10^{-7}$	<b>1.20</b> $10^{-8}$
I-128	D 1.0	<b>5.34</b> $10^{-11}$	<b>1.28</b> $10^{-11}$
I-129	D 1.0	<b>1.56</b> $10^{-6}$	<b>4.69</b> $10^{-8}$
I-130	D 1.0	<b>1.99</b> $10^{-8}$	<b>7.14</b> $10^{-10}$
I-131	D 1.0	<b>2.92</b> $10^{-7}$	<b>8.89</b> $10^{-9}$

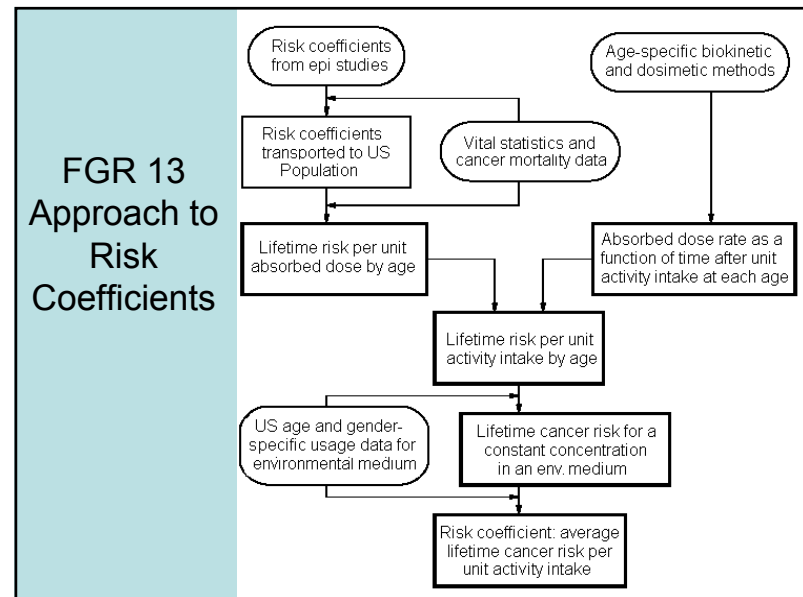
Inhalation dose Coefficients for Iodine

Table 2.1

Committed Dose Equivalent per Unit Intake (Sv/Bq)

Nuclide	Class/ $f_1$	Gonad	Breast	Lung	R Marrow	B Surface	Thyroid	Remainder	Effective
I-120	D 1.0	$1.07 \cdot 10^{-11}$	$1.28 \cdot 10^{-11}$	$4.33 \cdot 10^{-10}$	$1.28 \cdot 10^{-11}$	$1.17 \cdot 10^{-11}$	<b>1.55</b> $10^{-9}$	$5.02 \cdot 10^{-11}$	$1.20 \cdot 10^{-10}$
I-120m	D 1.0	$9.01 \cdot 10^{-12}$	$1.23 \cdot 10^{-11}$	$2.87 \cdot 10^{-10}$	$1.22 \cdot 10^{-11}$	$1.07 \cdot 10^{-11}$	$5.84 \cdot 10^{-10}$	$4.55 \cdot 10^{-11}$	<b>7.15</b> $10^{-11}$
I-121	D 1.0	$1.96 \cdot 10^{-12}$	$3.53 \cdot 10^{-12}$	$4.69 \cdot 10^{-11}$	$3.44 \cdot 10^{-12}$	$3.02 \cdot 10^{-12}$	<b>7.54</b> $10^{-10}$	$7.65 \cdot 10^{-12}$	$3.21 \cdot 10^{-11}$
I-123	D 1.0	$2.89 \cdot 10^{-12}$	$4.87 \cdot 10^{-12}$	$6.57 \cdot 10^{-11}$	$5.97 \cdot 10^{-12}$	$5.18 \cdot 10^{-12}$	<b>2.25</b> $10^{-9}$	$7.89 \cdot 10^{-12}$	$8.01 \cdot 10^{-11}$
I-124	D 1.0	$3.49 \cdot 10^{-11}$	$1.15 \cdot 10^{-10}$	$7.45 \cdot 10^{-10}$	$8.63 \cdot 10^{-11}$	$7.78 \cdot 10^{-11}$	<b>1.69</b> $10^{-7}$	$1.22 \cdot 10^{-10}$	$5.23 \cdot 10^{-9}$
I-125	D 1.0	$1.84 \cdot 10^{-11}$	$9.25 \cdot 10^{-11}$	$1.19 \cdot 10^{-10}$	$4.41 \cdot 10^{-11}$	$4.27 \cdot 10^{-11}$	<b>2.16</b> $10^{-7}$	$3.33 \cdot 10^{-11}$	$6.53 \cdot 10^{-9}$
I-126	D 1.0	$3.48 \cdot 10^{-11}$	$1.37 \cdot 10^{-10}$	$6.34 \cdot 10^{-10}$	$9.84 \cdot 10^{-11}$	$9.02 \cdot 10^{-11}$	<b>3.94</b> $10^{-7}$	$1.21 \cdot 10^{-10}$	$1.20 \cdot 10^{-8}$
I-128	D 1.0	$6.80 \cdot 10^{-13}$	$7.15 \cdot 10^{-13}$	$7.22 \cdot 10^{-11}$	$7.17 \cdot 10^{-13}$	$7.03 \cdot 10^{-13}$	$5.34 \cdot 10^{-11}$	$7.02 \cdot 10^{-12}$	<b>1.28</b> $10^{-11}$
I-129	D 1.0	$8.69 \cdot 10^{-11}$	$2.09 \cdot 10^{-10}$	$3.14 \cdot 10^{-10}$	$1.40 \cdot 10^{-10}$	$1.38 \cdot 10^{-10}$	<b>1.56</b> $10^{-6}$	$1.18 \cdot 10^{-10}$	$4.69 \cdot 10^{-8}$
I-130	D 1.0	$2.81 \cdot 10^{-11}$	$4.87 \cdot 10^{-11}$	$6.03 \cdot 10^{-10}$	$4.55 \cdot 10^{-11}$	$4.03 \cdot 10^{-11}$	<b>1.99</b> $10^{-8}$	$8.02 \cdot 10^{-11}$	$7.14 \cdot 10^{-10}$
I-131	D 1.0	$2.53 \cdot 10^{-11}$	$7.88 \cdot 10^{-11}$	$6.57 \cdot 10^{-10}$	$6.26 \cdot 10^{-11}$	$5.73 \cdot 10^{-11}$	<b>2.92</b> $10^{-7}$	$8.03 \cdot 10^{-11}$	$8.89 \cdot 10^{-9}$

FGR 11



FGR 13  
Example  
Risk Table

G = gas  
V = vapor  
F = fast  
M = moderate  
S = slow

Nuclide	AMAD (µm)	Type	$I_1$	Mortality (Bq <sup>-1</sup> )	Morbidity (Bq <sup>-1</sup> )	Dominant cancer type	% total mortality
<b>Iodine</b>							
I-125	(CH <sub>3</sub> I)	V	1.0E+00	7.75E-11	7.48E-10	thyroid	96.0
		G	1.0E+00	6.03E-11	5.83E-10	thyroid	96.1
		F	1.0E+00	2.97E-11	2.87E-10	thyroid	95.9
		M	1.0E-01	2.91E-11	8.71E-11	lung	63.4
I-129	(CH <sub>3</sub> I)	V	1.0E+00	4.42E-10	4.32E-09	thyroid	97.3
		G	1.0E+00	3.43E-10	3.36E-09	thyroid	97.8
		F	1.0E+00	1.68E-10	1.64E-09	thyroid	97.7
		M	1.0E-01	2.60E-10	7.64E-10	lung	74.9
I-131	(CH <sub>3</sub> I)	V	1.0E+00	1.48E-10	1.36E-09	thyroid	90.8
		G	1.0E+00	1.10E-10	1.06E-09	thyroid	95.0
		F	1.0E+00	5.55E-11	5.27E-10	thyroid	94.0
		M	1.0E-01	1.29E-10	2.20E-10	lung	76.8
I-132	(CH <sub>3</sub> I)	V	1.0E+00	1.12E-11	3.12E-11	lung	54.8
		G	1.0E+00	3.88E-12	2.09E-11	thyroid	44.9
		F	1.0E+00	2.46E-12	1.01E-11	none	-
		M	1.0E-01	6.10E-12	8.72E-12	lung	51.0
I-133	(CH <sub>3</sub> I)	V	1.0E+00	5.46E-11	4.38E-10	thyroid	77.2
		G	1.0E+00	3.76E-11	3.41E-10	thyroid	88.5
		F	1.0E+00	1.93E-11	1.69E-10	thyroid	85.2
		M	1.0E-01	4.02E-11	7.48E-11	lung	46.7
I-134	(CH <sub>3</sub> I)	V	1.0E+00	7.41E-12	1.19E-11	lung	73.7
		G	1.0E+00	1.38E-12	5.41E-12	none	-
		F	1.0E+00	1.15E-12	2.77E-12	none	-
		M	1.0E-01	2.47E-12	3.12E-12	lung	56.8

Useful software for calculating dose and risk from internally deposited radionuclides is available from:

- <http://www.epa.gov/rpdweb00/federal/techdocs.html>
- A CD is required but they will send it at no charge

FGR 13 Example Risk Table - excerpt

G = gas V = vapor F = fast M = moderate S = slow

Nuclide	Type	Mortality (Bq <sup>-1</sup> )	Morbidity (Bq <sup>-1</sup> )	Dominant cancer type	% total mortality
<b>Iodine</b>					
I-125	V	7.75E-11	7.48E-10	thyroid	96.0
	G	6.03E-11	5.83E-10	thyroid	96.1
	F	2.97E-11	2.87E-10	thyroid	95.9
	M	2.91E-11	8.71E-11	lung	63.4
I-129	V	4.42E-10	4.32E-09	thyroid	97.3
	G	3.43E-10	3.36E-09	thyroid	97.8
	F	1.68E-10	1.64E-09	thyroid	97.7
	M	2.60E-10	7.64E-10	lung	74.9
I-131	V	1.48E-10	1.36E-09	thyroid	90.8
	G	1.10E-10	1.06E-09	thyroid	95.0
	F	5.55E-11	5.27E-10	thyroid	94.0
	M	1.29E-10	2.20E-10	lung	76.8

Example of Ingestion Dose Coefficients from FGR-13 CD Supplement

I-131

Units = Sv/Bq

Description	Infant	1 y old	5 y old	10 y old	15 y old	Adult
f_1	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Pancreas	5.31E-10	3.70E-10	2.01E-10	1.22E-10	7.23E-11	6.10E-11
R_Marrow	5.14E-10	3.73E-10	2.22E-10	1.56E-10	1.16E-10	1.01E-10
Skin	4.75E-10	3.36E-10	1.80E-10	1.21E-10	8.13E-11	6.87E-11
Spleen	4.82E-10	3.35E-10	1.77E-10	1.10E-10	6.61E-11	5.36E-11
Testes	3.75E-10	2.52E-10	1.41E-10	8.11E-11	4.82E-11	4.04E-11
Thymus	2.26E-09	1.73E-09	8.45E-10	4.61E-10	2.25E-10	1.53E-10
<b>Thyroid</b>	<b>3.66E-06</b>	<b>3.56E-06</b>	<b>2.06E-06</b>	<b>1.04E-06</b>	<b>6.81E-07</b>	<b>4.32E-07</b>
Uterus	4.64E-10	3.22E-10	1.97E-10	1.15E-10	7.01E-11	5.92E-11
UB_Wall	1.92E-09	1.51E-09	1.44E-09	1.17E-09	1.01E-09	7.57E-10
e_50	1.84E-07	1.79E-07	1.04E-07	5.24E-08	3.42E-08	2.18E-08