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Occupational Internal Dosimetry

A Comprehensive Review

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Outline I

Concepts and Models

Program Development and Elements

Data to Intake to Dose

Other Programmatic Considerations

New ICRP Models

Summary

There are three general reasons for internal dose monitoring.

Why do we bother?

- To keep score
- To help with treatment
- As a last line of defense

Definition — Internal Dose

The energy, deposition, exposure, or risk obtained from radioactive material taken internally.

While there are no limits to internal dose specifically, there are limits to total (i.e., external plus internal) dose.

Definition — Dosimetry

The measurement or inference of dose.

Dose to a human being cannot be measured.

Definition — Internal Dosimetry

The sub-field of health physics that includes design and implementation of programs, calculation of dose, development of metabolic models, derivation of absorbed fractions and specific effective energies, etc.

Internal dose really cannot be measured.

Definition — Radiobioassay

Measurement of radiation contained in an individual's body (direct or in vivo counting) or their excreta (indirect or in vitro measurement).
A bioassay result, whether positive or negative, may or may not

mean anything and interpretation is required.

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It is important to distinguish between recommendations and requirements

Recommendations

- International Commission on Radiological Protection "Publications"
- National Council on Radiation Protection and Measurements "Reports"
- Health Physics Society ANSI Standards (N13)

Requirements

- Nuclear Regulatory Commission: 10CFR20
  - (Regulatory Guides)
  - (NUREG Reports)
- Department of Energy: 10CFR835
  - (Technical Standards)
  - (Handbooks)

Models for internal dosimetry are found in ICRP Publications.

- Operational dose coefficients: ICRP Publication 68 (119)
- Respiratory tract — ICRP Publication 66 (130)
- Alimentary tract — ICRP Publication 100
- Metabolic models and dose coefficients — ICRP Publications 56, 67, 69, 71, 72
- Anatomical and physiological data — ICRP Publication 89

ICRP Publications also include recommendations for protection.

- Individual monitoring — ICRP Publication 78
- Radiation protection principles — ICRP Publication 75
- General recommendations — ICRP Publication 103
- Nuclear decay data — ICRP Publication 107

The NCRP publishes reports some of which are relevant to internal dosimetry.

- Management of contaminated persons — NCRP Report No. 161
- Biokinetic wound model — NCRP Report No. 156
- Operational radiation protection — NCRP Report No. 127
- Inhaled radioactive substances — NCRP Report No. 125
- Bioassay procedures — NCRP Report No. 87
- Internal dosimetry concepts — NCRP Report No. 84

The Health Physics Society sponsors ANSI standards through the N13 Committee.

- Design of internal dosimetry programs — N13.39
- Radiobioassay performance — N13.30
- BOMAB specifications — N13.35
- Radionuclide-specific standards:
  - Uranium — N13.22
  - (Tritium — N13.14)
  - (Fission/Activation products — N13.42)
  - (Plutonium — N13.25)

Dose requirements are recommended by the ICRP and adopted (or not) by US regulatory bodies.

ICRP Recommendations

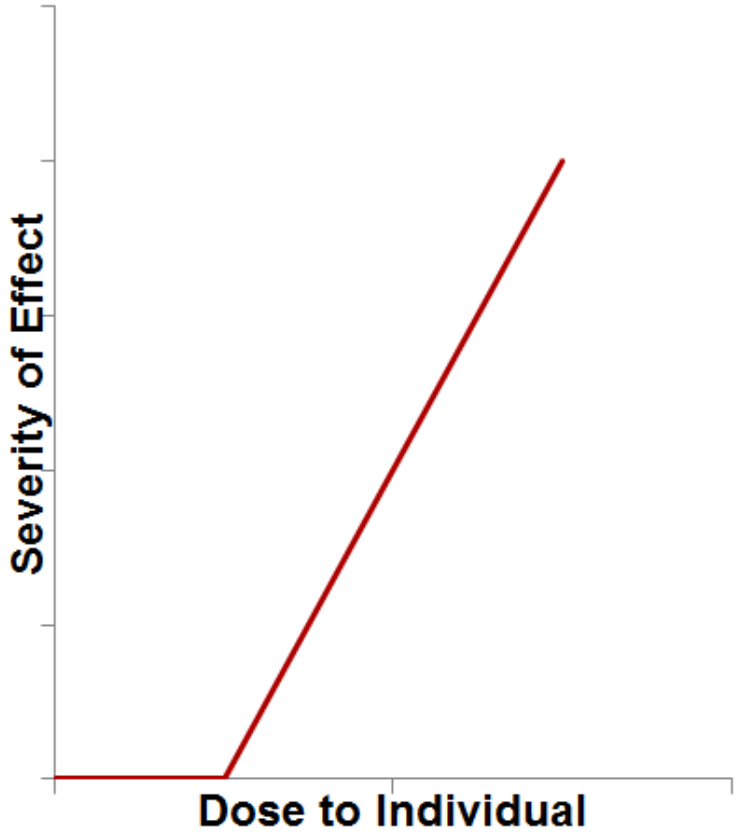
- 0.05 Sv/year
- 0.1 Sv/5 years
- Limits stochastic and deterministic effects

NRC/DOE Requirements

- 5 rem/year — stochastic effects
- 50 rem/year — deterministic effects

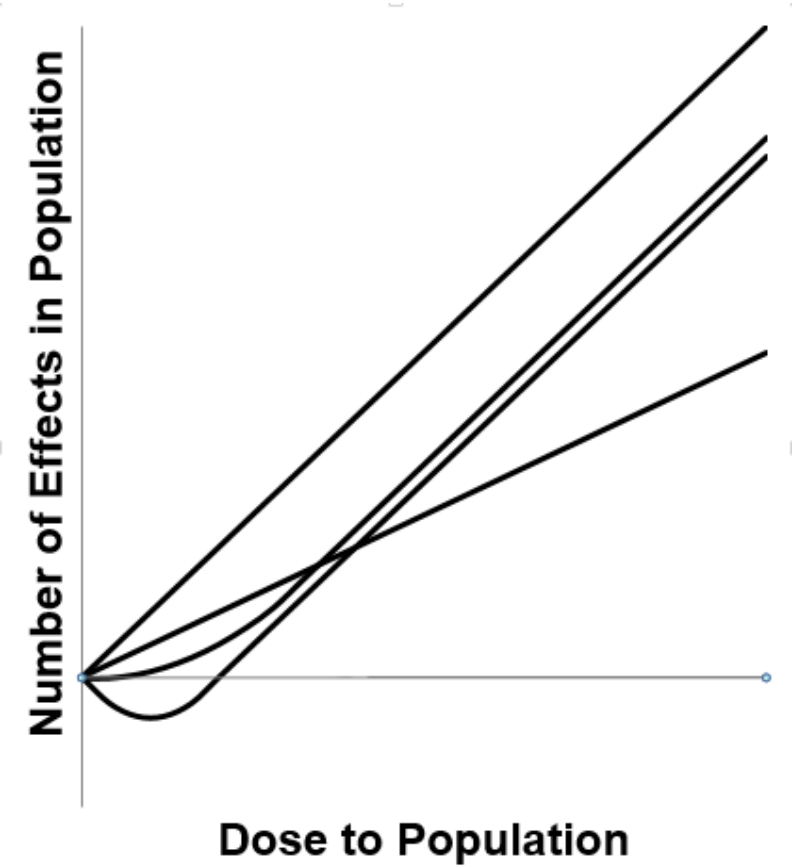
Deterministic effects are those you can see.

- Effect is on individual — not statistical
- No effect until threshold dose is reached
- Effect worsens with dose



Stochastic effects are probabilistic.

- Effect is statistical and on population
- Number of individuals with effect increases with dose to population.
- Dreaded “linear non-threshold”



Committed dose is integrated over time.

$$
\begin{aligned}
H_T(50) &= \int_0^{50\ y} H_T(t)\mathrm{d}t \\
&= \int_0^{50\ y} \mathrm{SEE}(\mathrm{T} \leftarrow \mathrm{S}) N_S(t)\mathrm{d}t \\
&= \mathrm{SEE}(\mathrm{T} \leftarrow \mathrm{S}) \int_0^{50\ y} N_S(t)\mathrm{d}t \\
&= \mathrm{SEE}(\mathrm{T} \leftarrow \mathrm{S}) U_S
\end{aligned}
$$

Committed dose protects the worker's health and livelihood.

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Worker protection from long-lived radionuclide:

5 rem annual = 250 rem committed!

Worker livelihood from long-lived radionuclide:

5 rem this year = 5 rem next year (and year after…)

Effective dose accounts for radiosensitivity of tissues in consideration of whole-body dose.

$$E = \sum_T w_T H_T$$

Tissue weighting factors continually change with revision of ICRP recommendations.

Organ/Tissue	ICRP-60 w_T	ICRP-103 w_T
Gonads	0.2	0.08
Bone marrow	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Oesophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone Surface	0.01	0.01
Remainder	0.05	0.05

In either system, two specific models and one general make up the human body.

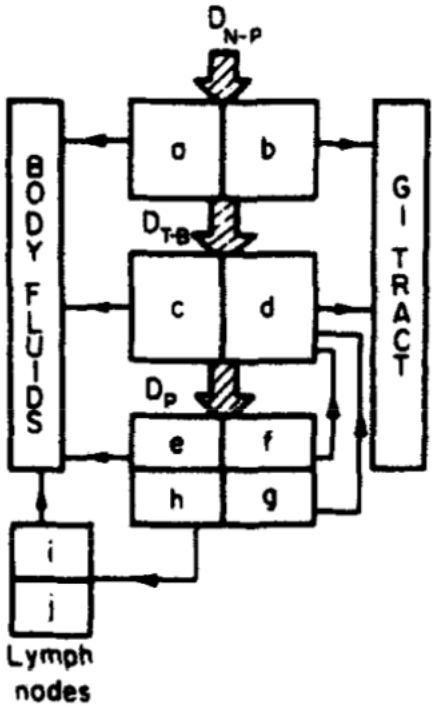
ICRP-30 contains all models necessary to determine dose coefficients.

- Dosimetric Model for the Respiratory System
- Dosimetric Model for the Gastrointestinal Tract
- General systemic model with element-specific parameters

ICRP-68 uses models across several publications.

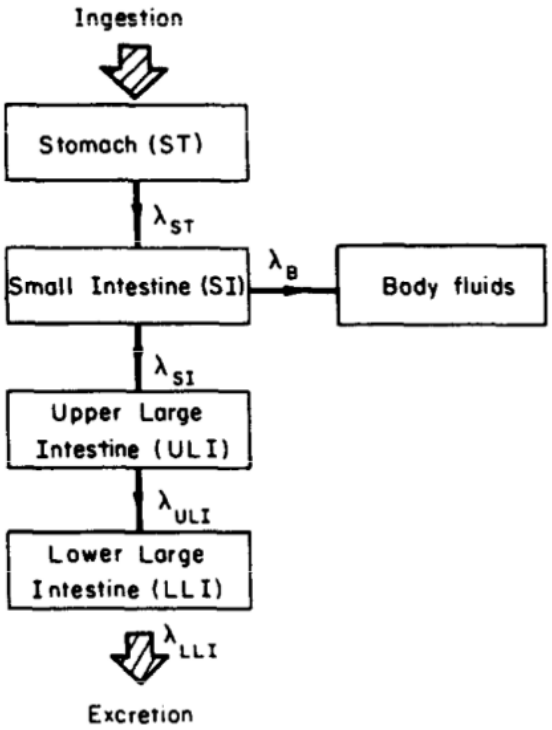
- Human Respiratory Tract Model (ICRP-66)
- Dosimetric Model for the Gastrointestinal Tract (ICRP-30)
- Various systemic models for particular elements (ICRP-30, 56, 67, 69, 71, 72)

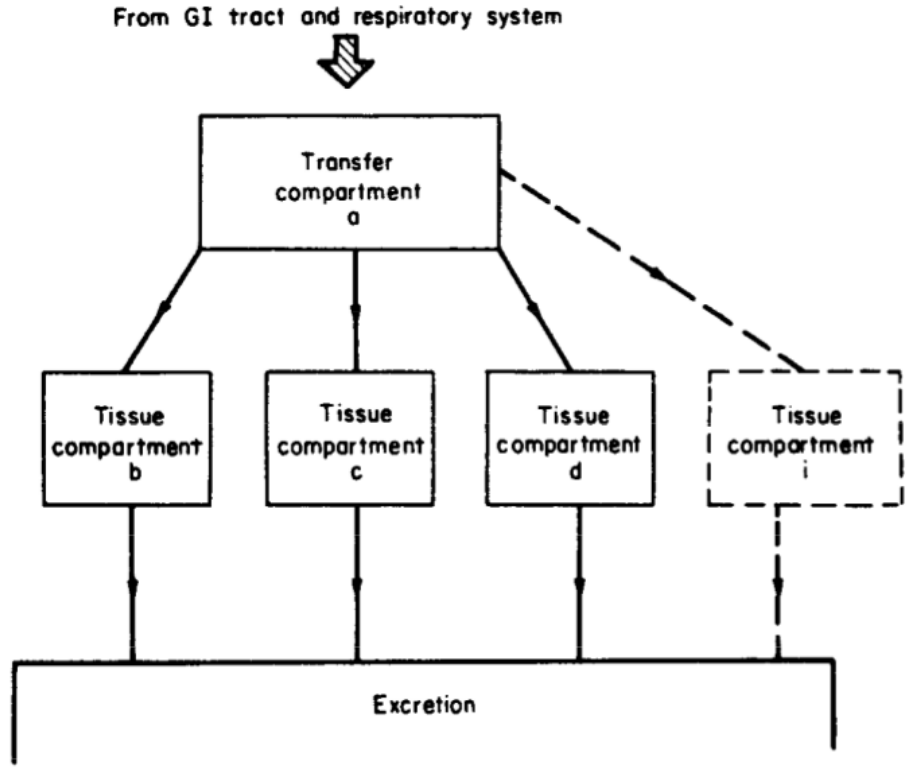
The ICRP-30 respiratory tract model separated clearance and absorption.



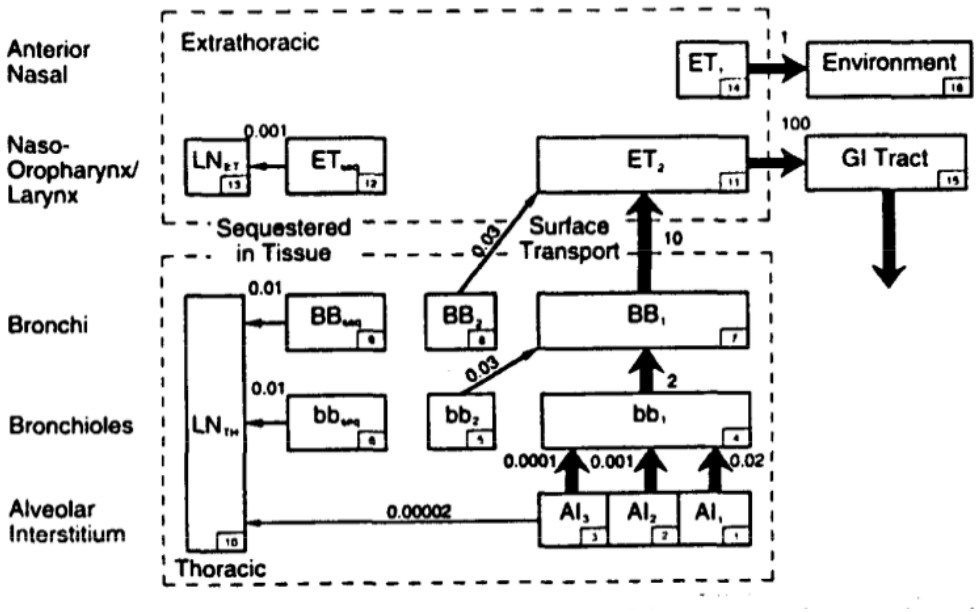
Region	Compartment	Class D T day	D F	W T day	W F	Y T day	Y F
N–P (D_{N-P} = 0.30)	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.40	0.99
T–B (D_{T-B} = 0.08)	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P (D_P = 0.25)	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1.0	0.4	1.0	0.4
	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1 000	0.9
	j	n.a.	n.a.	n.a.	n.a.	∞	0.1

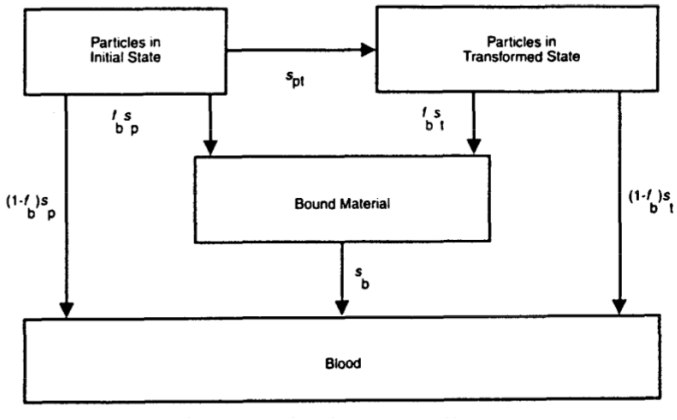
The ICRP-30 gastrointestinal and systemic models are simple once-through systems.





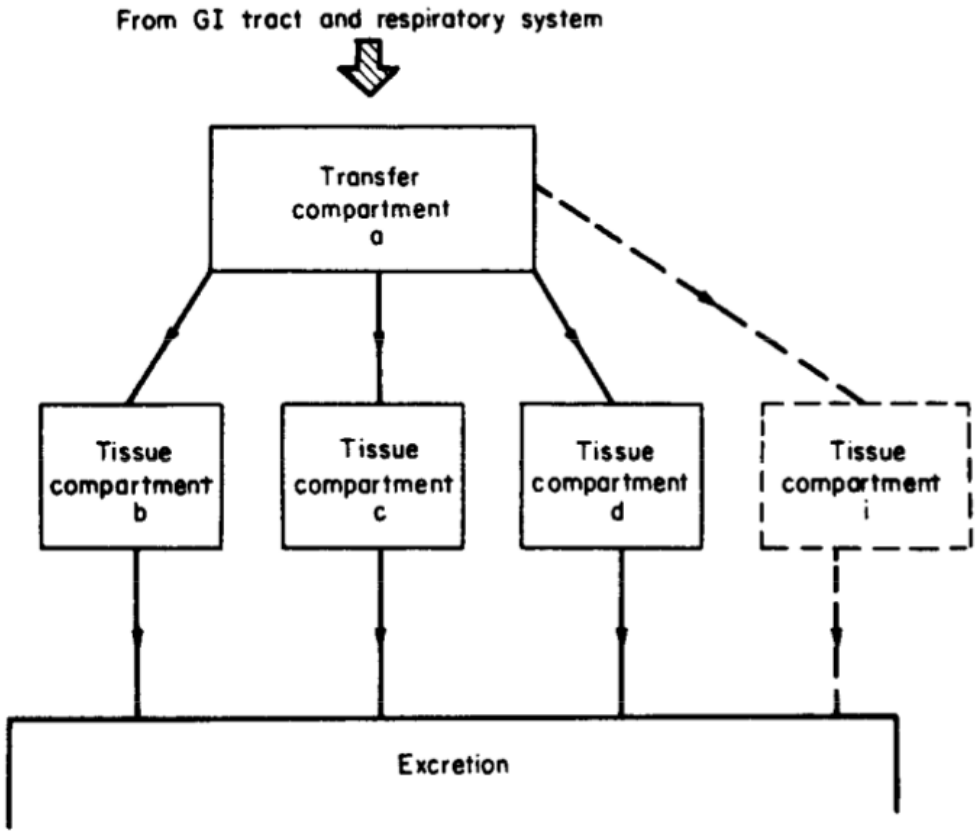
The ICRP-66 HRTM used in 10CFR835 competes clearance and absorption in each lung region.





Type of absorption behaviour		F (fast)	M (moderate)	S (slow)
Initial dissolution rate (d^{-1})	s_b	100	10	0.1
Transformation rate (d^{-1})	s_{pt}	0	90	100
Final dissolution rate (d^{-1})	s_t	–	0.005	0.0001
Fraction to bound state	f_b	0	0	0
Uptake rate from bound state (d^{-1})	s_b	–	–	–

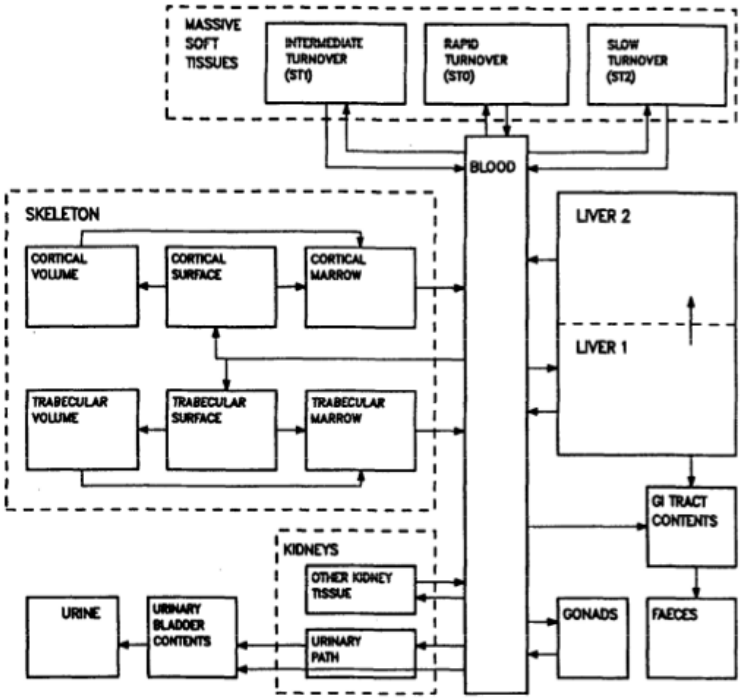
ICRP-30 type models are simple catenary kinetics.

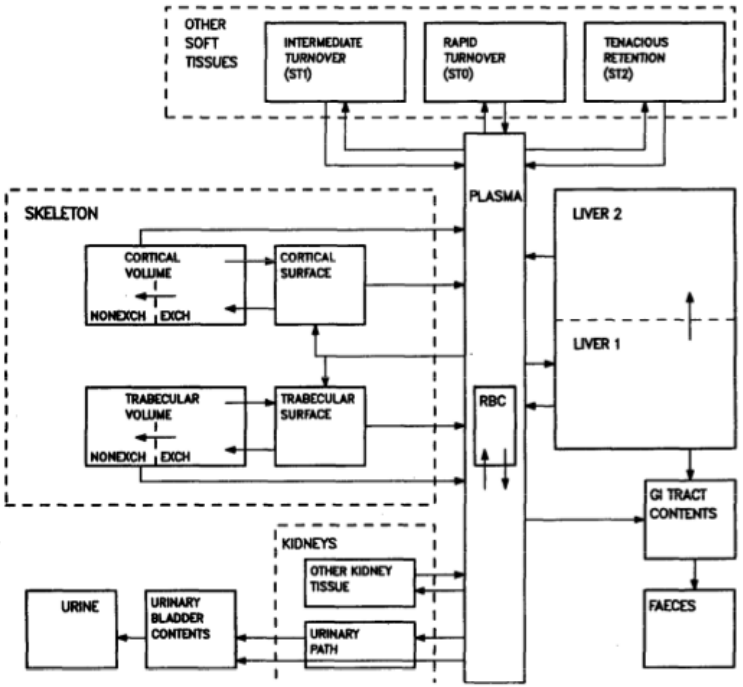


The fraction of systemic excretion is necessary to implement this model.

- Specific values are identified in ICRP-68.
- Ratio is assumed 50/50 unless specifically identified.
- New models include excretion as part of the model.

Modern systemic models are complex systems of organs and tissues.





Compartmental modeling is defined by a system of differential equations.

Assumption: The rate of change of amount of material in a particular compartment is proportional to the amount of material in that compartment.

$$\frac{dN_1(t)}{dt} = k_{2,1}N_2(t) - k_1N_1(t)$$
$$\frac{dN_2(t)}{dt} = k_{1,2}N_1(t) - k_2N_2(t)$$

Matrix algebra can be used to define this system of equations.

$$\begin{bmatrix} \frac{dN_1(t)}{dt} \\ \frac{dN_2(t)}{dt} \end{bmatrix} = \begin{bmatrix} -k_1 & k_{2,1} \\ k_{1,2} & -k_2 \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix}$$

Eigenvalues and Eigenvalues — solutions of particular equations — are used to solve the system.

$$|\mathbf{k} - \gamma \mathbf{I}| = 0$$
$$(\mathbf{k} - \gamma \mathbf{I})\,\mathbf{v} = 0$$

The set of solution functions are *intake retention functions*

$$N(t) = N_1(0) \sum_{i=1}^{n} C_i \mathbf{v_i} e^{-\gamma t}$$

$$r(t) = \frac{N(t)}{N_1(0)} = \sum_{i=1}^{n} C_i \mathbf{v_i} e^{-\gamma t}$$

r(t) is a set of equations for each compartment represented in the catenary system.

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Summary

The ICRP provides recommendations for institution of program.

- the handling of large quantities of gaseous and volatile materials, e.g. tritium and its compounds in large scale production processes, in heavy water reactors and in luminising,
- the processing of plutonium and other transuranic elements,
- the processing of thorium ores and use of thorium and its compounds,
- the milling and refining of high grade uranium ores,
- natural and slightly enriched uranium processing and reactor fuel fabrication,
- the production of large quantities of radionuclides,
- workplaces where radon levels exceed the action level, and
- the handling of large quantities of ^{131}I, e.g. for therapy.

The NRC requirement for monitoring can be found in 10CFR20 §20.1502

"Each licensee shall monitor (see §20.1204) the occupational intake of radioactive material by and assess the committed effective dose equivalent to

(1) Adults likely to receive, in 1 year, an intake in excess of 10 percent of the applicable ALI(s) in table 1, columns 1 and 2, of appendix B to §§20.1001–20.2402"

NRC does have some radionuclide-specific guidance.

- Reg Guide 8.11 *Applications of Bioassay for Uranium* (July, 2015): "Licensee determinations regarding participation in the uranium bioassay program should be based on estimates of the type and quantity of intakes that may occur using procedures that are expected to take place at each facility during the monitoring year."
- Reg Guide 8.22 *Bioassay at Uranium Mills* (May, 2014): "Bioassay program determinations regarding participation and frequency should be based on estimates of the type and quantity of intakes that may occur based on the procedures that are expected to take place at the licensee's facility during the monitoring year."

More NRC Guidance

- Reg Guide 8.20 *Applications of Bioassay for Radioiodine* (September, 2014): "The decisions on the type of monitoring, who is to be monitored, the frequency of monitoring, and other aspects of the program must be based on estimates of what types and quantities of intakes may occur given the kinds of activities that are expected to take place at the licensee's facility during the monitoring year."
- Reg Guide 8.32 *Critera for Establishing a Tritium Bioassay Program* (July 1988, R October 2011): "Routine bioassay is necessary when quantities of tritium processed by an individual at any one time or the total amounts processed per month exceed those shown in Table 1 for each form of tritium."

The DOE requirement for monitoring can be found in 10CFR835 §835.402(c)

"For the purpose of monitoring individual exposures to internal radiation, internal dosimetry programs (including routine bioassay programs) shall be conducted for:
(1) Radiological workers who, under typical conditions, are likely to receive a committed effective dose of 0.1 rem (0.001 Sv) or more from all occupational radionuclide intakes in a year…"

DOE performance requirements are in 10CFR835 §835.402(d).

"Internal dose monitoring programs implemented to demonstrate compliance with §835.402(c) shall be adequate to demonstrate compliance with the dose limits established in subpart C of this part and shall be:
(1) Accredited, or excepted from accreditation, in accordance with the DOE Laboratory Accreditation Program for Radiobioassay…"

The DOE RadCon standard provides guidance as to the necessity of a program.

DOE-STD-1098-2008 Radiological Control Part 2 Section 521 (4):
"Individuals whose routine duties may involve exposure to surface or airborne contamination or to radionuclides readily absorbed through the skin, such as tritium, should be considered for participation in the bioassay program."

Management has prime responsibility for activities.

- Management:
  - establishes and funds the safety programs, which include the Internal Dosimetry Group and RadCon Group
  - establishes and enforces fundamental safety policies
    - workers can raise safety concerns without fear of retaliation
    - each worker is responsible for his own safety
- Because safety programs are typically not revenue centers, establishing an adequate, balanced safety program is no mean task

Workers are our are primary customer.

- As internal dosimetrists we sometimes underestimate how important what we do can be to some individuals
- Good communication skills are essential for keeping workers informed and building trust
- Once trust is lost it is not easily regained

Radiological Control is an essential element.

- The radiological control (RadCon) group is responsible for implementing radiation safety programs in the workplace
  - job planning and coverage
  - workplace surveys
  - workplace air monitoring
  - incident response and recovery
- RadCon are our eyes, ears, and feet
- We can tell a worker the dose he got from an intake — RadCon can prevent the intake

A good relationship with the analysis laboratory is indispensable.

- There are commercial and government radiobioassay laboratories
  - USDOE facilities may have their own dedicated laboratory
  - government labs are not permitted to compete with commercial laboratories on non-government work
  - specialized analyses like TIMS for Pu in urine and Pu/Am chest counting are not available commercially
- We are the customer of the lab and we should make every effort to tell them what we need and check to see if we are getting it

The internal dosimetrist is the focal point for internal dosimetry activities.

- Designs programs to monitor workers for intakes of radioactive materials
- Interprets the monitoring data to determine if the operation is in compliance with regulatory limits
- Communicates these interpretations to all interested stakeholders

Qualification requirements for internal dosimetrists do not exist.

- In the US:
  - There are no minimal qualifications, training, experience, or education specified for an internal dosimetrist at the professional (HPS) or regulatory (USDOE, USNRC) level
  - There are no accreditation programs for the internal dose assessment process
- Canada is in the beginning stages of implementing a "certification program" for dosimetry services
  - Regulatory Standard S-106 Revision 1, Technical and Quality Assurance Requirements for Dosimetry Services, May 2006
  - Internal Dosimetrist == Internal Dosimetry Services
- In the end, the burden of certifying that an individual is qualified to perform occupational internal dose calculations usually rests with the management of the organization

There is some guidance as to qualifications for internal dosimetrists.

- ISO/IEC 17025:2005 *General requirements for the competence of testing and calibration laboratories*
  - Intended for testing and calibration laboratories, but if you consider the determination of dose as part of the analysis, it applies to what we do
- ANSI/HPS N13.39-2001 (R2011) *Design of Internal Dosimetry Programs*
  - Provides suggested training and education for internal dosimetrists

Regulations and guidance organizations have different approaches

- ICRP: “monitoring”
- NRC: “assessing”
- DOE: “conducting”

…and the dreaded “likely to receive”…

Is *likelihood* the same as *potential*?

- Few workers in the US nuclear industry are truly “likely” to exceed the monitoring level as a result of routine operations
- However, because of difficulties associated with determining likelihood, we tend to monitor workers who have a reasonable potential to exceed the monitoring level

Likelihood is defined in therms of dependencies.

- The likelihood of exceeding the monitoring level will depend on
  - the amount of radioactive material present and the radionuclides involved
  - the physical and chemical form of the radioactive material
  - the type of containment used
  - the operations performed
  - the general working conditions
  - past operating history
  - skill and training of workers
- However, little guidance is offered concerning how to actually determine the likelihood of exceeding the monitoring level

There are different approaches to inferring the likelihood.

To estimate a priori likelihood of exceeding the monitoring level use:

- some sort of predictive formula involving the amount of material
- in process and the level of containment (ala NUREG 1400)
- available data from existing air monitoring program
- available data from existing bioassay program

- We are seeking to justify our estimate of the probability (likelihood) that a person will have an intake that will deliver over the monitoring level
- We are not seeking to prove that no worker will receive (or has received) an intake that will deliver over the monitoring level

Can general air monitoring be used to determine likelihood?

Assumptions when using general (room) air monitoring.

1. Retrospective air monitors are representative.
   - Note that in order to use this assumption in this context the monitors only need to be representative enough to make probabilistic statements about likelihood. The monitors do not have to be representative in the usual sense, which normally means that they are representative 100% of the time.
2. Workers entering areas >0.1 DAC (2.4 DAC-hours per 24 hour day) wear respiratory protection.
3. Workers wearing respiratory protection are unlikely to exceed 0.1 rem.
4. Workers entering areas >0.1 DAC who do not wear respiratory protection are placed on a special bioassay program (they are likely to exceed 0.1 rem).

5. Any excursions in air activity that exceed 2.4 DAC-hours in a day and fall under assumptions 3 or 4 are not included in the assessment of likelihood.
6. Occupancy time is 1000 hours per year and the air samplers run around the clock (8760 hours per year).

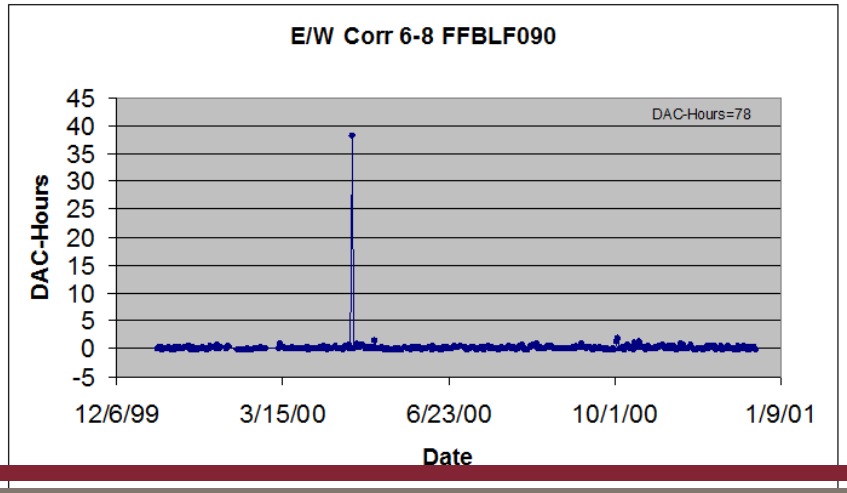
The last assumption means that the occupancy factor is 8.76, which means that a room must exceed a fairly uniform annual exposure of

$$(8.76)(40 \text{ DAC-hours}) = 350 \text{ DAC-hours}$$

before a worker could be considered likely to exceed 100 mrem.

One spike in an air sample likely will not matter.

- The retrospective air sampler in E/W Corridor 6-8 (FFBLF090) registered 78 DAC-hours for the year
- The high result on 4/26/00 (38 DAC-hours) may be ignored in the assessment of likelihood if workers entering this area on 4/26/00 either wore appropriate respiratory protection or were placed on a special bioassay program.
- Ignoring the 4/26/00 result, workers are unlikely to exceed 100 mrem in a year because the occupancy factor and the uniform exposure over the year



Monitor unexposed individuals at your own risk.

- Assume you monitor a worker who a priori you decided has no potential for an intake exceeding the monitoring level
  - you go ahead and put a person on a bioassay program even though in your view he has no potential
- Further, assume a bioassay result for this person turns out to be both positive and dosimetrically “unattractive”
- You can not, after the fact, discount this result simply because the person “could not have had the intake” in the first place
  - do not pencil-whip your mistake

There are different bioassay program types.

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Common bioassay program types

- Routine
- Confirmatory
- Special
- Baseline/Termination
- Operational

Confirmatory bioassay is useful if positive results are not expected.

- Performed at prescribed times that are not directly related to work activities
- Collected from workers exposed to “known” levels of radioactive material
  - where “known” could be zero
- Shows that engineered and procedural controls have been effective in preventing or controlling intakes
- Final QC check of radiological protection program

Routine bioassay is required for continuous radiological work.

- Same as confirmatory but meets the requirements for routine monitoring.
- Usually administered at periodic frequencies.
- Follows chronic intakes.
- Unusual during current times due to minimization of contamination in the workplace.

Special bioassay is for unexpected intakes.

- Collected from workers potentially exposed to unexpected or unknown levels of radioactive material that could result in a CED in excess of the monitoring level or other investigation levels
- Used to confirm and evaluate intakes of radioactive material by workers and determine compliance with regulations

Internal dosimetry programs frequently set requirements for special bioassay.

- Facial or nasal contamination
- Potential exposure to airborne radioactivity without respiratory protection
- Damage to or failure of a respirator
- Protection factor of respirator exceeded
- Significant skin contamination
- Significant workplace contamination

Baseline or termination bioassay are sometimes appropriate.

- Baseline bioassay
  - Collected from new workers prior to beginning work with a potential for occupational exposure
- Termination bioassay
  - Collected from workers when they terminate participation in a routine bioassay program
- Both are used to establish the radiological status of the worker when starting or stopping participation in a bioassay program

But, baseline especially may not be necessary.

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Baseline Bioassay Advice

- If a worker has never worked in a radiological facility, then don't bother performing a baseline bioassay
- If a worker has been on a bioassay program before, then perform a baseline bioassay for radionuclides of interest to you
- If you don't perform a baseline bioassay, then you may end up owning all subsequent positive results
- If you commit a Type I or Type II error on a baseline bioassay, then you may end up owning all subsequent positive results

Operational bioassay covers a particular job.

- Collected from workers after completion of specified tasks (aka job-specific bioassay)
- Surrogate for confirmatory program for short term workers
- Provides detailed information on exposures related to the specific job
- Provides more timely detection of intakes and increases probability of detecting intakes

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Summary

Indication of intake begins at the work site.

Airborne Radioactivity Indicators

- Positive nasal smear or contamination inside a respirator mask.
- A worker is exposed to airborne radioactivity in excess of 8 DAC-h in a day or the indicated air concentration could greatly underestimate that to which the worker was exposed (protection factor included).

Workplace Contamination Indicator

- An unplanned release of radioactive material produces contamination on accessible surfaces in excesses of 1500 d/m per 100 cm^2 alpha or 15,000 d/m per 100 cm^2 beta-gamma if respiratory protection is not in use.

Personal contamination may also indicate possibility of intake.

Personal Contamination Indicator

- Contamination is measured on a single-layer protective clothing in excess of 10,000 d/m per 100 cm^2 alpha or 100,000 d/m per 100 cm^2 beta-gamma if respiratory protection is not in use.
- Contamination is measured on the inner layer of multiple-layer protective clothing in excess of 10,000 d/m per 100 cm^2 alpha or 100,000 d/m per 100 cm^2 beta-gamma if respiratory protection is not in use.
- Any detectable personal contamination is measured on the hair, face, neck, chest, arms, or hands, or anywhere else on the body in excess of 1000 d/m per 100 cm^2 alpha or 10,000 d/m per 100 cm^2 beta-gamma if respiratory protection is not in use.

A positive bioassay result may or may not be an indicator of intake.

A bioassay result value greater than the detection level may mean:

- The individual is carrying activity from a legacy intake.
- The individual had an intake from non-work-related activities (eating deer meat, drinking water…).
- The individual “crapped up” his sample.
- You are at the pointy end of the Gaussian curve.

Or…that he actually had an intake!!!

Workplace monitoring and control is the prime indicator.

If your workplace monitoring and control processes are effective, you should already know that this individual probably has had an intake and have made changes to that person's bioassay protocol accordingly.

An intake is an intake when you say it is.

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So when is it officially an intake?

- One strike rule
- Two strike rule
- Bayesian criteria

You are responsible for developing and implementing the technical basis used to confirm an intake.

What is the difference between DL and MDA?

- Frequently misused and misinterpreted
- Critical (detection) level
  - tells us whether or not there is radioactivity in the sample itself.
- Lower limit of detection (or MDA which is in terms of activity)
  - describes the ability of the counting system, i.e., the activity that the system will consistently detect.

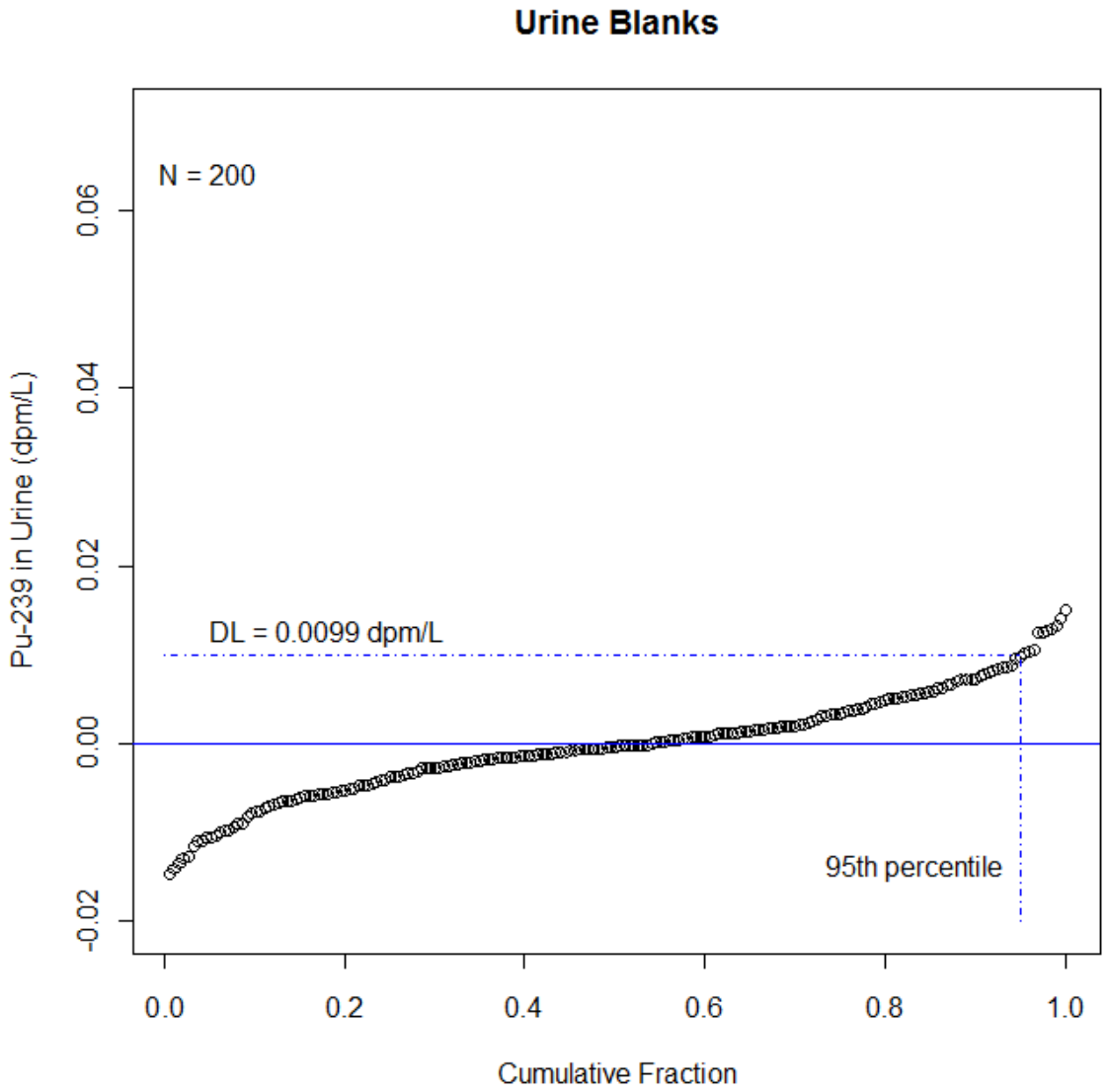
As an example, we can look at DL and MDA empirically.

- To illustrate what the DL and MDA really are, let's estimate the DL and MDA for ^{239}Pu in urine analysis without any of those messy formulas
  - analyze 200 urine blanks using the normal process,
  - order the results from smallest to largest
  - calculate the fraction of the samples less than the ith sample, where i goes from 1 to 200

Detection level tells us about the sample.

- A *blank sample* contains no analyte
- As a result of random processes, we will get a range of results when we repeatedly measure the amount of analyte in a blank sample
- The amount of analyte above which we would measure < α% (usually α= 5 %) of the time in the blanks is referred to as the detection level (DL).
  - Samples above the DL are declared to contain analyte.
  - If the sample does not actually contain analyte, this error is referred to as a false positive

Blanks should follow a distribution around zero.



A Type I error is a “false positive.”

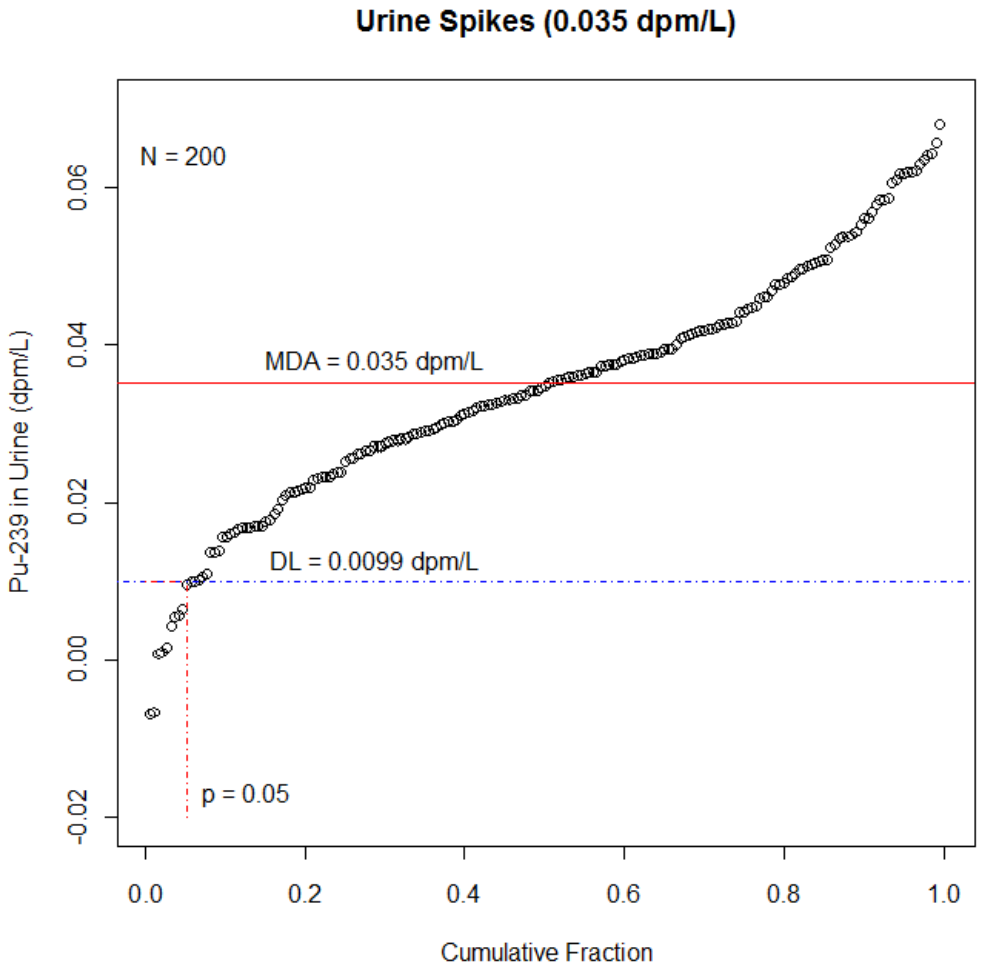
You conclude that there is analyte present when in fact there is none

Reality	Conclusion: Analyte	Conclusion: No Analyte
Analyte	Correct	Incorrect (false negative)
No Analyte	Incorrect (false positive)	Correct

Minimum detectable activity tells us about the analytical system.

- The DL tells us nothing about the risk of deciding that analyte is not present when indeed it is (a false negative)
- The minimum detectable amount is the amount of analyte that would fall below the DL β% (usually β= 5%) of the time (false negative)
  - Used for design of bioassay programs and to describe the detection capabilities of a type of bioassay
  - Should not be used to determine significance of any particular result

Spikes where β falls below DL should follow a distribution around the MDA.



A Type II error is a “false negative.”

You conclude that there is no analyte present when in fact there is

Reality	Conclusion: Analyte	Conclusion: No Analyte
Analyte	Correct	Incorrect (false negative)
No Analyte	Incorrect (false positive)	Correct

Theory and practice differ in terms of use of these statistics.

- The DL is used to decide if a sample contains analyte
  - we can't tell a false positive from a true positive
- The MDA is used to characterize the ability of an analytical method to detect analyte in the sample
  - the MDA is not used to decide if a sample contains analyte

This example is one realization of the DL and MDA.

- If you run this experiment again you are likely to get a different DL and MDA
- If you do this experiment many times, the mean DL and mean MDA will be good estimates of the long-run DL and MDA
  - this is usually not feasible to do
- A menagerie of DL and MDA formulas have been developed in an attempt to calculate the mean DL and mean MDA without incurring the trouble and expense of running all the blank and spike analyses
- At least be aware of how your bioassay lab is calculating the DL and MDA

A Type III error is when you came to right conclusion for the wrong reason

- You correctly conclude that there is no analyte present, but it is the wrong analyte
- You correctly conclude that there is analyte present, but it did not come from the person

Reality	Conclusion: Analyte	Conclusion: No Analyte
Analyte	Correct	Incorrect (false negative)
No Analyte	Incorrect (false positive)	Correct

Last word on DL/MDA

While there are many recommendations on how to calculate DL and MDA, there is no requirement that you do it a certain way.

There are many ways to determine effective dose.

Calculate intake or dose directly?

- Models can be used to calculate intake followed by inferring dose.
  - NUREG/CR-4884: IRFS for ICRP-30 system
  - Potter, HPJ, 2002: IRFS for ICRP-68 system
- Models can be used with probability algorithm to calculate dose directly
  - Certain computer codes (IMBA)

$$IRF(t) = \sum_i C_i \exp^{\gamma_i t}$$

Single point-estimated intakes are acceptable for low doses.

If date is known, appropriate intake retention fraction can be used.

$$I = \frac{M}{IRF(t)}$$

- *M* is measurement
- *IRF(t)* is intake retention fraction evaluated at time *t*

If date is unknown, time might be based on monitoring period.

$$I = \frac{M}{IRF(T/2)}$$

- *IRF(T/2)* is intake retention fraction evaluated at midpoint of monitoring interval *T*
- Recommended by ICRP and EURADOS

For this presentation we will concentrate on minimizing the reduced chi-square statistic.

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Minimizing the χ^2_ν optimizes the fitting parameters (intakes).

- Process is similar to minimizing the sums of the squares of the errors (least-squares fit).
- Remember: optimum value of χ^2_ν is 1, not 0.
- Process eliminates chi-square test as measure of goodness of fit.

$$\chi^2_\nu = \frac{1}{\nu} \sum \frac{(y_i - \langle y \rangle_i)^2}{\sigma_i^2}$$

Minimization results in a general equation for intake.

$$\langle y_i \rangle = I F_i$$

$$\begin{aligned} 0 = \frac{\partial \chi^2_\nu}{\partial I} &= \frac{\partial}{\partial I} \frac{1}{\nu} \sum \frac{(y_i - I F_i)^2}{\sigma_i^2} \\ &= \frac{1}{\nu} \sum \frac{2\,(y_i - I F_i)\,(-F_i)}{\sigma_i^2} \\ &= \sum \frac{\left(-y_i F_i + I F i^2\right)}{\sigma_i^2} \\ &= I \sum \frac{F_i^2}{\sigma_i^2} - \sum \frac{y_i F_i}{\sigma_i^2} \end{aligned}$$

$$I = \frac{\sum \frac{y_i F_i}{\sigma_i^2}}{\sum \frac{F_i^2}{\sigma_i^2}}$$

Models of variance give meaning to the general equation.

$$I = \frac{\sum \frac{y_i F_i}{\sigma_i^2}}{\sum \frac{F_i^2}{\sigma_i^2}}$$

Variance models define σ with the assumption that an expectation (theoretical) variance being larger than a measurement variance is more representative of the true variance.

Unweighted $\sigma_i^2 = \sigma^2$

Ratio of the Means $\sigma_i^2 = \kappa \langle y_i \rangle$

Average of the Slopes $\sigma_i^2 = \phi^2 \langle y_i^2 \rangle$

Uncertainty in the intake is obtained by propagation of error

$$\sigma_I^2 = \sum \left(\frac{\partial I}{\partial y_i} \right)^2 \sigma_i^2$$

$$\sigma_I^2 = \frac{1}{\sum \frac{F_i^2}{\sigma_i^2}}$$

To estimate the coefficients, the reduced chi-square statistic can be normalized to unity.

If:

$$\sigma_i^2 = C \times VAR$$

then:

$$1 = \frac{1}{\nu} \sum \frac{(y_i - \langle y \rangle_i)^2}{C \times VAR}$$

$$C = \frac{1}{\nu} \sum \frac{(y_i - IF_i)^2}{VAR}$$

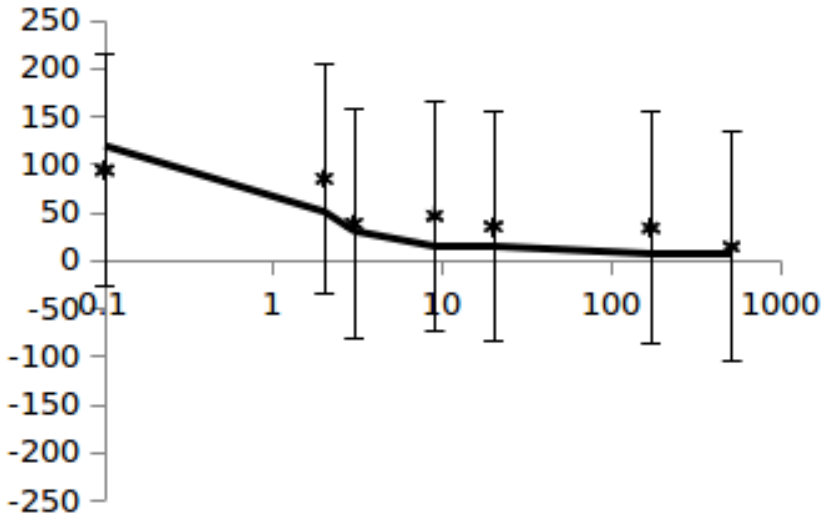
An unweighted fit assumes all variances are equal

$$\sigma_i^2 = \sigma^2$$

$$I = \frac{\sum \frac{y_i F_i}{\sigma_i^2}}{\sum \frac{F_i^2}{\sigma_i^2}} = \frac{\sum y_i F_i}{\sum F_i^2}$$

$$\sigma^2 = \frac{1}{\nu} \sum (y_i - I F_i)^2$$

$$\sigma_I^2 = \frac{\sigma^2}{\sum F_i^2}$$



$$I = 250 \pm 220 \text{ nCi @ } 95\% \ (1.96\sigma)$$

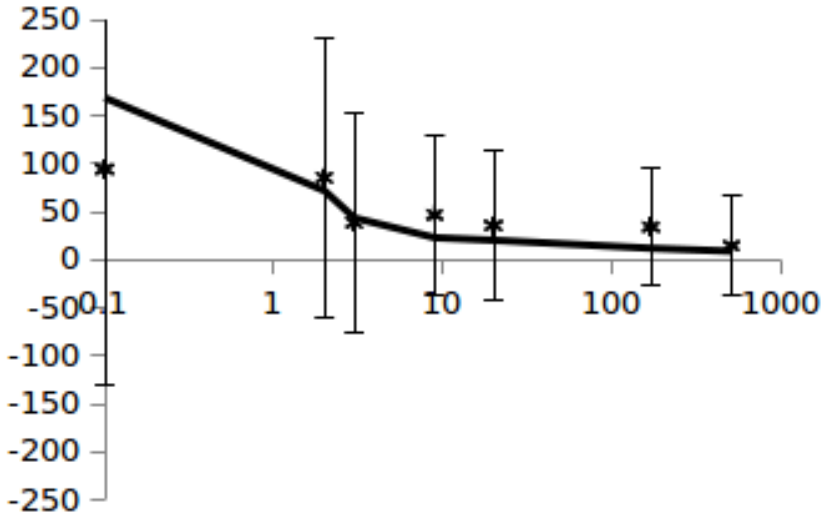
A ratio of the means fit assumes variance is proportional to the expectation value.

$$\sigma_i^2 = \kappa \langle y_i \rangle = \kappa I F_i$$

$$I = \frac{\sum y_i}{\sum F_i}$$

$$\kappa = \frac{1}{\nu} \sum \frac{(y_i - I F_i)^2}{I F_i}$$

$$\sigma_I^2 = \frac{\kappa I}{\sum F_i}$$



$$I = 350 \pm 320 \text{ nCi @ } 95\% \ (1.96\sigma)$$

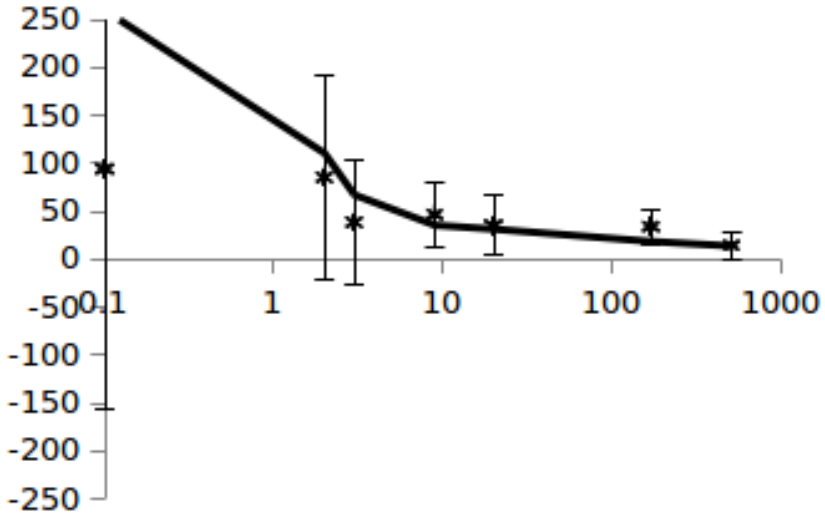
An average of the slopes fit assumes variance is proportional to the square of the expectation value.

$$\sigma_i^2 = \phi\langle y_i\rangle^2 = \phi I^2 F_i^2$$

$$I = \frac{1}{n}\sum \frac{y_i}{F_i}$$

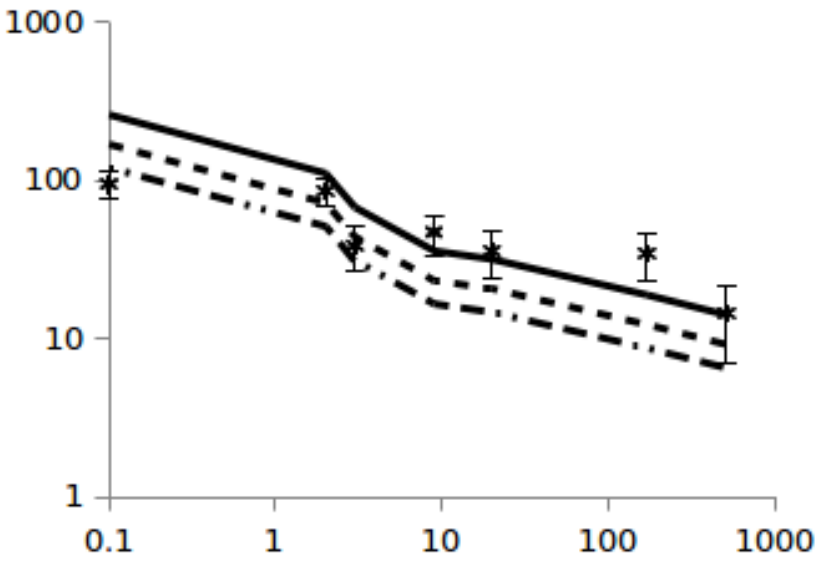
$$\phi = \frac{1}{\nu}\sum \frac{(y_i - IF_i)^2}{I^2 F_i^2}$$

$$\sigma_I^2 = \frac{\phi^2 I^2}{n}$$



$$I = 540 \pm 200 \text{ nCi @ } 95\% \ (1.96\sigma)$$

Viewing the data with the expectation fits is an important step in determining the appropriate model.



Observations on variance models

- Fit line maintains shape
- Unweighted fit favors larger magnitudes
- Average of slopes favors smaller errors

Dose is inferred by multiplying intake by dose coefficient (ICRP-68) or radio of dose standard (2 or 5 rem) and stochastic ALI.

The European Dosimetry Group (EURADOS) has developed a consistent methodology for data interpretation.

The IDEAS methodology calls for differing rigor based on the anticipated dose.

- Level 0 0.1 mSv/a — No evaluation of dose needed.
- Level 1 0.1 mSv $<$ E(50) $<$ 1 mSv — Simple "reference" evaluation with ICRP defaults.
- Level 2 1 mSv $<$ E(50) $<$ 6 mSv — Sophisticated evaluation generally using additional information from the workplace to give a more realistic assessment of dose.
- Level 3 E(50) $\geq$ 6 mSv — More sophisticated evaluation performed by expert user.

Different distributions describe and approximate bioassay measurements

All counting data is binomial.

A time period is analogous to a "trial" with the rate constant as the probability.

$$\mu = np$$
$$\sigma = np(1-p)$$

If n > 30, Poisson distribution approximates normal:

$$\sigma^2 = \mu$$

As n gets large, a binomial distribution can be approximated by a normal distribution.

$$\mu = \frac{\sum_i x_i}{n}$$
$$\sigma^2 = \frac{\sum_i (x - \bar{x})}{n-1}$$

Bioassay measurements tend to follow a lognormal distribution.

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In a lognormal distribution, the natural log of the measurement is distributed normally.

- mean μ = median
- "Scattering factor" SF describes the uncertainty
- SF similar to σ; 68% of distribution.

All uncertainty in measurements should be considered

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There are two types of uncertainty in a bioassay measurement

Type A Measurement errors associated with counting statistics

Type B Errors independent of radioactivity amount or counting time.

Example Type B uncertainty causes

- Detector Positioning
- Body Dimensions
- Activity Distribution
- Spectrum Evaluation
- Background Signal
- Overlaying Structures
- Calibration

Scattering factors are determined for uncertainty components and combined.

$$SF_A = \exp\left[\frac{\sigma_A}{M}\right]$$

- M is measurement value
- σ_A is counting uncertainty

Type B scattering factors are *a priori* determinations of normalized uncertainty similar to efficiency.

Scattering factors are combined:

$$SF = \exp\left[\sqrt{\sum_i \ln^2\left(SF_i\right)}\right]$$

The *method of maximum likelihood* solution is a weighted average of point-estimated intakes.

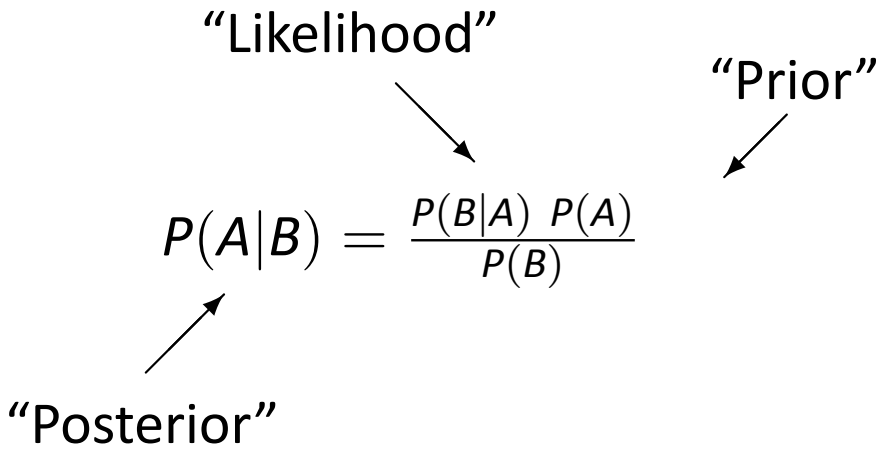
$$\ln(I) = \frac{\sum_{i=1}^{n} \frac{\ln(I)_i}{[\ln(SF_i)]^2}}{\sum_{i=1}^{n} \frac{1}{[\ln(SF_i)]^2}}$$

- I_i is point-estimated intake
- Scattering factor is assumed dominated by Type B errors
- This causes scattering factor term to divide out.

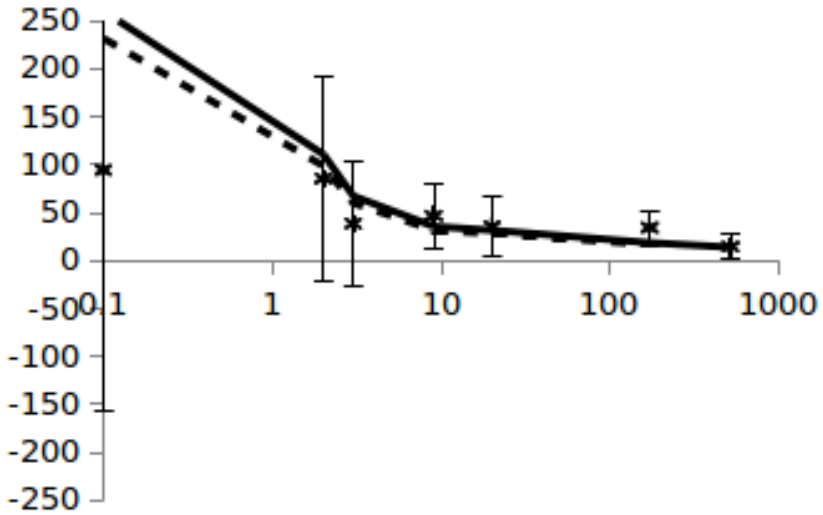
Best estimate is geometric mean of point estimates:

$$I = \sqrt[n]{\prod_{i=1}^{n} I_i}$$

The likelihood is a part of Bayes' rule.



Which intake value is wrong?



	Unweighted	Ratio of Means	Avg. of Slopes	Method of Maximum Likelihood
Intake	250	350	540	480
Uncertainty	220	320	200	420

Multiple intakes can be resolved using matrices.

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_n \end{bmatrix} = \begin{bmatrix} IRF_{11} & IRF_{12} & \dots & IRF_{1m} \\ IRF_{21} & IRF_{22} & \dots & IRF_{2m} \\ IRF_{31} & IRF_{32} & \dots & IRF_{3m} \\ \vdots & \vdots & \ddots & \vdots \\ IRF_{n1} & IRF_{n2} & \dots & IRF_{nm} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_m \end{bmatrix}$$

$$\mathbf{I} = \left[\mathbf{IRF}^{\mathsf{T}}\mathbf{IRF}\right]^{-1}\left[\mathbf{IRF}^{\mathsf{T}}\mathbf{Q}\right]$$

A ratio of the means fit can be obtained by defining new matricies in terms of expectation values

$$z = \frac{q_i}{\sqrt{\langle q_i \rangle}}$$

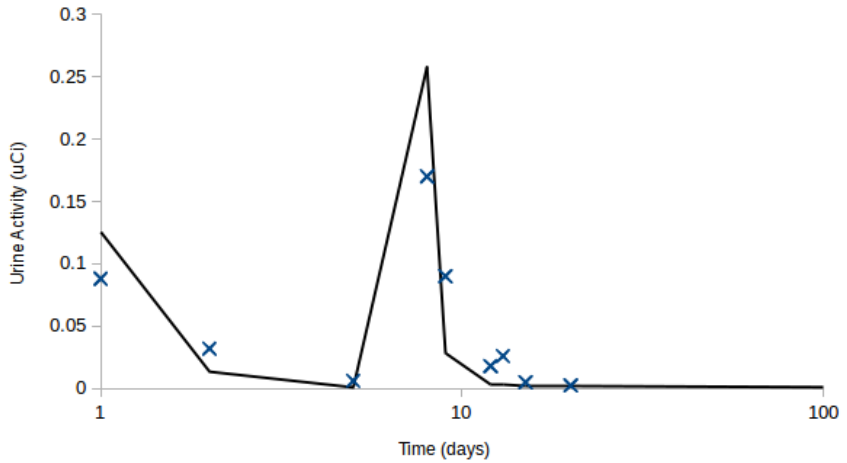
$$w = \frac{IRF_{i,j}}{\sqrt{\langle q_i \rangle}}$$

$$\mathbf{I} = \left[\mathbf{W}^{\mathsf{T}}\mathbf{W}\right]^{-1}\left[\mathbf{W}^{\mathsf{T}}\mathbf{Z}\right]$$

Caveats:

- An unweighted fit must first be done to determine expectation values.
- This is an iterative process — continue until intake values stop changing.
- The diagonals of the matrix formed by the first half of the equation are variances in the intakes.

Iteration continues until reduced chi-square remains constant within desired precision.



Iteration	I_1	I_2	χ^2_ν
1 (UW)	6.145	3.117	0.01517
2 (ROM)	4.349	8.857	0.06662
3	4.335	8.872	0.06661
4	4.333	8.874	0.06661
5	4.333	8.874	0.06661

$I_1 = 4 \pm 23\ \mu Ci$ @ 95%
$I_2 = 9 \pm 32\ \mu Ci$ @ 95%

The uncertainty shown

represents:

$$\sigma_I^2 = \frac{1}{\sum \frac{F_i^2}{\sigma_i^2}}$$

Dose is inferred using a dose coefficient

Remember the general equqtion for IRF:

$$N(t) = N_1(0) \sum_{i=1}^{n} C_i \mathbf{v_i} \exp\left(-\gamma t\right)$$

A *replacement function* can be identified for number of disintegrations, *U*:

$$U_s = \lambda \int_0^{50y} N(t)dt$$

$$U_s = N_1(0) \sum_{i=1}^{n} C_i \mathbf{v_i} \frac{\lambda\left(1 - \exp \gamma_i t\right)}{\gamma_i}$$

Dose coefficients are published in ICRP-68 (119) or ALIs can be used.

$$E(50) = 1.6 \times 10^{-10} U_s SEE(T \leftarrow S)$$

Following our example for ^{60}Co:

- ICRP-68 (119) dose coefficient: 1.7×10^{-8} *Sv Bq*$^{-1}$
  - Class S, 5 μm AMAD
- ICRP-30 ALI: 1×10^{6} *Bq*
  - Equates to 1.5×10^{-7} *Sv Bq*$^{-1}$
  - Class Y, 1 μm AMAD

Some final thoughts on estimating internal dose …

- Estimating effective dose is not particularly difficult.
- Charting bioassay data with the data fit line is very important.
- Final effective dose will depend on the regulatory standard that is required.

Understanding of source term is extremely important.

- Workers at a USDOE site were exposed to airborne radioactive material
- The material was classified as mixed fission products by operations and RadCon personnel
- Only whole-body counts were prescribed
- A radiochemical analysis of an air filter from the event gave the results shown here

Radio-nuclide	Activity Fraction	Dose Fraction
^{144}Ce	0.744851	0.410925
^{90}Sr	0.092095	0.176569
^{106}Ru	0.058049	0.040903
^{137}Cs	0.045004	0.002121
^{95}Zr	0.022306	0.000779
^{134}Cs	0.017871	0.001220
^{95}Nb	0.012797	0.000110
^{103}Ru	0.004513	0.000060
^{238}Pu	0.000603	0.349137
^{241}Am	0.000015	0.009832
^{239}Pu	0.000010	0.006336
^{242}Cm	0.000006	0.000153
^{244}Cm	0.000005	0.001830

Naturally-occurring radionuclides can also present a challenge.

- Workers at a uranium mill were exposed to natural uranium (yellowcake)
- Urine bioassay for elemental uranium was prescribed
- A radiochemical analysis of an air filter from routine operations gave the results shown here

Radio-nuclide	Activity Fraction	Dose Fraction
^{234}U	0.492449	0.337783
^{238}U	0.471930	0.288754
^{235}U	0.020519	0.013017
^{230}Th	0.012647	0.358399
^{226}Ra	0.001567	0.001171
^{210}Pb	0.000491	0.000580
^{210}Po	0.000397	0.000297

The chemical form (solubility) can make a great difference in inference of dose.

- A worker accidentally cut through a ^{137}Cs irradiation source, releasing airborne contamination
- A whole-body count showed that the worker had inhaled some of the material, and a dose was assigned assuming Type F ^{137}Cs (CsCl)
- A subsequent literature search showed that the source was fabricated with a relatively insoluble ceramic form of cesium, which delivers ~4x more dose per unit intake than the CsCl

Why are source term and solubility not known as a matter of course?

- A proper analysis of the source term is usually not easy, inexpensive, or quick to do
- Data from current routine operations and generic ICRP models are applied to specific events because it is readily available
- This ignores the possibility of
  - legacy radionuclides
  - concentration of radionuclides during processing
  - impurity radionuclides that are not important to the process
  - problems with data collected for a different use

What should you do when there is a known exposure?

- Strongly consider performing a proper isotopic analysis of the contamination associated with a known exposure event
  - don't automatically assume that the material is what everyone thinks it is
  - use waste stream characterization data with a modicum of caution
- Don't automatically think every material will act the way the ICRP says it will

Outline

Concepts and Models

Program Development and Elements

Data to Intake to Dose

Other Programmatic Considerations

New ICRP Models

Summary

Dose coefficients relate intake and dose.

- Gives 50-year committed dose to organ or tissue from a unit intake of radioactive material
  - For example, the Sv to bone surfaces from 1 Bq inhalation intake of Type S ^{239}Pu
- Includes dose from daughters that grow in after the intake

The *intake retention fraction* describes fraction of intake in a compartment of interest.

- *m(t)* – fraction of the intake that is present in a bioassay compartment at t days after the acute intake I
  - the intake retention fraction (IRF)
- *M(t)* – the quantity of activity estimated to be present in the same bioassay compartment at t days after the acute intake I
  - the bioassay measurement

Reference values are measured quantities above which some specified action or decision should be taken.

Reference values include:

- *recording levels* above which a result should be recorded, lower values being ignored;
- *investigation levels*, above which the cause or the implication of the result should be examined;
- *action levels*, above which some remedial action should be considered.

Reference levels are easily calculated once the reference dose is identified.

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Reference level equation

$$\textit{reference level} = \frac{(\textit{reference level})\, m(t)}{DCF}$$

Inhalation class F ^{63}Ni, monthly urine sampling, 10 mrem recording level

$$\frac{1 \times 10^{-4}\ \text{Sv}\left(4.72 \times 10^{-5}\right)}{5.2 \times 10^{-10}\ \text{Sv/Bq}} = 9.07\ \text{Bq}$$

ANSI HPS N13.39 recommends several different reference levels.

Screening level The level of intake below which a bioassay result need not be considered for investigation of intake and assignment of dose. (0.002 SALI)

Verification level The level of unexpected intake at or above which an attempt to confirm the intake as real should be made. (0.02 SALI)

Investigation level The level of intake at or above which a bioassay or air monitoring results shall be investigated for purposes of confirming intake and assessing dose. (0.1 SALI)

Medical Referral level The level of intake at or above which the medical staff shall be notified. (1 SALI)

Reference levels are in terms of the stochastic ALI (0.05 µCi for Class S U).

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Monthly sampling using ALI from 10CFR20

Level	f SALI	Intake	24-h Urine	24-h Feces
Screening	0.002	0.1 nCi	0.8 pCi	40 pCi
Verification	0.02	1 nCi	8 pCi	400 pCi
Investigation	0.1	5 nCi	40 pCi	2 nCi
Medical	1	50 nCi	400 pCi	20 nCi

The minimum detectable dose concept can be used to support decisions.

- MDD is used to gauge the ability of a given bioassay program to detect an intake of a specific radioactive material
  - Used as an aid in the design of bioassay programs
  - Is not used to assign a dose that may have occurred but was undetected
- A dose that may have occurred but was undetected and is assigned nevertheless is referred to as a missed dose
- MDD can help qualify a “negative” bioassay result.

$$MDD(t) = DCF\frac{MDA}{m(t)}$$

The relationship between the MDD and IL can support or undermine your program.

- The MDD is much less than the IL
  - this is good
- The MDD is more than the IL but below the regulatory limit
  - this is not as good, but still OK
  - might require compensatory actions
- The MDD is above the regulatory limit
  - this is a problem

Bioassay may or may not be conclusive depending on the analyte.

- The routine bioassay program for typical high-energy gamma emitting radionuclides can be used *by itself* to detect doses at the monitoring level
  - This is clearly where you want to be
- The routine bioassay program for some actinides (type S ^{239}Pu) *cannot by itself* be used to detect doses at the monitoring level and, even worse, *cannot by itself* be used to demonstrate compliance with the annual dose limit of 0.05 Sv
  - Take “Defense in Depth” approach
  - Use alternate bioassay methods to lower the MDD

A *defense in depth* approach is useful for radionuclides that are difficult to detect.

- Keep workers and radioactive materials apart
- Have systems in place to tell you when they inadvertently get together
- Invoke special bioassay programs to detect and assess the intake and dose
- A confirmatory monitoring program may act as a last line of defense.

The MDD can be lowered.

- Lower the MDA
  - Mass spectrometry
  - Fission Track
- Increase the IRF
  - Fecal sampling
  - Personal air sampling
  - Shorten the time between the intake and the collection of the sample

$$MDD(t) = DCF\frac{MDA}{m(t)}$$

Personal air sampling can be used to infer dose.

Three parameters required

- Measurement
- Dose coefficient (dose conversion factor)
- Intake retention fraction

Intake retention fraction

- Fraction of intake expected to be present in the "compartment of interest" at the time of measurement.
- The "compartment of interest" can be:
  - Whole-body or fraction (organ/tissue)
  - Excreta (urine or feces)
  - Air sample!

The IRF for an air sampler is related to the flow rate.

$$m(t) = \frac{\textit{Flow Rate}_{\textit{Air Sampler}}}{\textit{Breathing Rate}_{\textit{Reference Man}}}$$

$$\frac{3.5 \text{ l/m}}{20 \text{ l/m}} = 0.175$$

Personal air sampling greatly increases the IRF.

Nuclide	Class	Period (d)	Type	IRF
^{3}H	Vapor	14	Urine (inst.)	9.52×10^{-3}
^{238}U	M	180	Urine (24 hr)	6.42×10^{-5}
^{239}Pu	S	180	Urine (24 hr)	1.60×10^{-7}
^{241}Am	M	180	Urine (24 hr)	1.10×10^{-5}
^{90}Sr	F	180	Urine (24 hr)	4.64×10^{-5}
^{137}Cs	F	365	Whole Body	4.62×10^{-2}
Any	Any	Real Time	PAS	0.175

Minimum detectable doses are typically better for PAS.

Nuclide	Class	Period	Type	MDA	MDD
^{3}H	Vapor	14	Urine (inst)	1000 pCi/l	0.007
^{238}U	M	180	Urine (24hr)	0.1 µg/l	4
^{239}Pu	S	180	Urine (24hr)	0.05 pCi/l	100,000
^{241}Am	M	180	Urine (24hr)	0.05 pCi/l	600
^{90}Sr	F	180	Urine (24hr)	5 pCi/l	20
^{137}Cs	F	365	Whole Body	8.9 nCi	5

Nuclide	Class	Emission	MDD (mrem)
^{238}U	M	alpha	0.02
^{239}Pu	S	alpha	1
^{241}Am	M	alpha	0.3
^{90}Sr	F	beta	0.001
^{137}Cs	F	beta	0.0003

DOE has allowances for using air monitoring data.

(b) The estimation of internal dose shall be based on bioassay data rather than air concentration values unless bioassay data are (10CFR835.209):

1. Unavailable;
2. Inadequate; or
3. Internal dose estimates based on air concentration values are demonstrated to be as or more accurate.

NRC specifically allows for use of air monitoring for internal dosimetry.

(a) For purposes of assessing dose used to determine compliance with occupational dose equivalent limits, the licensee shall, when required under §20.1502, take suitable and timely measurements of (10CFR20.1204):

1. Concentrations of radioactive materials in air in work areas; or
2. Quantities of radionuclides in the body; or
3. Quantities of radionuclides excreted from the body; or
4. Combinations of these measurements.

Outline

Concepts and Models

Program Development and Elements

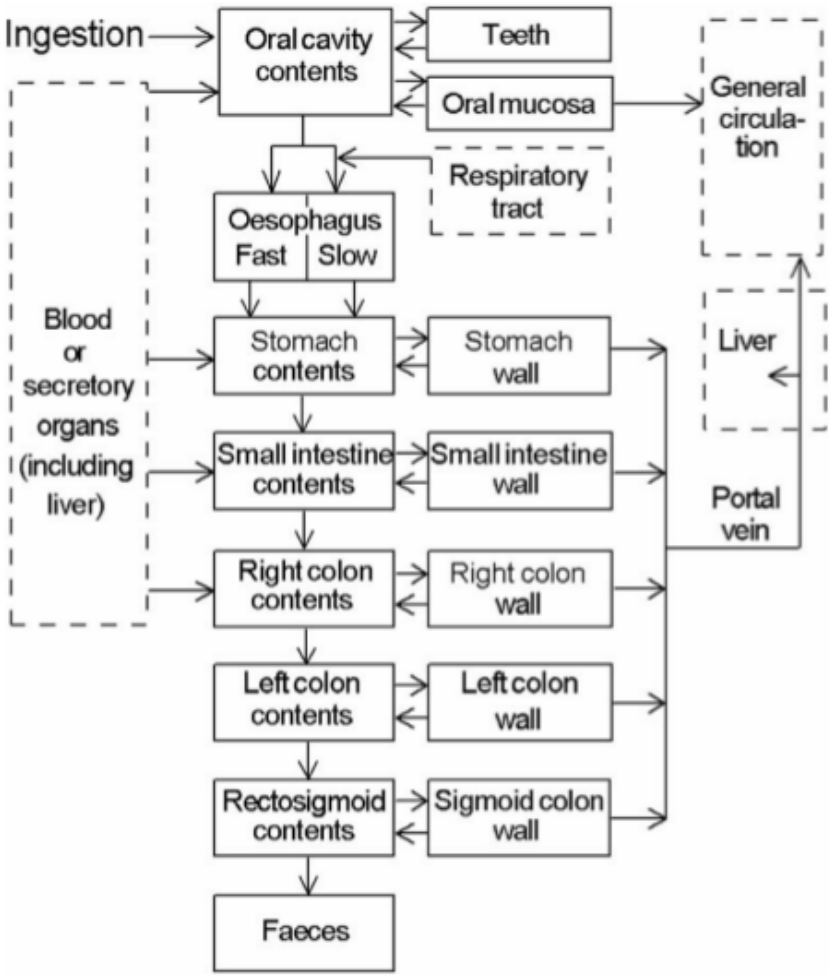
Data to Intake to Dose

Other Programmatic Considerations

New ICRP Models

Summary

ICRP Publication 100 (2006) introduced an updated *Human Alimentary Tract Model for Radiological Protection*



Differences from ICRP-30

- Entry moved from stomach to oral cavity
- Three regions of large intestine
- Radionuclide retention in alimentary tissue
- Absorption in areas other than small intestine
- Age and gender-specific transit times

The 2007 Recommendations of the ICRP, ICRP

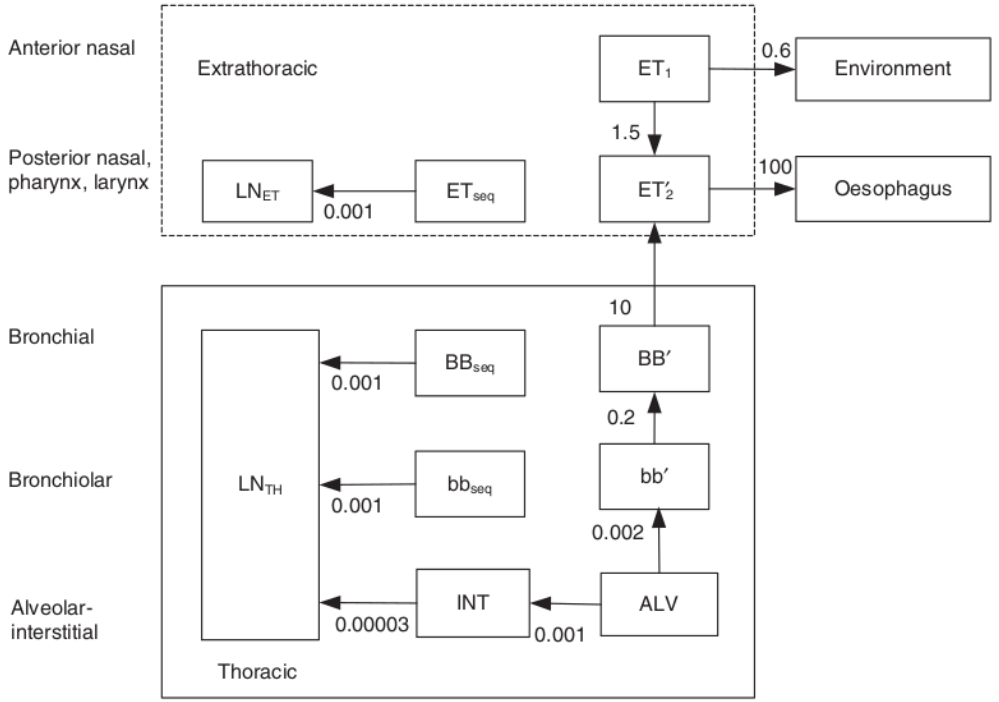
Publication 103 provided updated tissue weighting factors

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

Organ or tissue	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30

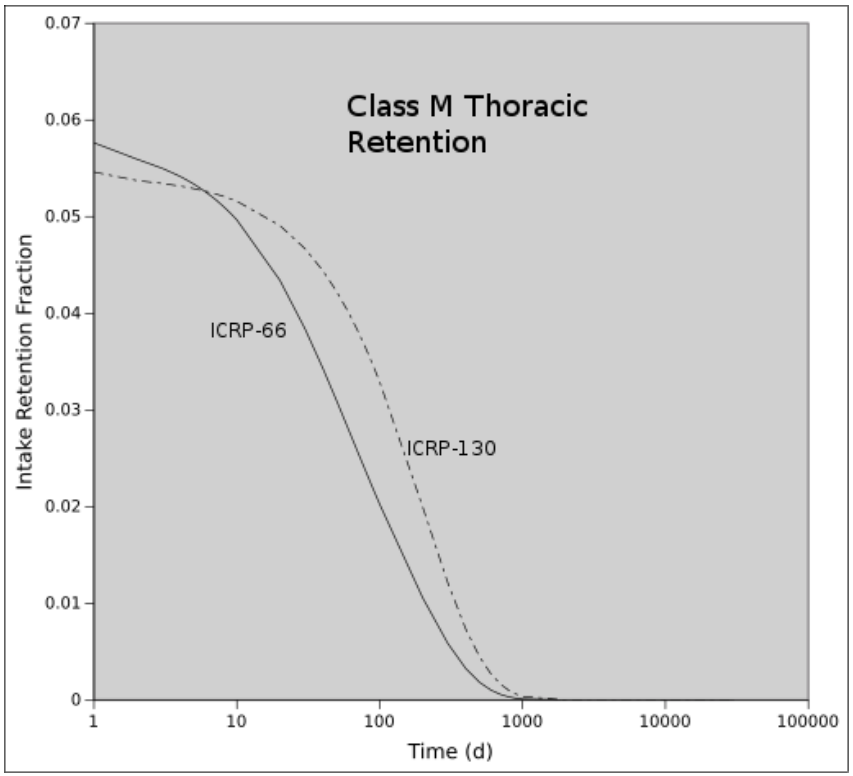
Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05[2,3]

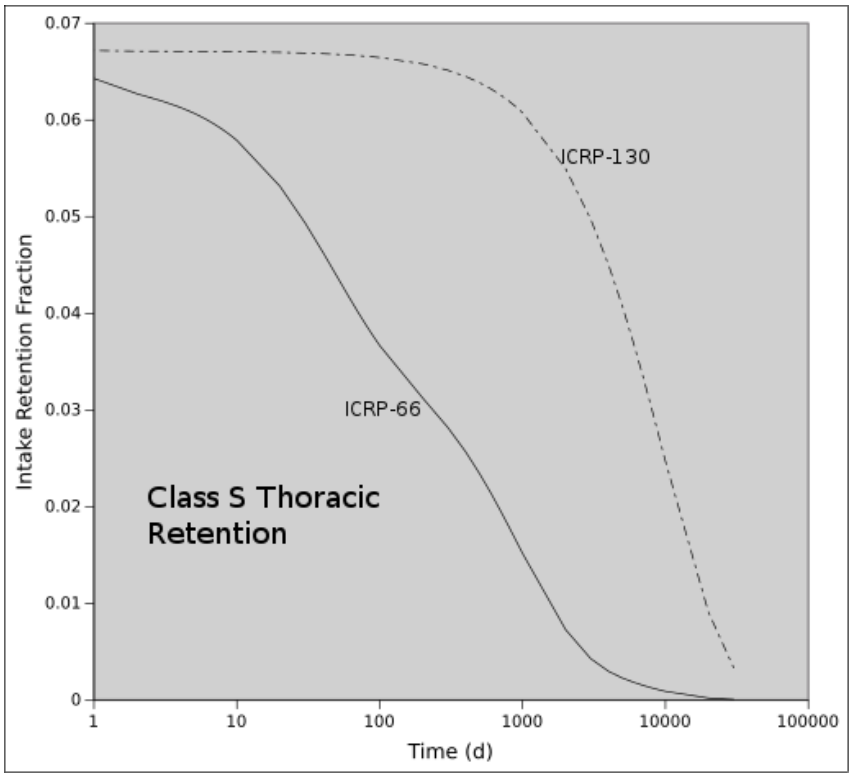
ICRP-130, *Occupational Intakes of Radionuclides: Part 1* promises more changes to come.



Type		F (fast)	M (moderate)	S (slow)
Fraction dissolved rapidly	f_r	1	0.2	0.01
Dissolution rates:				
Rapid (d^{-1})	s_r	30‡	3§	3§
Slow (d^{-1})	s_s	–	0.005	0.0001

Retention in thoracic lung increases under new lung parameters





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Summary

Requirements and Recommendations

- Recommendation organizations include ICRP, NCRP, and HPS (ANSI).
- There are a lot of recommendations, so you need to pick and choose what makes sense for your program.
- In the US, the DOE and NRC set the regulations.
- Both DOE and NRC provide guidance (although NRC has more).

Program Elements

- Radiation protection program infrastructure is an important part of the internal dosimetry program.
- There are requirements for when programs must exist.
- HPS ANSI N13.39 is a good place to start.

Summary

Bioassay monitoring programs

- Program types include:
  - Routine
  - Confirmatory
  - Special
  - Operational
- Baseline samples should be considered.
- Termination sampling may be required.

Who should be monitored?

- This isn't necessarily an easy question to answer.
- Workplace indications are an important part of this decision.
- You probably don't want to over-monitor.
- Don't forget the dreaded "likelihood."

Summary

MDA vs. DL

- MDA tells you about your analysis capability.
- DL tells you about a specific sample.
- Make sure you know the difference.
- You can calculate them any way you want.

Summary

Reference Levels

- Clear recommendations are found in HPS ANSI N13.39.
- They provide indicators of what to do next once you've decided a sample contains activity.
- They may include:
  - Screening
  - Verification
  - Investigation
  - Medical referral

Summary

Intake and dose assessment

- We are protecting the worker from deterministic and stochastic effects.
- Committed and effective concepts both make some sense from an operational perspective.
- Workplace indicators of intake are helpful and probably necessary.
- Know your missed dose (minimum detectable dose).

Summary

Personal air sampling

- Personal air sampling can be useful, especially where bioassay won't do the job.
- Intake is easy to calculate.
- You don't need a minimum sample volume since you're not calculating airborne concentration.
- It's allowed by NRC and under certain circumstances by DOE.

The last (and first) word:

- The only way internal dosimetry actually helps anybody, is by detecting workplace control failures that were otherwise undetected.
- Being able to get a good estimate of dose may play an important role in medical treatment of severely overexposed individuals.
- Scorekeeping is required.