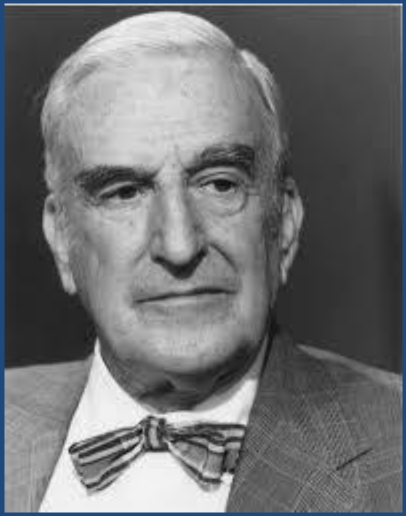
Dosimetry of Internal Emitters: Contribution of Radiation Protection Bodies and Radiological Events

39th Lauriston S. Taylor Lecture

K.F. Eckerman



Correction 3/23/15

Dr. Taylor’s 50+ year career

- 1925 Worked at Western Electric (Bell labs)
- 1925 Formation of ICRU (age 23)
- 1927 Began at Natl. Bureau of Standards
- 1928 Formation of ICRP
- 1965 National Academy of Sciences
- 1972 Retires to work for NCRP
- 1977 Retires from NCRP
- Honorary President of NCRP until age 102

NCRP Past Presidents

Lauriston S. Taylor
1929–1977

Warren K. Sinclair
1977–1991

Charles B. Meinhold
1991–2002

Thomas S. Tenforde
2002-2012

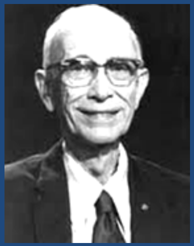
Past Taylor Lectures

H. M. Parker
H. O. Wyckoff
M. Eisenbud
H. P. Schwan
A. C. Upton
E. W. Webster
A. M. Kellerer
E. J. Hall
W. L. Nyborg
A. J. Gonzales
P. W. Durbin
C. E. Land
J. Till

E. E. Pochin
J. F. Crow
H. H. Rossi
S. Jablon
J. N. Stannard
W. K. Sinclair
S. Abrahamson
N. H. Harley
R. J. Preston
J. B. Little
D. W. Moeller
E. A. Blakely
F. A. Mettler, Jr.

H. L. Friedell
E. L. Saenger
J. H. Harley
B. Lindell
V. P. Bond
R. J. M. Fry
W. J. Bair
S. J. Adelstein
C. B. Meinhold
R. L. Brent
J. D. Boice, Jr.
A. L. Brooks

Past Lectures on Internal Emitters



- J. Newell Stannard
  - Radiation Protection and the Internal Emitter Sage

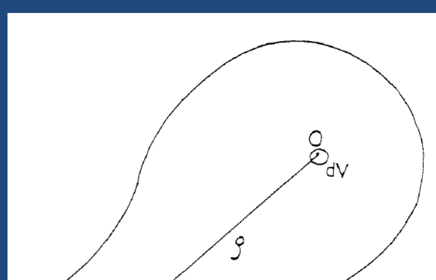
- William J. Bair
  - Radionuclides in the Body: Meeting the Challenge

- Patricia W. Durbin
  - The Quest for Therapeutic Actinide Chelators

Computational Dosimetry

- Availability of manmade radionuclides
- Marinelli, Quimby and Hine (1948) procedure
  - Beta particles locally absorbed
  - Gamma rays absorbed over extended range

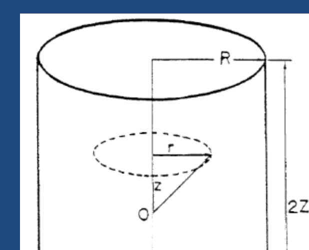
Volume *V* contains a concentration of activity and the cylinder on the right represents the total body.



$$g = \int_V \frac{e^{-\mu\rho}}{\rho^2}\,\mathrm{dV}$$

For a sphere

$$g = \frac{4\pi}{\mu}\left(1 - e^{-\mu R}\right)$$



Radiation Protection

- 1946 NCRP, chaired by Dr. Taylor, formed:
  - External dose committee (G. Failla)
  - Internal dose committee (K.Z. Morgan)

- Tripartite Conferences (1949 – 1953)
  - Canada, United Kingdom, United States
  - Importance of Standardization
    - Standard Man – anatomical and physiological parameters
    - Respiratory Tract – soluble and insoluble chemical forms
    - Use of radium experience
    - Dose quantity – energy absorbed or ionizations produced
    - Dr. Morgan (ORNL) took on computational role
- First set of recommendations NBS Handbook 52

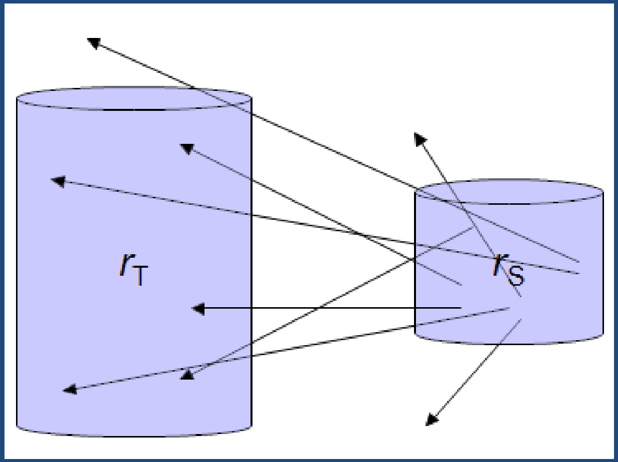
ICRP Publication 2 (1959)

- Secondary limits for occupational
  - Maximum Permissible Body Burdens
  - Maximum Permissible Air Concentrations
- Doses to critical organs assuming
  - Dose evaluated in 50^{th} year of continuous exposure
  - Standard Man – spherical organs
  - Prompt uptake in organs – single elimination rate
  - Relative damage factor *n* (5) applied to bone seekers
  - RBE or quality factor of 10 applied to alpha emissions
- U.S. radiation protection standard till 1987

Dosimetric Formulations

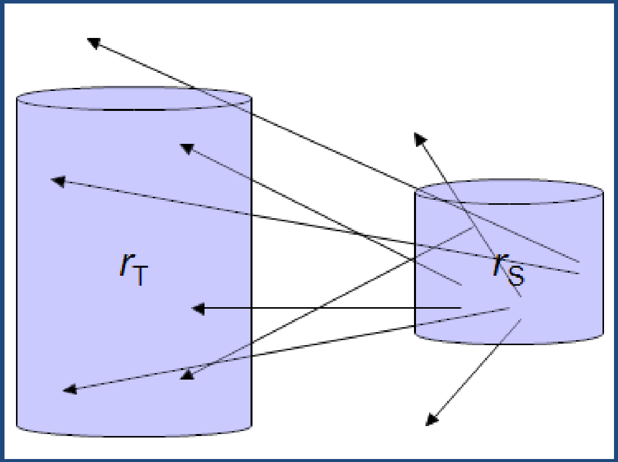
- Earlier formulations; e.g., Marinelli *et al*.,:
  - Multiple sets of equations involved
- ICRU (1953) Absorbed dose (rad) as 100 erg/g
- Ellett *et al*. 1964-65 papers:
  - Monte Carlo calculation of absorbed energy
  - Defined absorbed fraction quantity
- Medical Internal Radiation Dose Committee
  - Form in 1965 by Society of Nuclear Medicine
  - General and consistent formulation possible
  - Series of pamphlets issued

Absorbed Fraction Quantity



- $AF(r_T \leftarrow r_S)$ fraction of energy emitted in r_S that is absorbed in r_T
- Concept applicable to all radiations
- Value depends on type and energy of the radiation and spatial relationship of regions

Absorbed Dose Rate Quantity



Absorbed dose rate $\dot{D}(r_\mathrm{T})$ due to nuclide of activity *A* in r_S is

$$\dot{D}(r_T \leftarrow r_S) = A(r_S)\frac{1}{M(r_T)}\sum_i Y_i\, E_i\, AF(r_T \leftarrow r_S, E_i)$$

where Y_i is the number of radiation emitted per nuclear transformation with energy E_i and $M(r_\mathrm{T})$ is the mass of the target region

Absorbed Dose Quantity

Absorbed dose, $D(r_T)$ is integral of $\dot{D}(r_T)$

$$\dot{D}(r_T \leftarrow r_S) = A(r_S)\frac{1}{M(r_T)}\sum_i Y_i\, E_i\, AF(r_T \leftarrow r_S, E_i)$$

if no time-dependence in *AF* then

$$D(r_T \leftarrow r_S) = \tilde{A}(r_S)\frac{1}{M(r_T)}\sum_i Y_i\, E_i\, AF(r_T \leftarrow r_S, E_i)$$

where $\tilde{A}(r_S) = \int_0^\tau A(r_S)dt$ and τ is the commitment period.

Absorbed Dose Quantity

$$D(r_T) = \tilde{A}(r_S)\frac{1}{M(r_T)}\sum_i Y_i\, E_i\, AF(r_T \leftarrow r_S, E_i)$$

Define SAF$(r_T \leftarrow r_S)$ = $\frac{1}{M(r_T)} AF(r_T \leftarrow r_S)$

Define $S(r_T \leftarrow r_S) = \sum_i Y_i\, E_i\, SAF(r_T \leftarrow r_S, E_i)$

and thus

$$D(r_T) = \tilde{A}(r_S)\, S(r_T \leftarrow r_S)$$

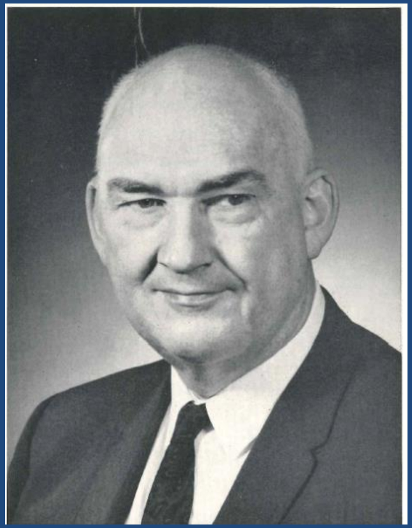
where *S* embodies the nuclide emissions and the anatomical relationships of r_T and r_S and *A* reflects its behavior in the body.

MIRD Pamphlets

- Pamphlet 1. R. Loevinger and M. Berman: A scheme for absorbed-dose calculations for biologically distributed radionuclides. 1968
- Pamphlet 2. MJ Berger: Energy deposition in water by photons from point isotropic sources. 1968
- Pamphlet 3. GI Brownell, WH Ellett, AR Reddy: Absorbed fractions for photon dosimetry. 1968
- Pamphlet 4. LT Dillman, Radionuclide decay schemes and nuclear parameters for use in radiation-dose estimation. 1969
- Pamphlet 5. WS Synder *et al*., Estimates of specific absorbed fractions for monoenergetic photon sources in various organs of a heterogeneous phantom. 1969

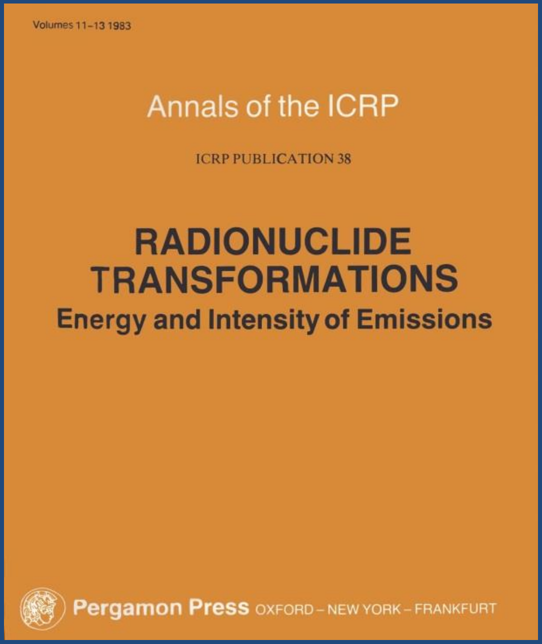
ICRP Publication 30 and Later

- Computational framework similar to MIRD's
- Absorbed, equivalent and effective dose
- RBE, *Q*, radiation weighting factor
- Relative damage factor *n* dropped (bone seekers)
- Task Group on Dose Calculations (DOCAL 1974)
- Membership
  - W.S. Snyder, Chaired to 1977
  - Mary R. Ford, Chaired from 1977
  - S.R. Bernard
  - L.T. Dillman, from 1977
  - K.F. Eckerman, from 1980
  - J.W. Poston, to 1980
  - Sarah B. Watson, from 1978



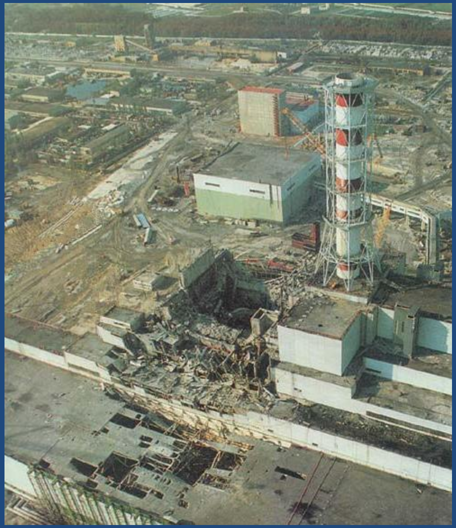
ICRP Committee 2 DOCAL Task Group

- Formed for ICRP 30 calculations
- Expected to disband after Publication 38
- National authorities develop public coefficients
- DOCAL membership international



Public Dose Coefficients

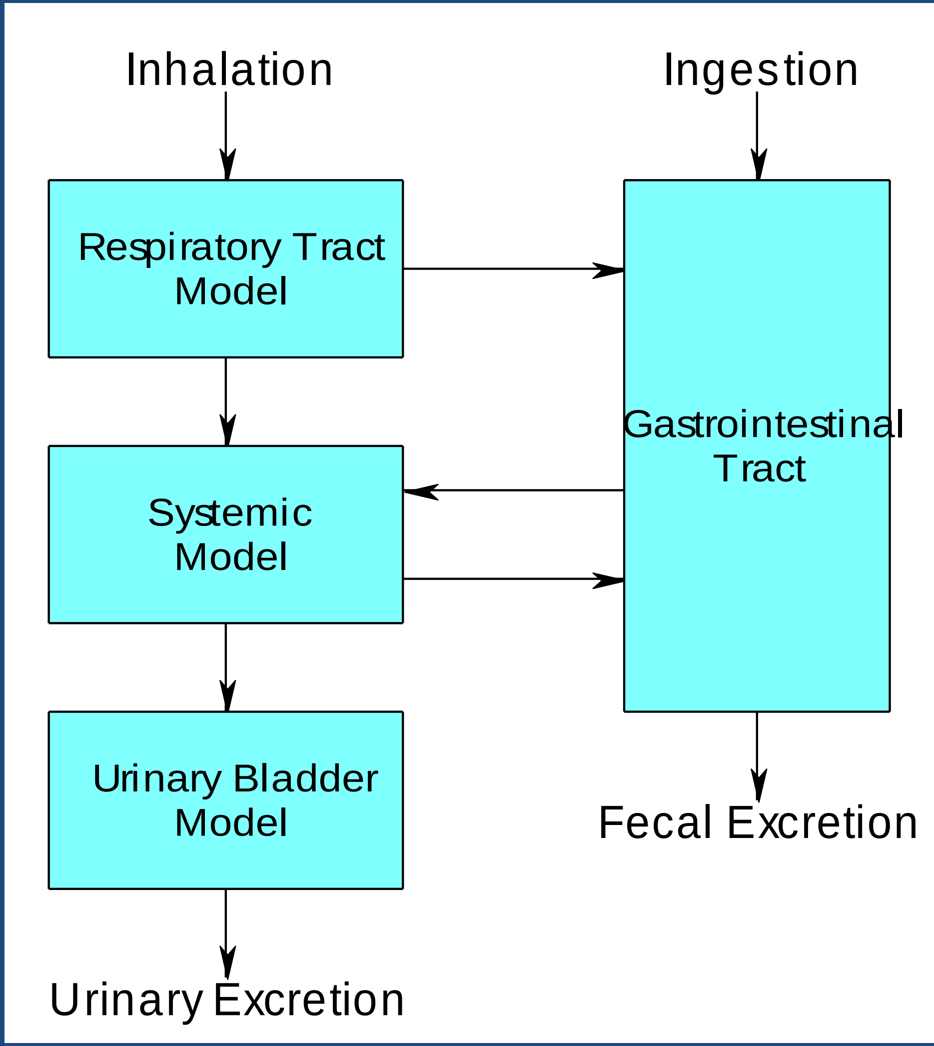
- Chernobyl Accident (April 1986)
  - Standardization - consensus coefficients
  - ICRP Publication 56 issued (1990)
  - DOCAL redirected to support development
- Giogania Incident (Sept 1987)



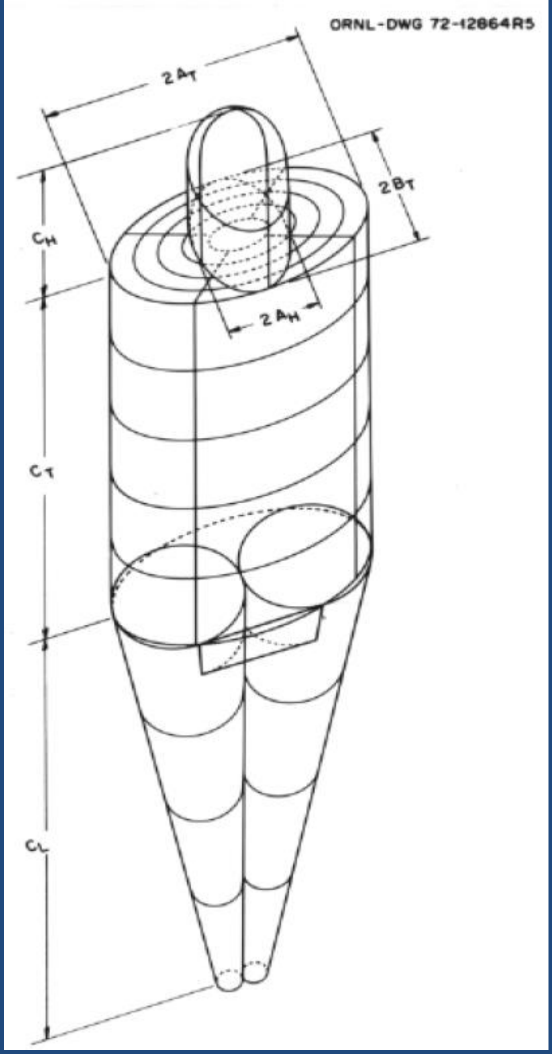
DOCAL Meeting

Computational Models

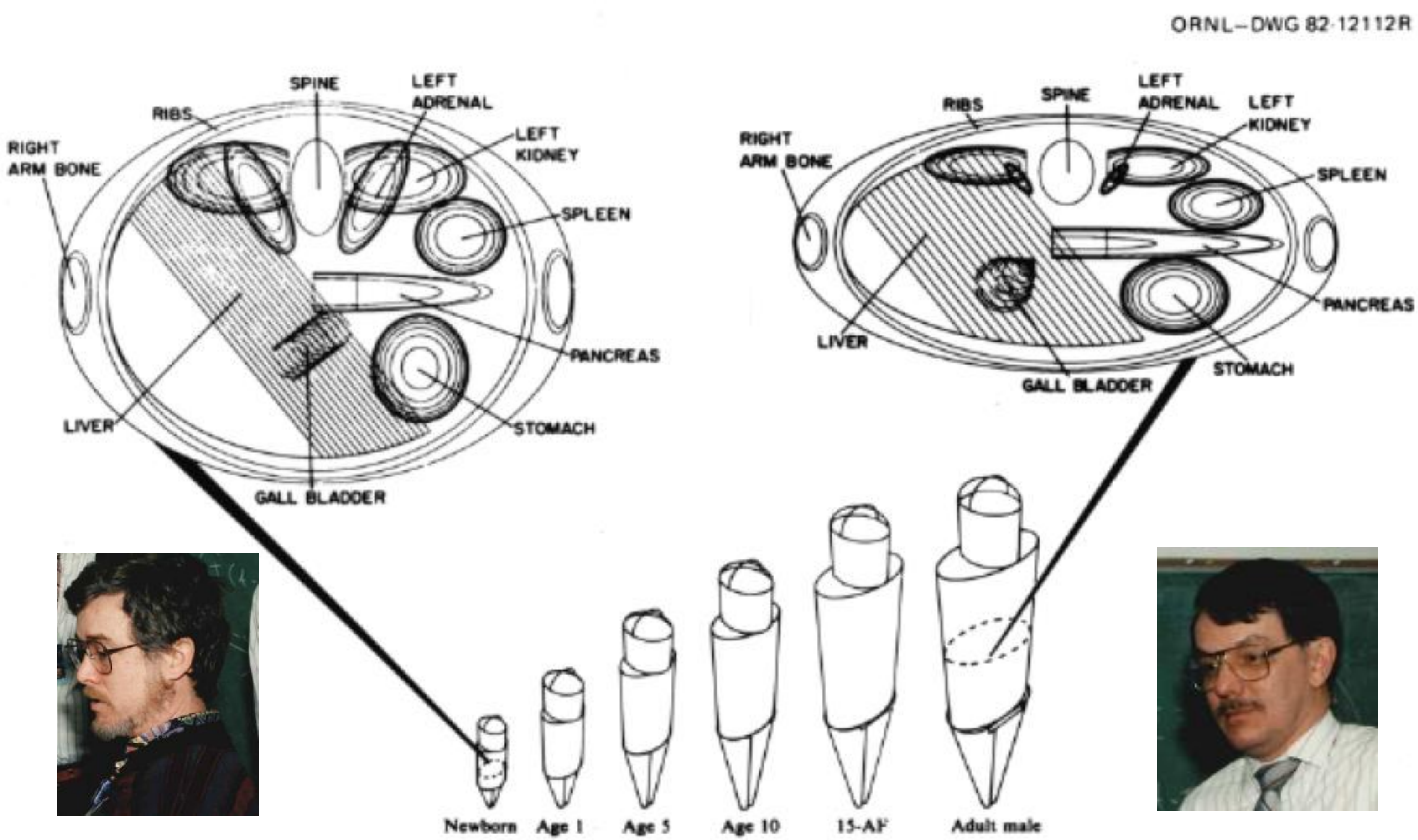
- Intake models
  - Lung
  - GI-tract
- Systemic model
  - Absorbed material
- Excretion model
  - Fecal and urinary
- Dosimetric model



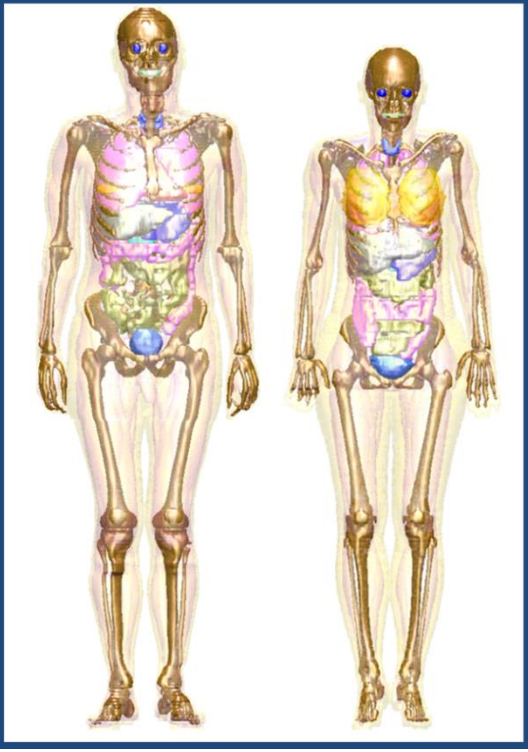
Anatomical Model (Phantom)



Anatomical Model (Phantom)

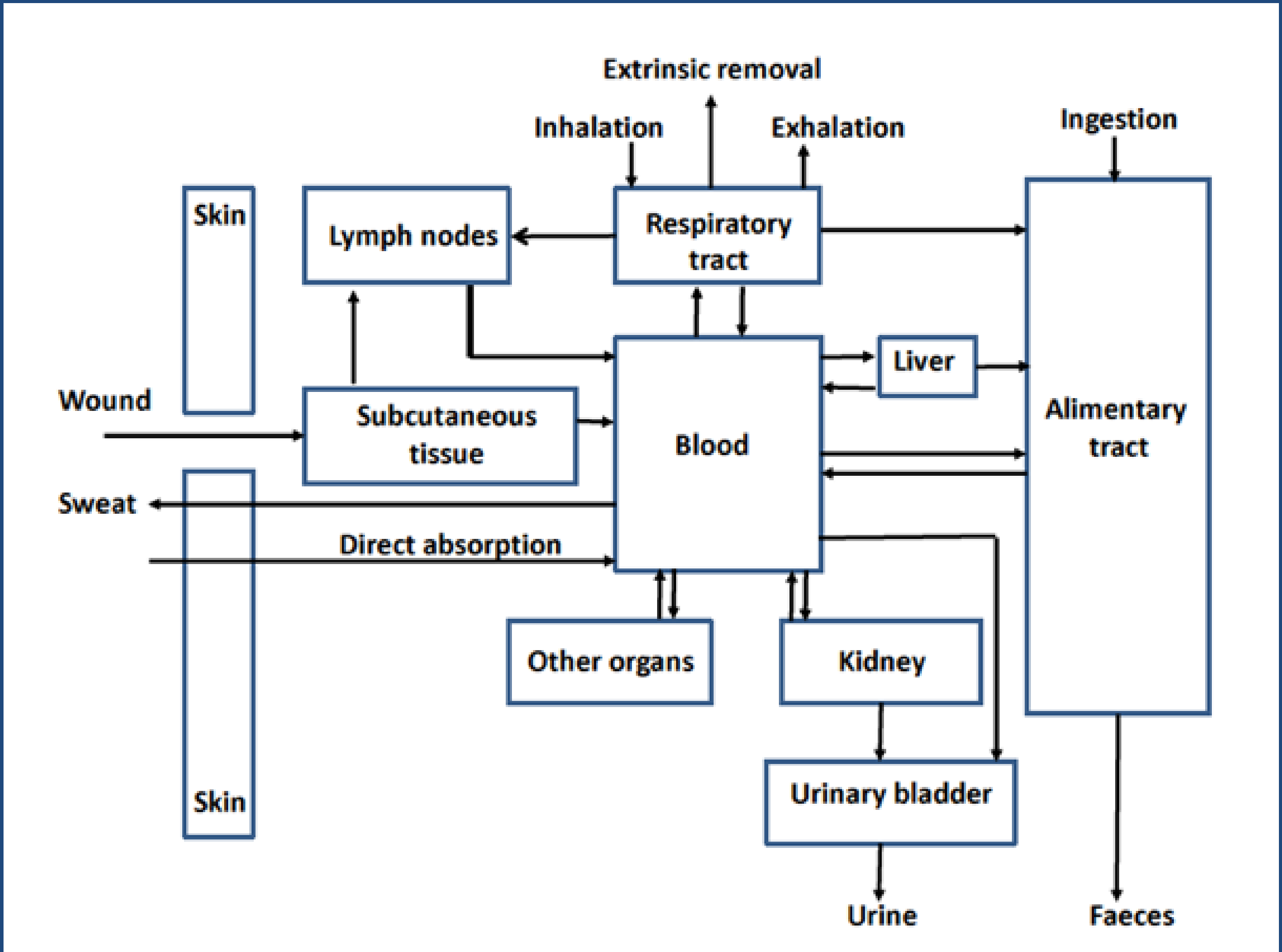


ICRP 110 Computational Phantoms

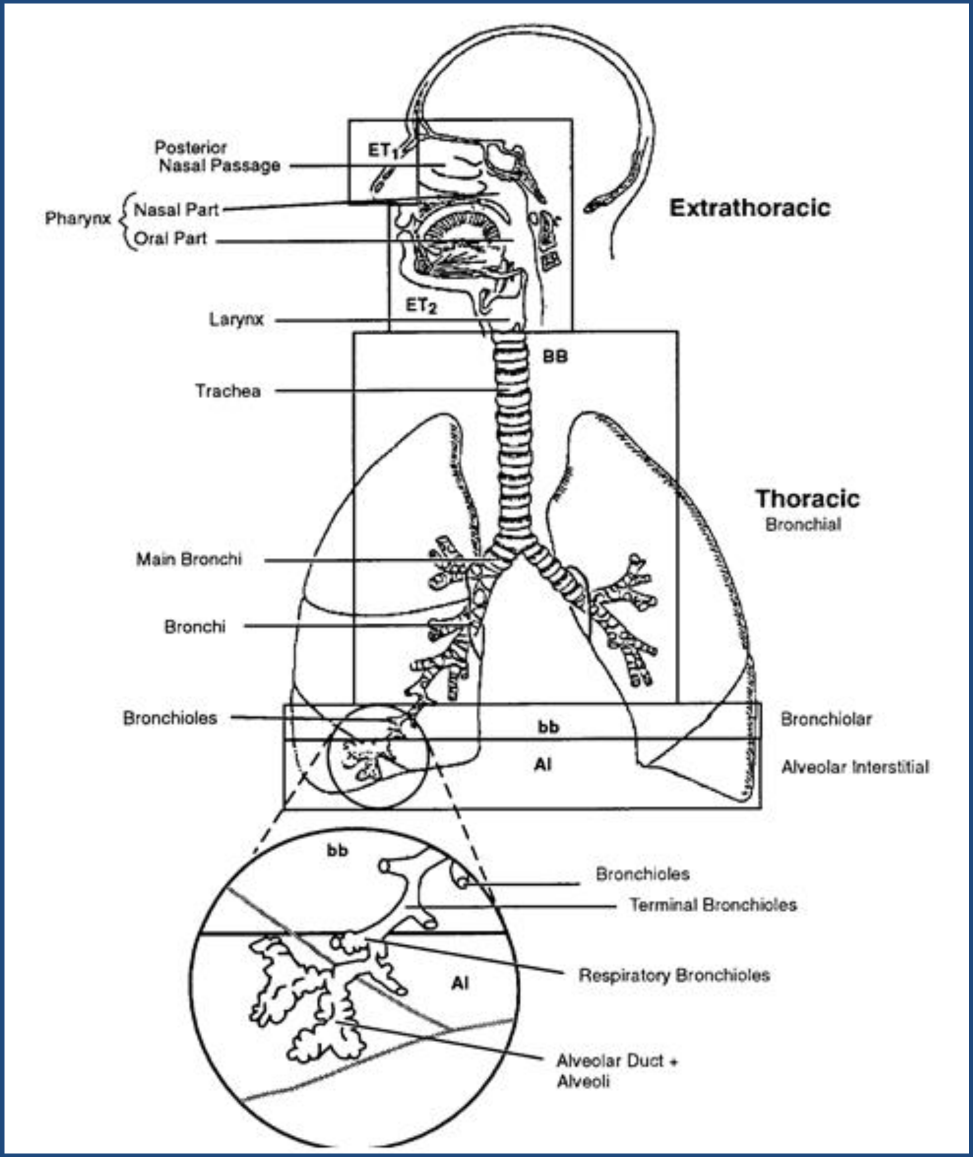


Main Characteristics of adult Reference Computational Phantoms		
Property	Male	Female
Height (m)	1.76	1.63
Mass (kg)	73	60
Number tissue voxels	1,946,375	3,886,020
Voxel volume (mm^3)	36.54	15.25
Voxel in-plane resolution (mm)	2.137	1.775
Number of slices	222	348

Routes of intake and uptake

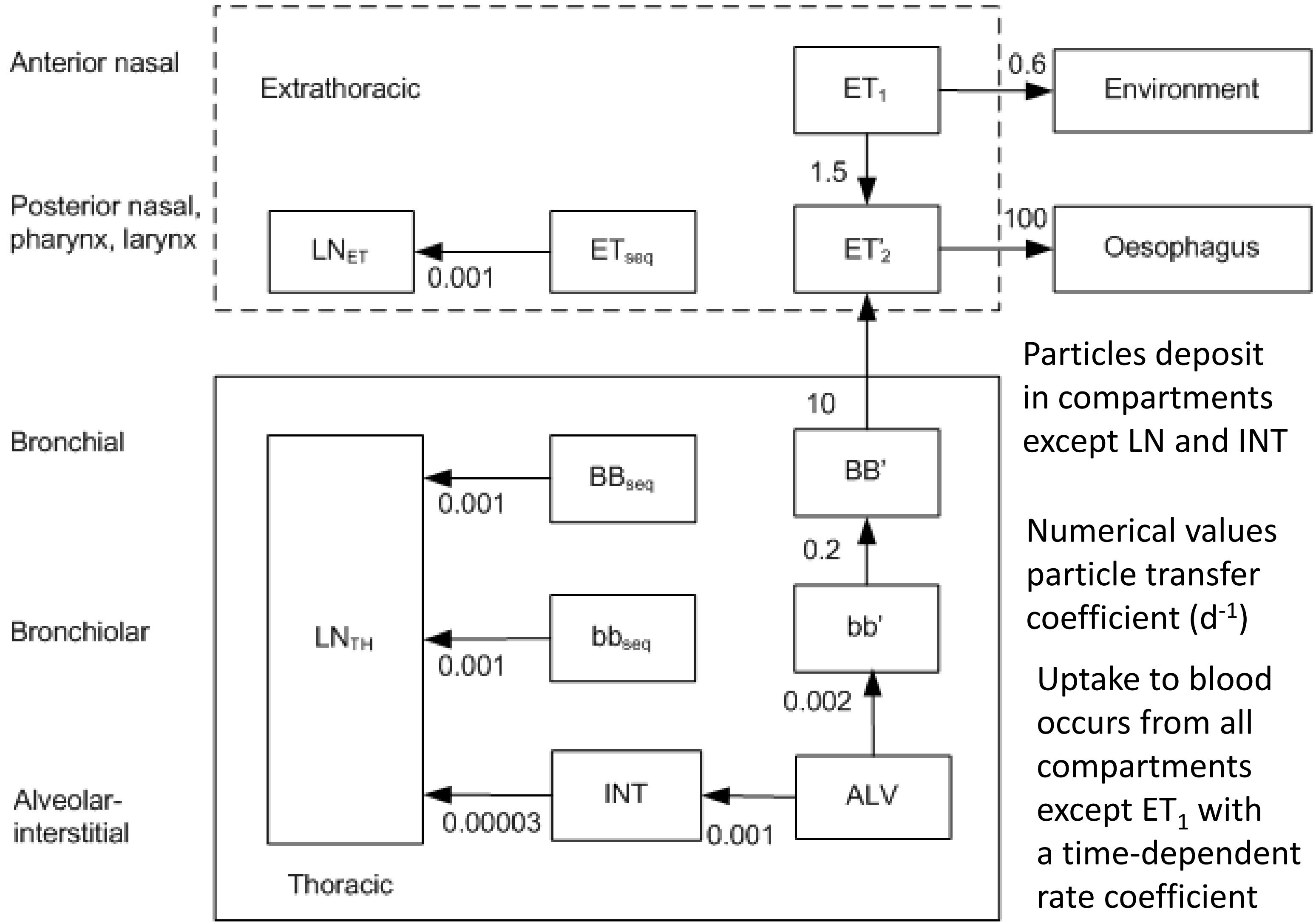


Human Respiratory Tract Model



Bill Bair ICRP 66

Revised HRTM

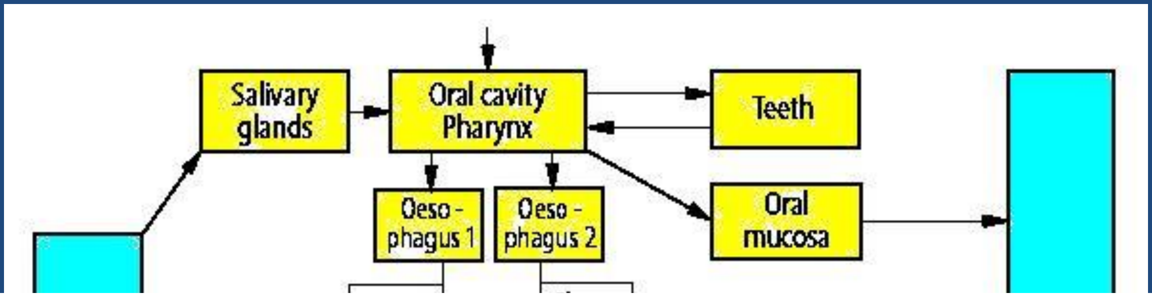


Particles deposit in compartments except LN and INT

Numerical values particle transfer coefficient (d^{-1})

Uptake to blood occurs from all compartments except ET_1 with a time-dependent rate coefficient

Human Alimentary Tract Model



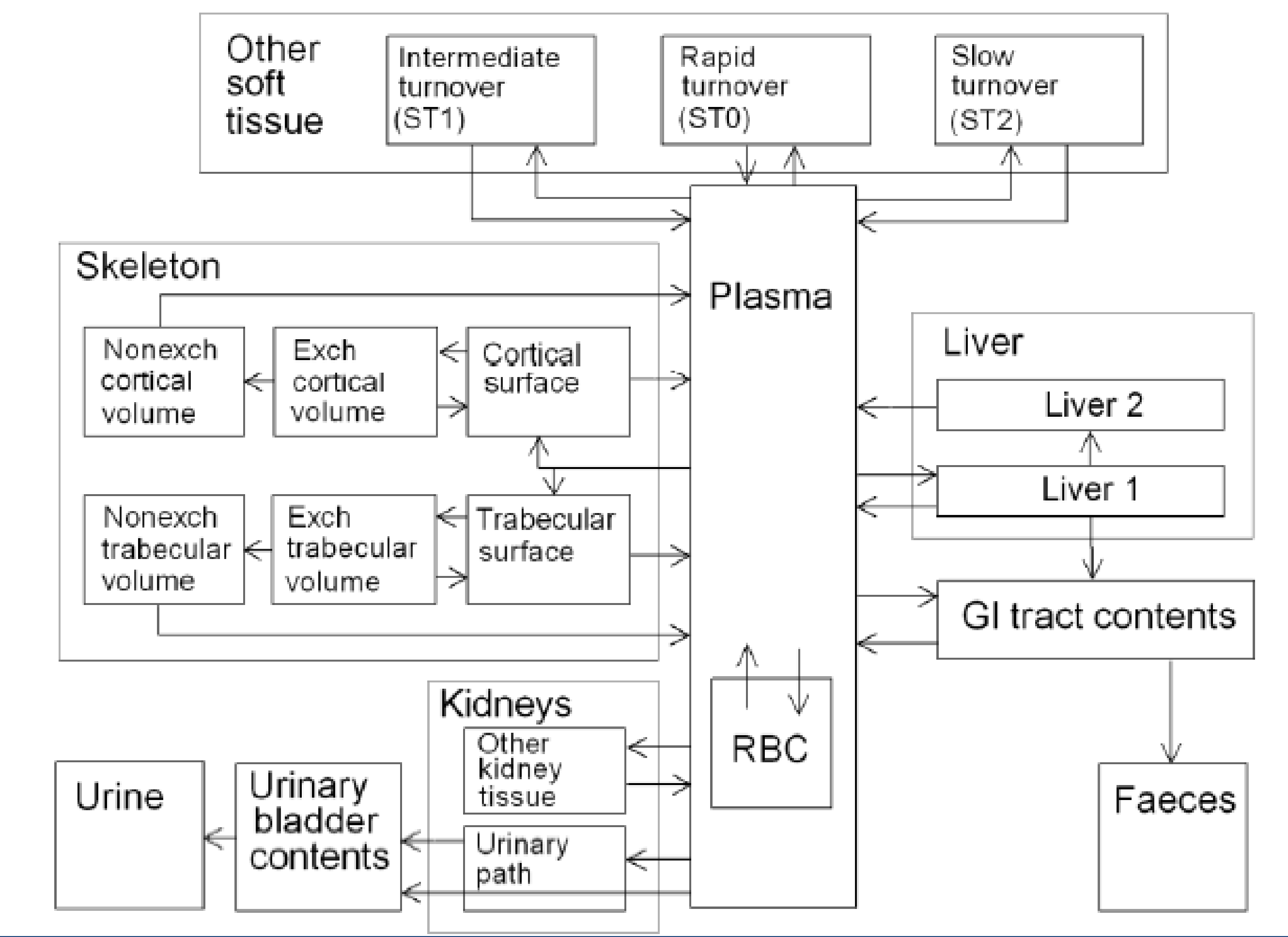
HATM transfer coefficients (d^{-1}) for reference worker

From	To	Transfer coefficient (d^{-1})
Oral cavity contents	Oesophagus Fast	6480
Oral cavity contents	Oesophagus slow	720
Oesophagus Fast	Stomach contents	12300
Oesophagus Slow	Stomach contents	2160
Stomach contents	Small intestine contents	20.57
Small intestine contents	Right colon contents	6
Right colon contents	Left colon contents	2
Left colon contents	Rectosigmoid contents	2
Rectosigmoid contents	Faeces	2

Systemic Biokinetics Models

- Behavior following introduction to blood
- ORNL effort lead by Rich Leggett
- Developed using
  - Radionuclide specific studies in man
  - Physiological information
  - Information on member of chemical family
  - Information on animal studies
- Models predict distribution in body for:
  - Organ/tissue dose estimates
  - Interpretation of bioassay measurements

Systemic Model: An Example



Structure of systemic model (ICRP Publication 72) for bone-volume seekers; e.g. Ca, Sr, Ba, Pb, Ra and U.

Description of Kinetics

The activity $A_{i,j}(t)$ of radionuclide *i* in compartment *j* at time *t* is given by

$$\frac{dA_{i,j}(t)}{dt} = \sum_{\substack{k=1 \\ k \neq j}}^{M} A_{i,k}\, \lambda_{i,k,j} - A_{i,j}\left[\sum_{\substack{k=1 \\ k \neq j}}^{M} \lambda_{i,j,k} + \lambda_i^P\right] + \sum_{k}^{i-1} A_{k,j}\, \beta_{k,i}\, \lambda_i^P$$

where *M* is the number of compartments, $\lambda_{i,j,k}$ is the transfer coefficient of chain member *i* from compartment *j* (donor compartment) to compartment *k* (recipient compartment), λ_i^P is the decay constant of member *i*, and $\beta_{k,i}$ is the fraction of member *k* decays forming *i.*

With the initial conditions specified for the compartments, $A_{i,j}(0)$, the set of differential equations defines the dynamic behavior of the parent nuclide and its progeny in the body.

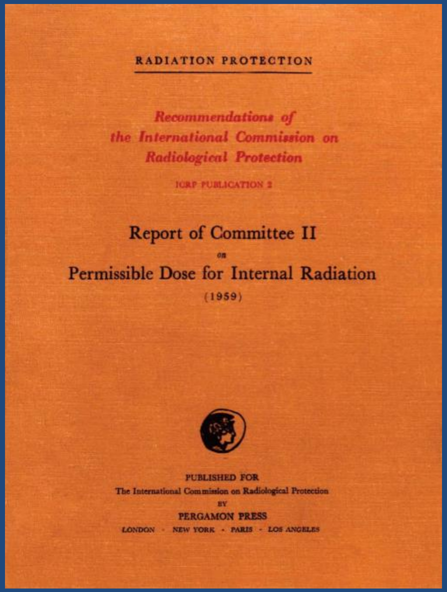
Current desktop computers can handle the computational needs.

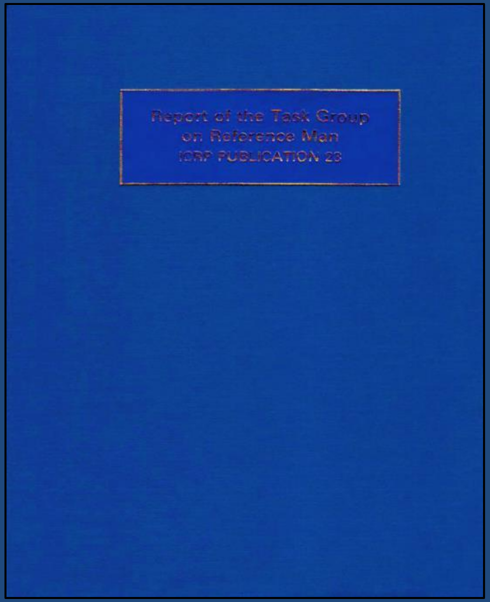
ICRP Decisions

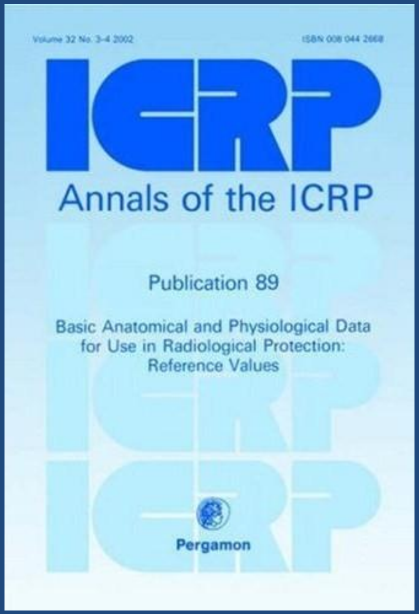
- Undertake age-specific dose coefficients
  - Improved biokinetic modeling efforts
  - Benefit to worker coefficients as well
- Committee 2 responsible for bioassay
  - Transfer from Committee 4 to Committee 2
  - Improve biokinetic modeling
  - Realistic vs. conservative coefficients
- Methodology use beyond radiation protection
  - Limitation; e.g., of effective dose
  - Maintain scientific rigor

Standard and Reference Man

- ICRP 2 Permissible dose for internal radiation
- ICRP 23 Report of Task Group on Reference Man
- ICRP 89 Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values







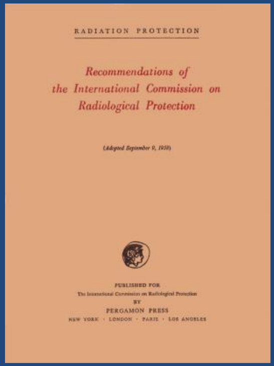
Radiation Protection Recommendations

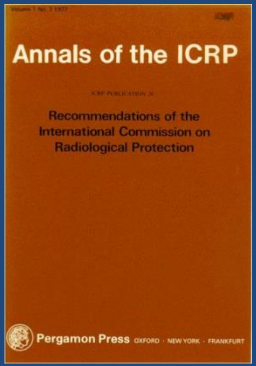
ICRP 1 Recommendations of the International Commission on Radiological Protection

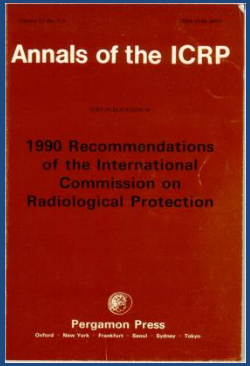
ICRP 26 Recommendations of the ICRP

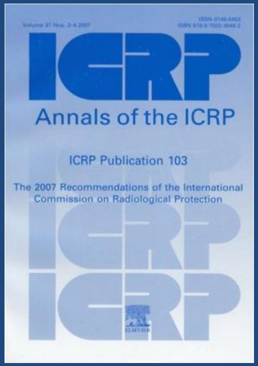
ICRP 60 1990 Recommendations of the International Commission on Radiological Protection

ICRP 103 The 2007 Recommendations of the International Commission on Radiological Protection









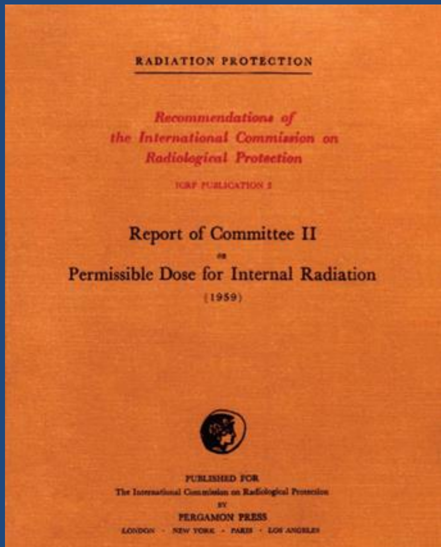
Occupational Dose Coefficients

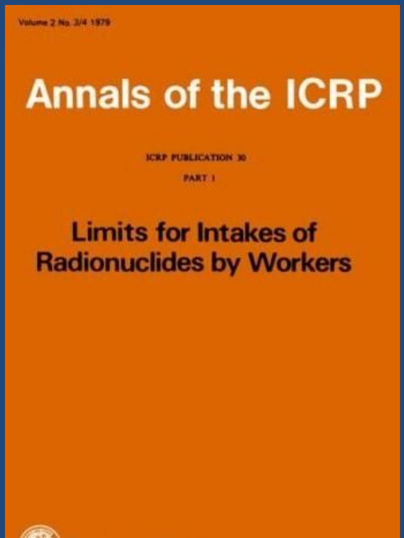
ICRP 2 Permissible Dose for Internal Radiation

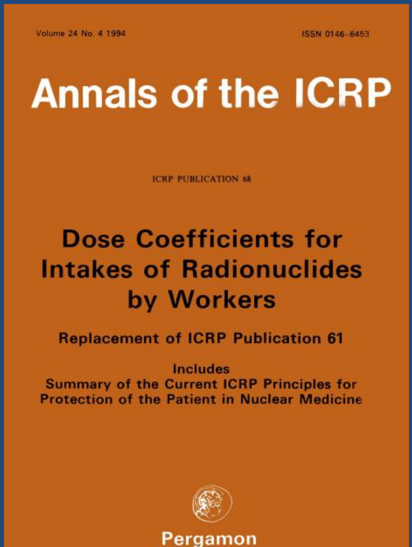
ICRP 30 Limits for Intakes of Radionuclides by Workers

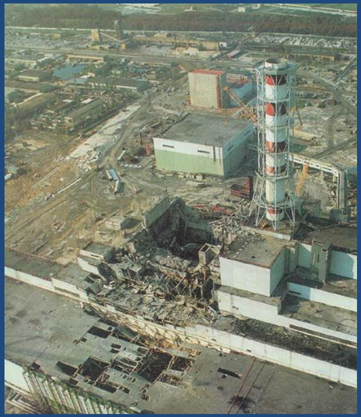
ICRP 68 Dose Coefficients for Intakes of Radionuclides by Workers

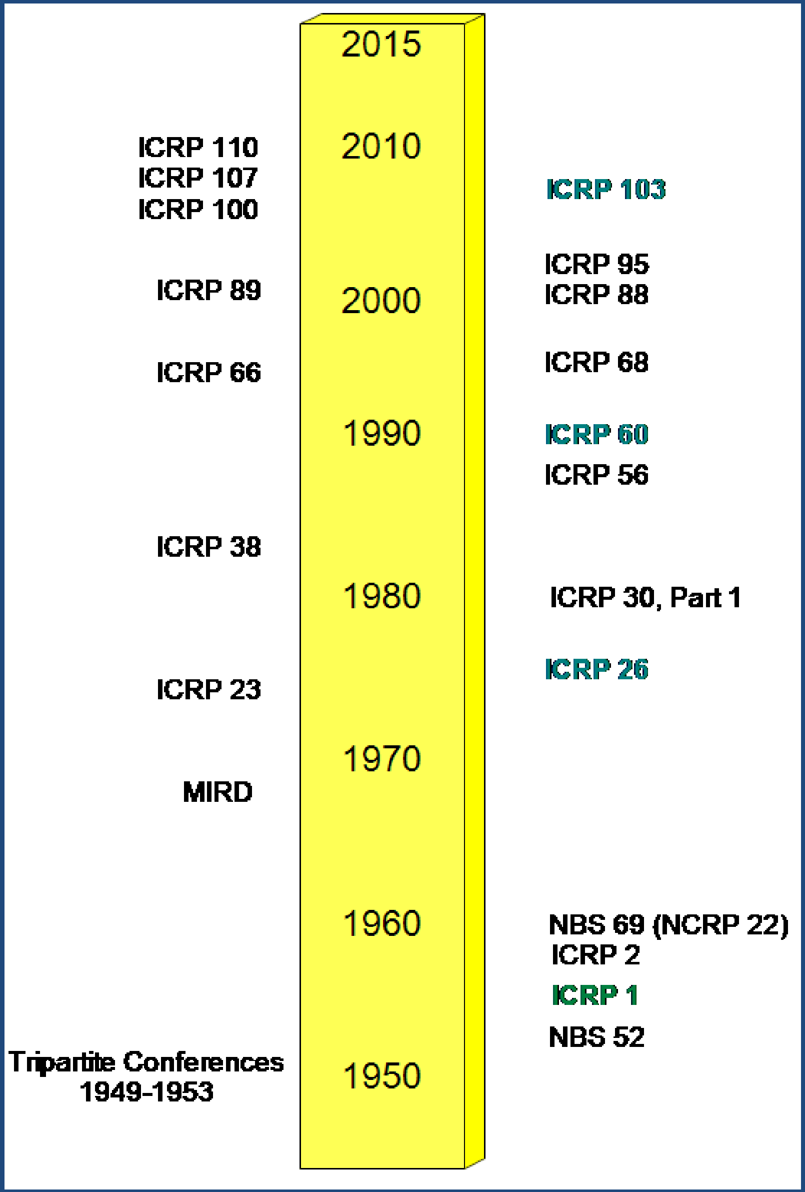
ICRP 13X Occupational Intakes of Radionuclides










2015
2010
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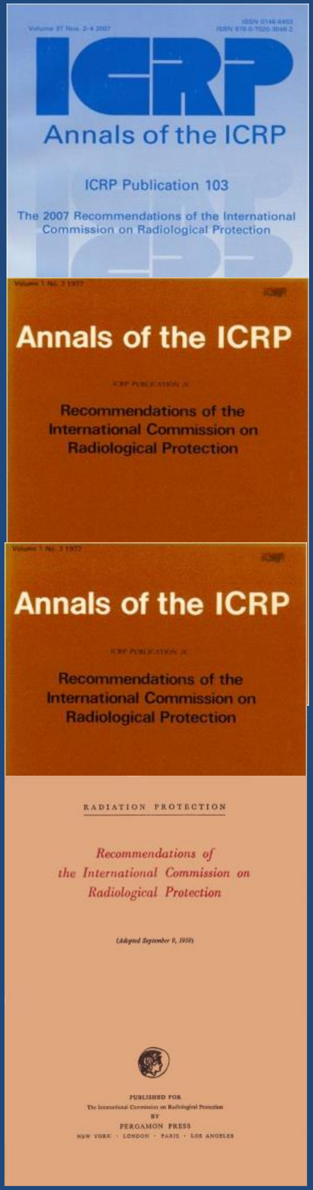
ICRP 110
ICRP 107
ICRP 100
ICRP 89
ICRP 66
ICRP 38
ICRP 23
MIRD
Tripartite Conferences
1949-1953
ICRP 103
ICRP 95
ICRP 88
ICRP 68
ICRP 60
ICRP 56
ICRP 30, Part 1
ICRP 26
NBS 69 (NCRP 22)
ICRP 2
ICRP 1
NBS 52


ICRP
Annals of the ICRP
ICRP Publication 103
The 2007 Recommendations of the International Commission on Radiological Protection
Annals of the ICRP
Recommendations of the International Commission on Radiological Protection
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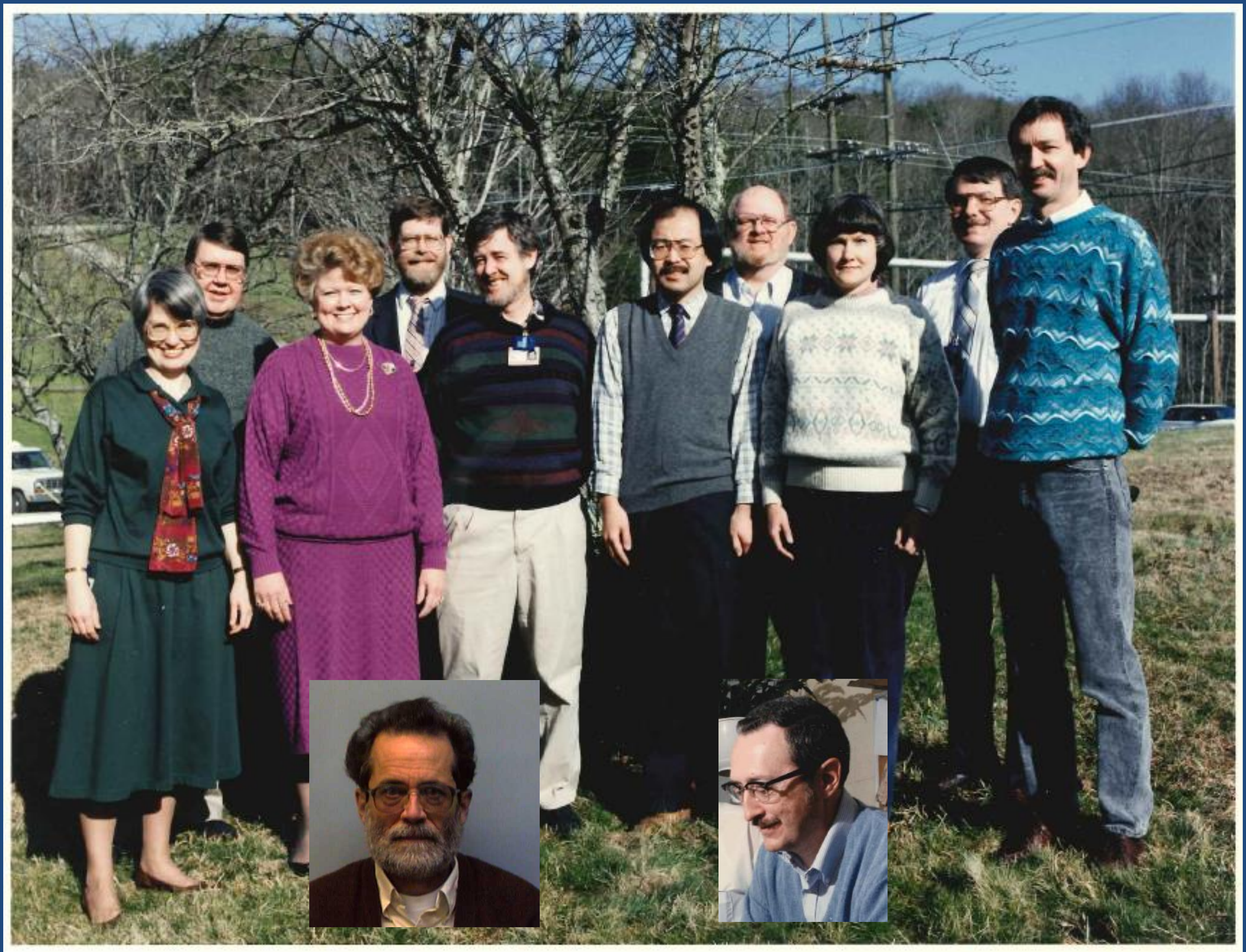
Early ORNL Team



ORNL Center Radiation Protection Knowledge

Richard Leggett

Michael Bellamy

Nolan Hertel

Shaheen Dewji

Patricia Eckerman

The Family

Thanks for your attention