Steven L. Simon, Ph.D.
Head, Dosimetry Unit, DCEG

Occupational Dosimetry and Uncertainties in Doses

Radiation Epidemiology & Dosimetry Course

National Cancer Institute www.dceg.cancer.gov/RadEpiCourse

Occupational dosimetry is usually discussed in the context of **operational radiation protection**, however, this discussion is limited to the context of **radiation epidemiology**.

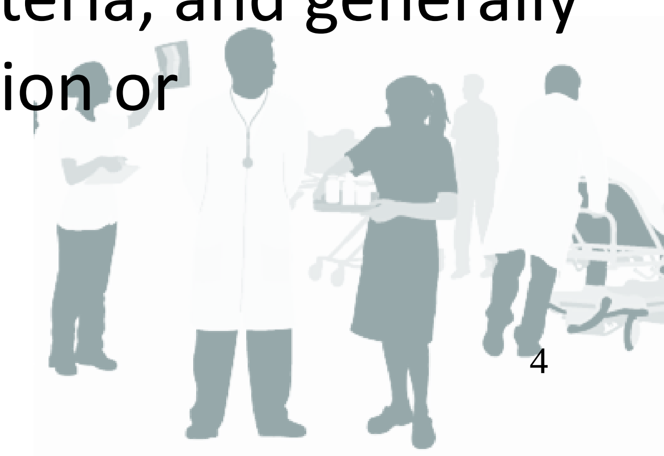
Outline of Today's Presentation

1. What is occupational exposure?
2. Review of dose units (occupational vs. dose reconstruction)
3. Occupationally exposed populations…Who are they?...What are representative doses for current occupations?
4. Who regulates occupational exposure to radiation in the U.S.?
5. Occupational dose limits
6. Limitations of dose monitoring records for estimating occupational exposures
7. Strategies for occupational dose estimation with emphasis on historical estimation
8. Uncertainty in occupational doses
9. Concluding points

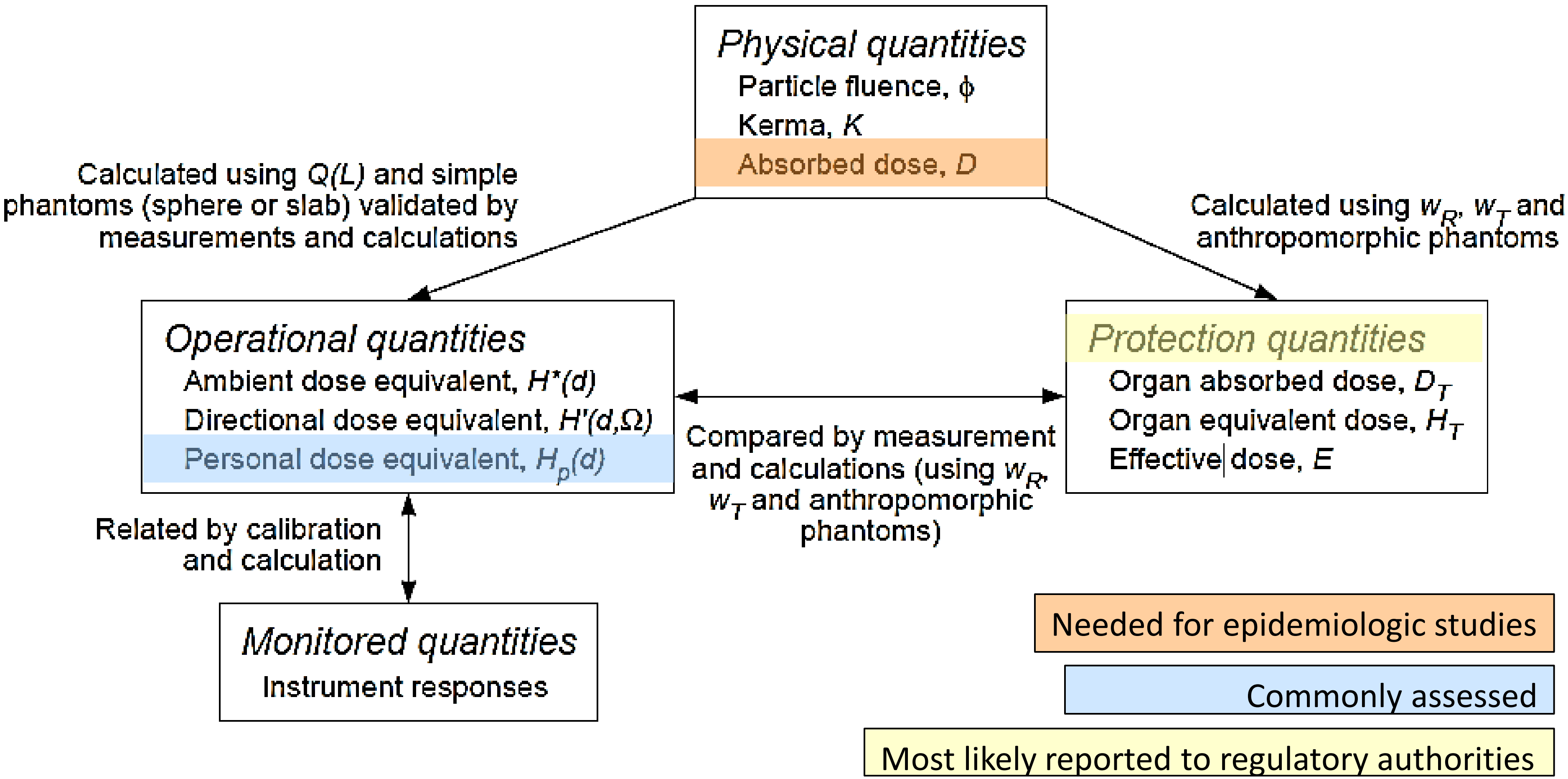
Occupational Exposure: *What is it?*

The term ***occupational exposure*** refers to any exposure that occurs as a result or condition of a person's employment.

Those working radiation epidemiology must be mindful that the intent of worker radiation dose monitoring programs is to support **compliance** with statutory or facility-specific dose limits or other criteria, and generally ***not*** for retrospective dose reconstruction or epidemiology.



Review of Dose Units



Relationship of quantities for radiological protection purposes
(IAEA SAFETY GUIDE No. RS-G-1.3 1999.)

Occupationally Exposed Populations

Who are they?

Occupational Categories Exposed to Radiation (1/2)

Medical radiation practitioners (Radiology, Dentistry, Vet med)

Nuclear energy workers (fuel production, reactor operations and emergency)

Industrial applications (radiographers and welders)

Occupational Categories Exposed to Radiation (2/2)

Research

Mining

Military

High-altitude

Civilian aviation

Astronauts

How many people receive occupational radiation exposures?

According to Frachette (2007)*:

• United States, 1.5 million radiation workers with 300,000 employed in the commercial nuclear power industry.

•Canada, whose population is one tenth that of the United States, >550,000 radiation workers in more than 80 occupations (commercial nuclear-power, academic research, food processing, industrial imaging, weld-defect inspection, leak tracing, automobile-steel testing, mineral-deposits activities).

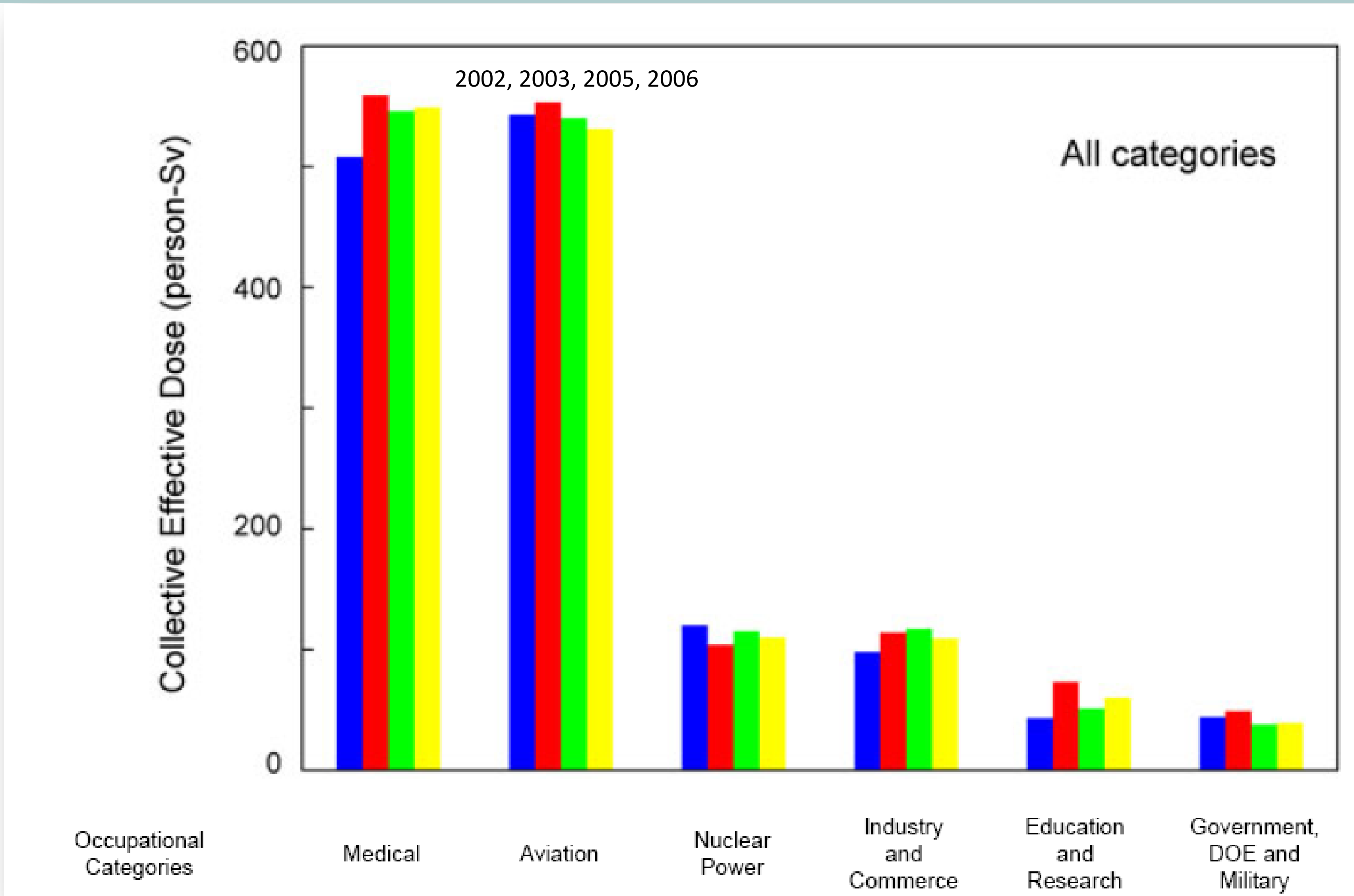
• Switzerland, radiation workers number 60,000;

• South Korea, 65,000.

According to NCRP Report 160 (2009): 3.8 million monitored workers in the U.S. across occupations of Medical, Aviation, Nuclear Power, Industry, Education/Research, and Government/Military: 1,400 person-Sv, average effective dose = 1.14 mSv (2006),

Data: Frachette, K. Am J Public Health. 97(10), 2007

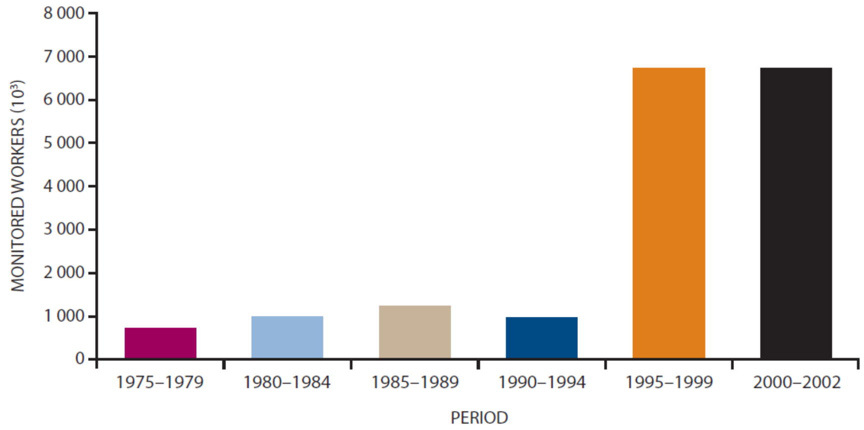
Annual Collective Effective Dose for Occupation Categories

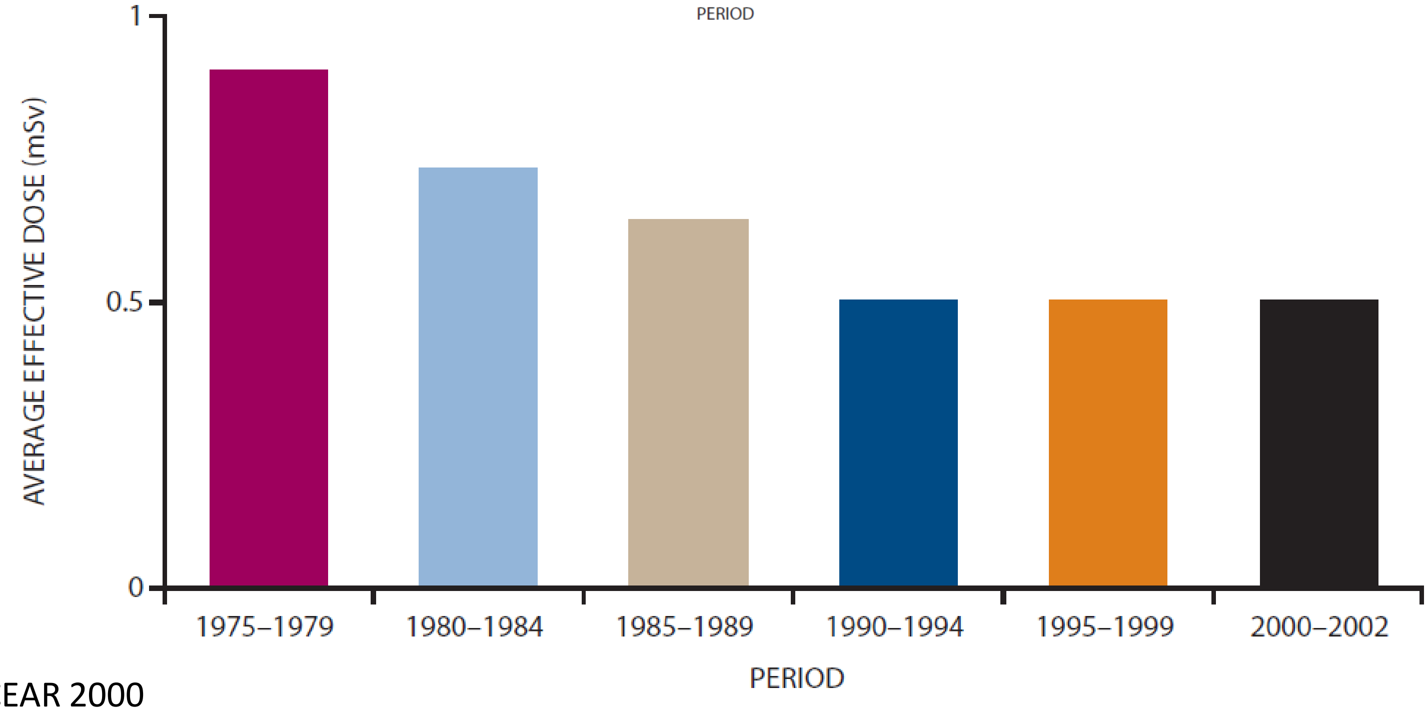


Source: NCRP Report 160, 2009

Occupational Exposure in Diagnostic Medicine

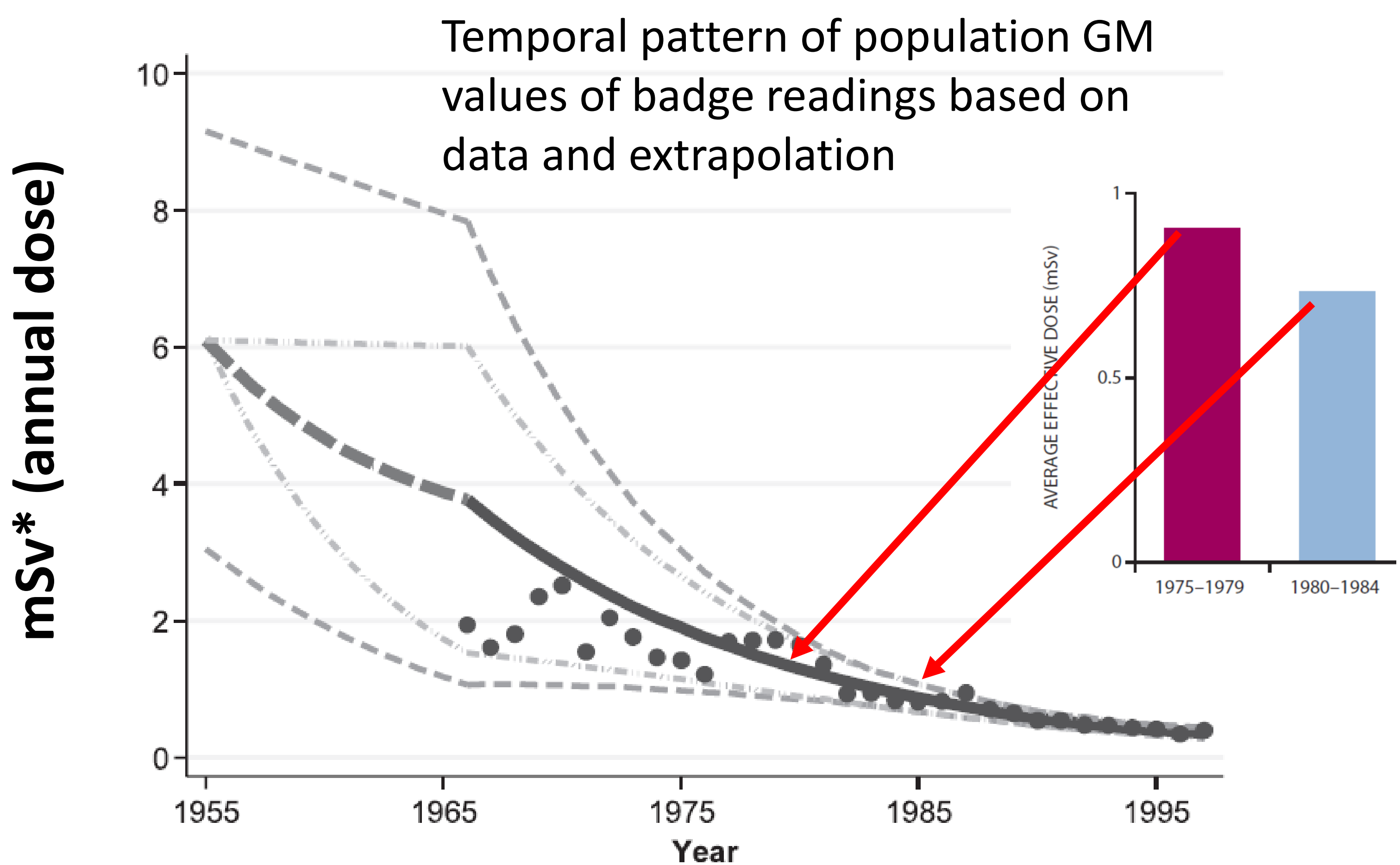
25 years of data on occupational dose from diagnostic radiology





Source: UNSCEAR 2000

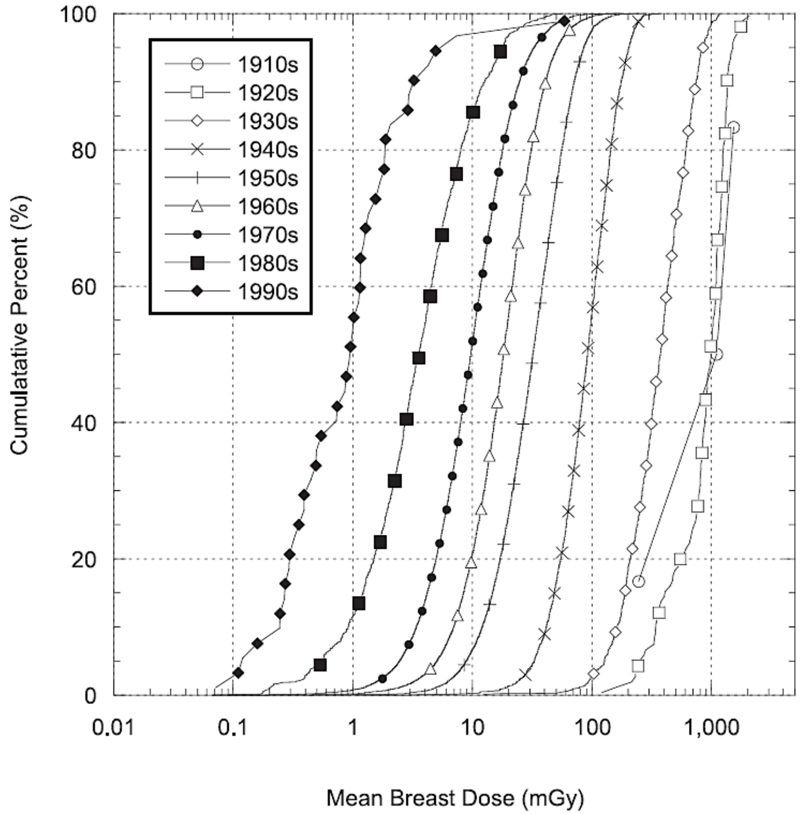
Historical occupational exposure by radiologic technologists – USRT Study

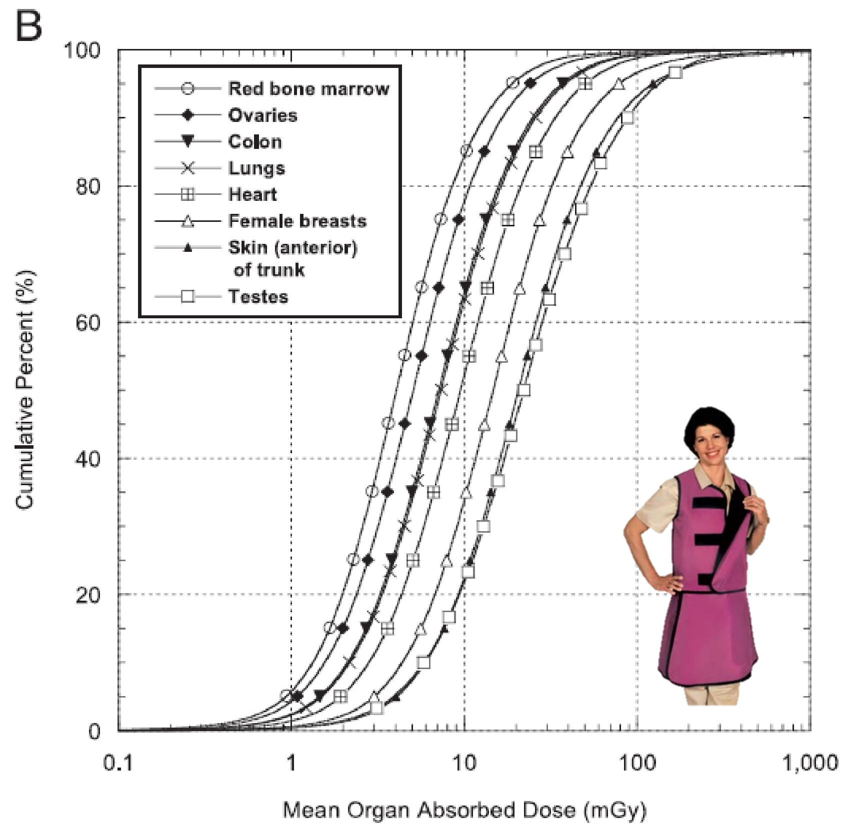


*personal dose equivalent, $H_p(10)$

Source: Simon et al. 2015

Occupational Dose Reconstruction for Radiologic Technologists – USRT Study



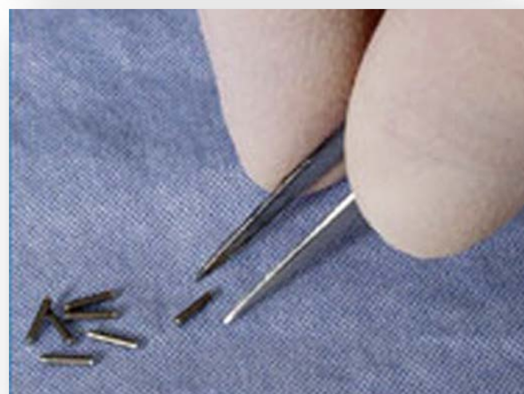


Source: Simon et al. 2015, Radiation Res

Occupational Exposure for Therapeutic Medicine

Interventional radiology and cardiology

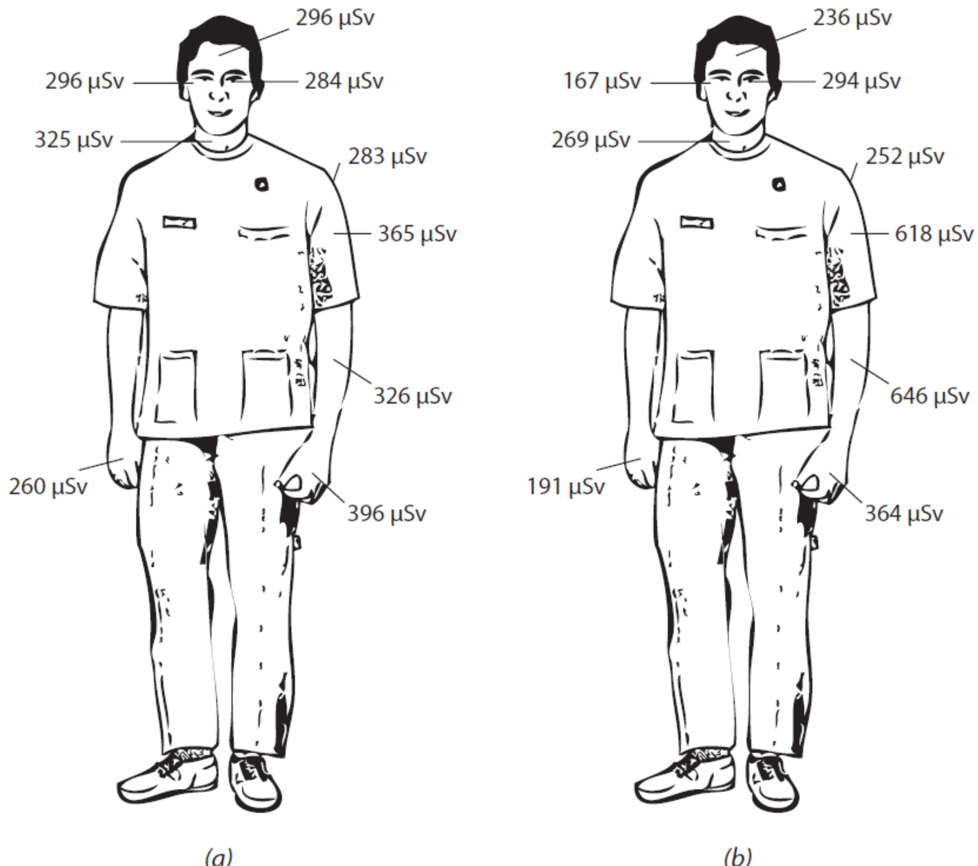
Brachytherapy



Nuclear Medicine (therapeutic)

Occupational Exposure for Therapeutic Medicine

Note: 1000 µSv = 1 mSv

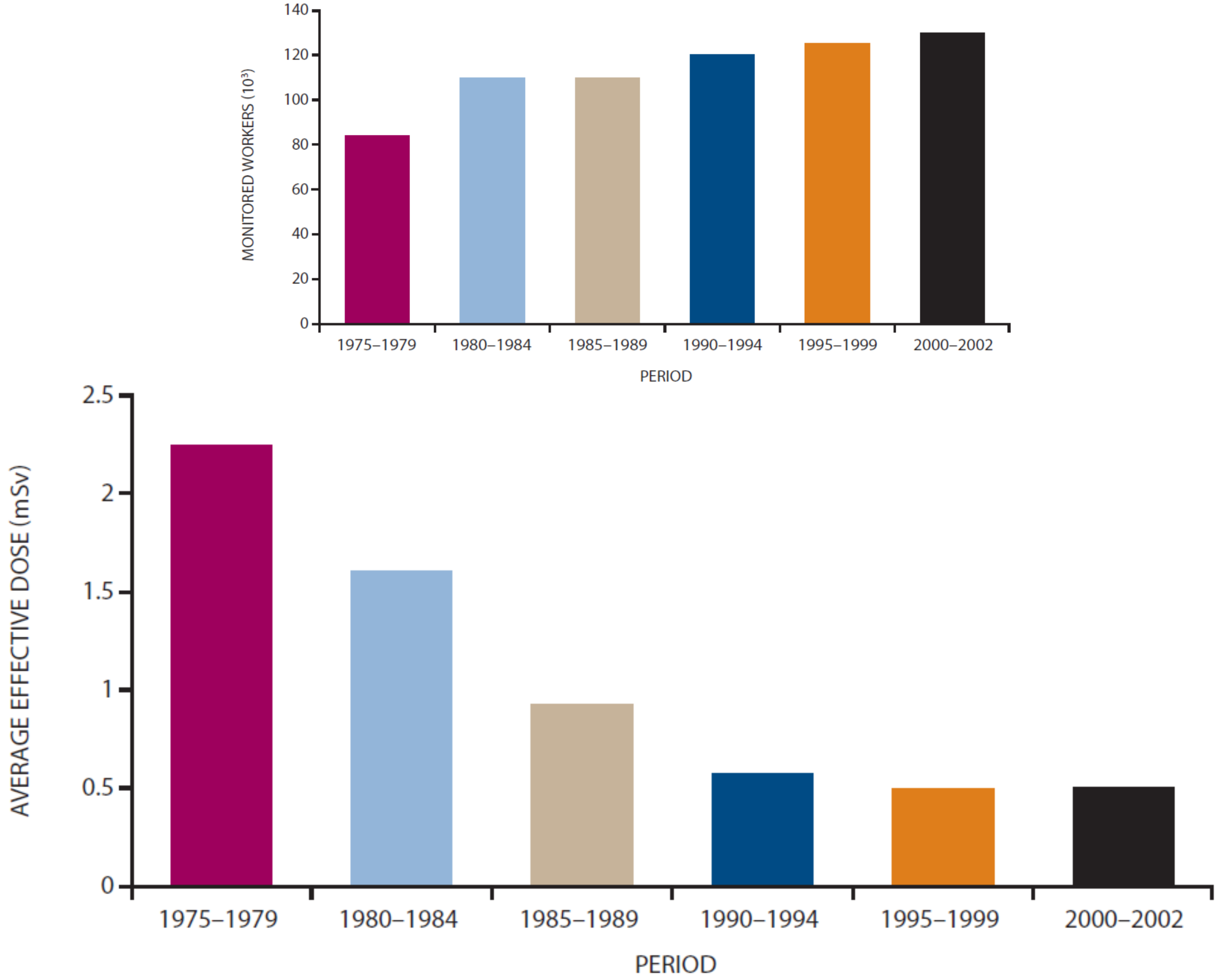


Interventional radiologist Interventional cardiologist

Per procedure dose (average of 83 procedures by 10 specialists in 6 facilities)

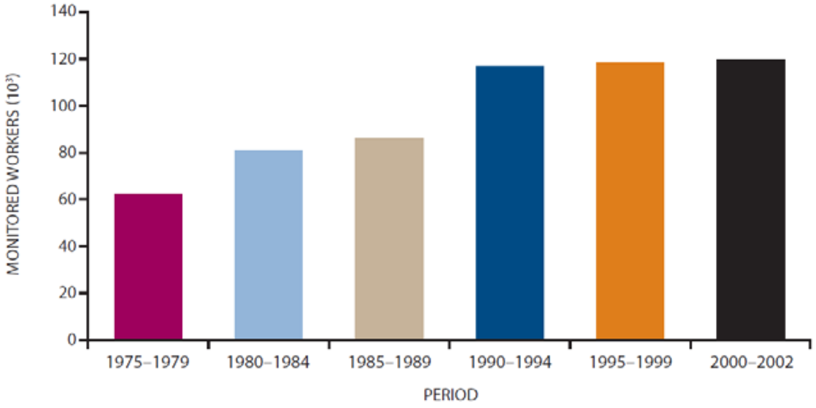
Source: UNSCEAR 2000, Vano et al., 1998

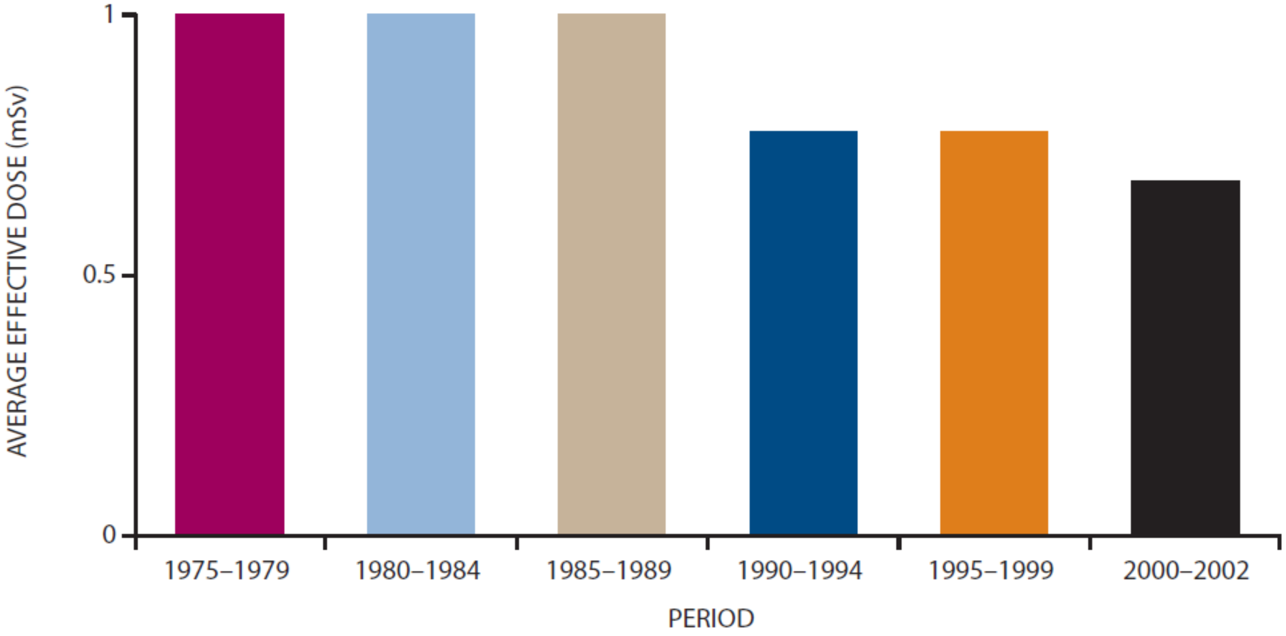
25 years of data on occupational dose from radiotherapy



Source: UNSCEAR 2000

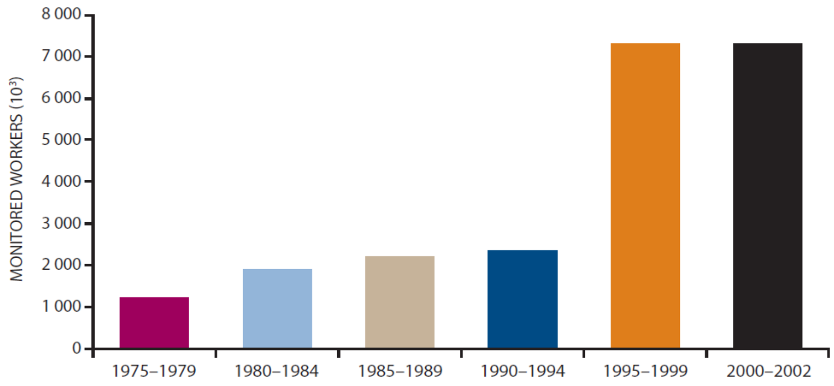
25 years of data on occupational dose from nuclear medicine

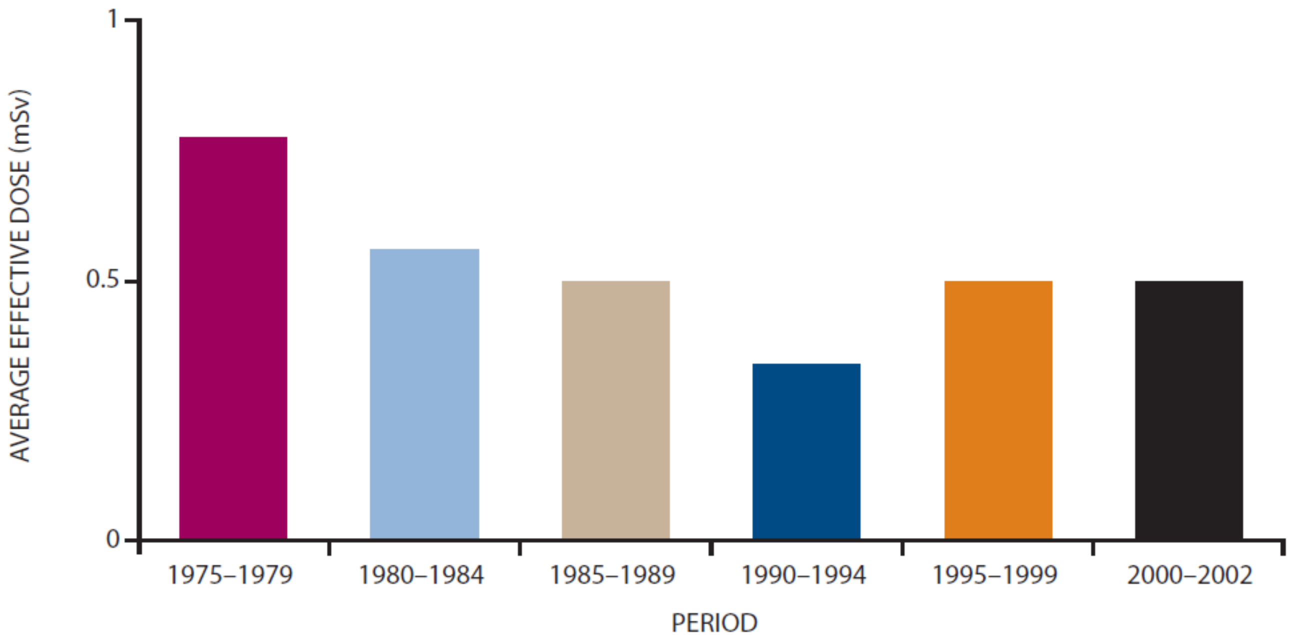




Source: UNSCEAR 2000

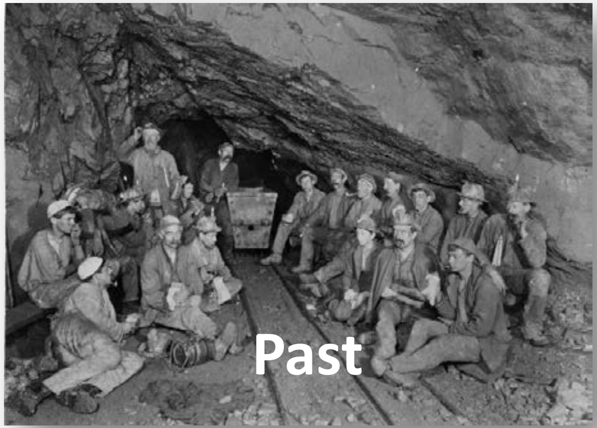
25 years of data on occupational dose – all types of medicine



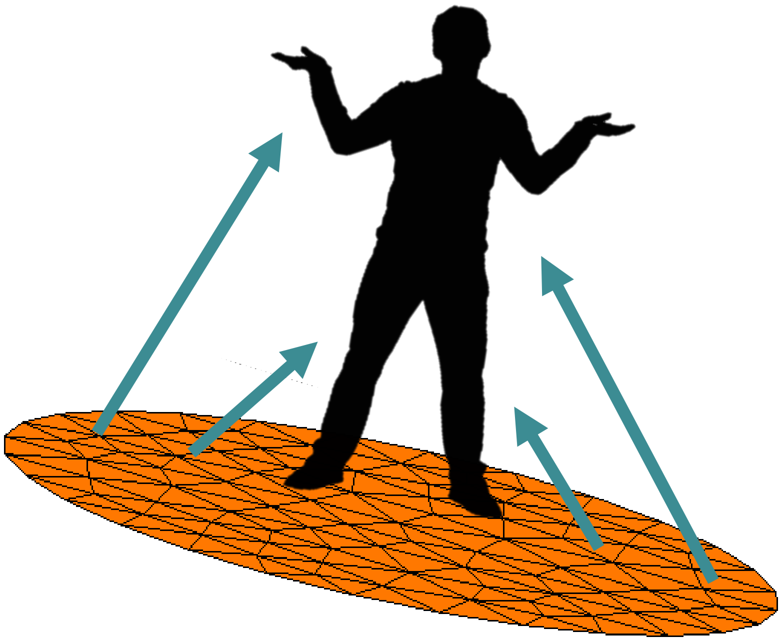


Source: UNSCEAR 2000

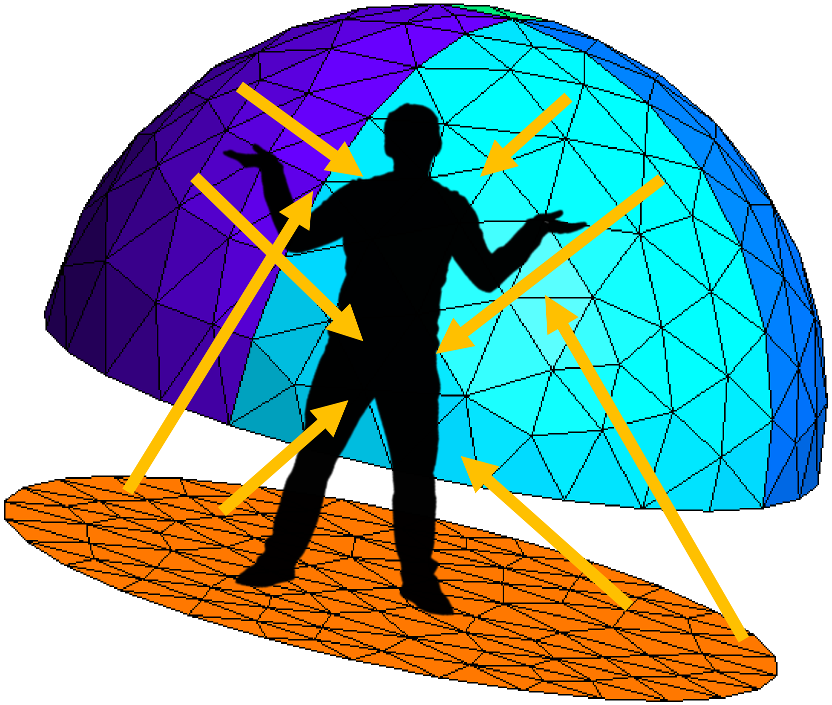
Occupational Exposure in Underground Mining



Occupational (Gamma Ray) Exposure in Underground Mines

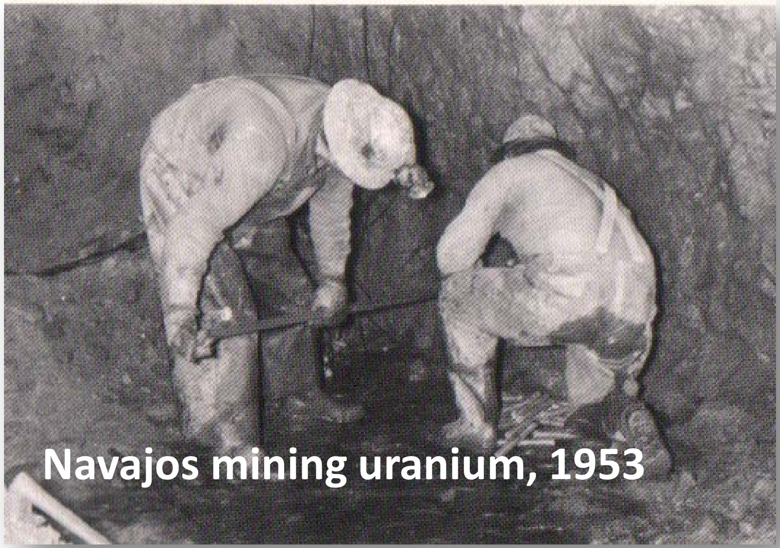


Planar radiation source

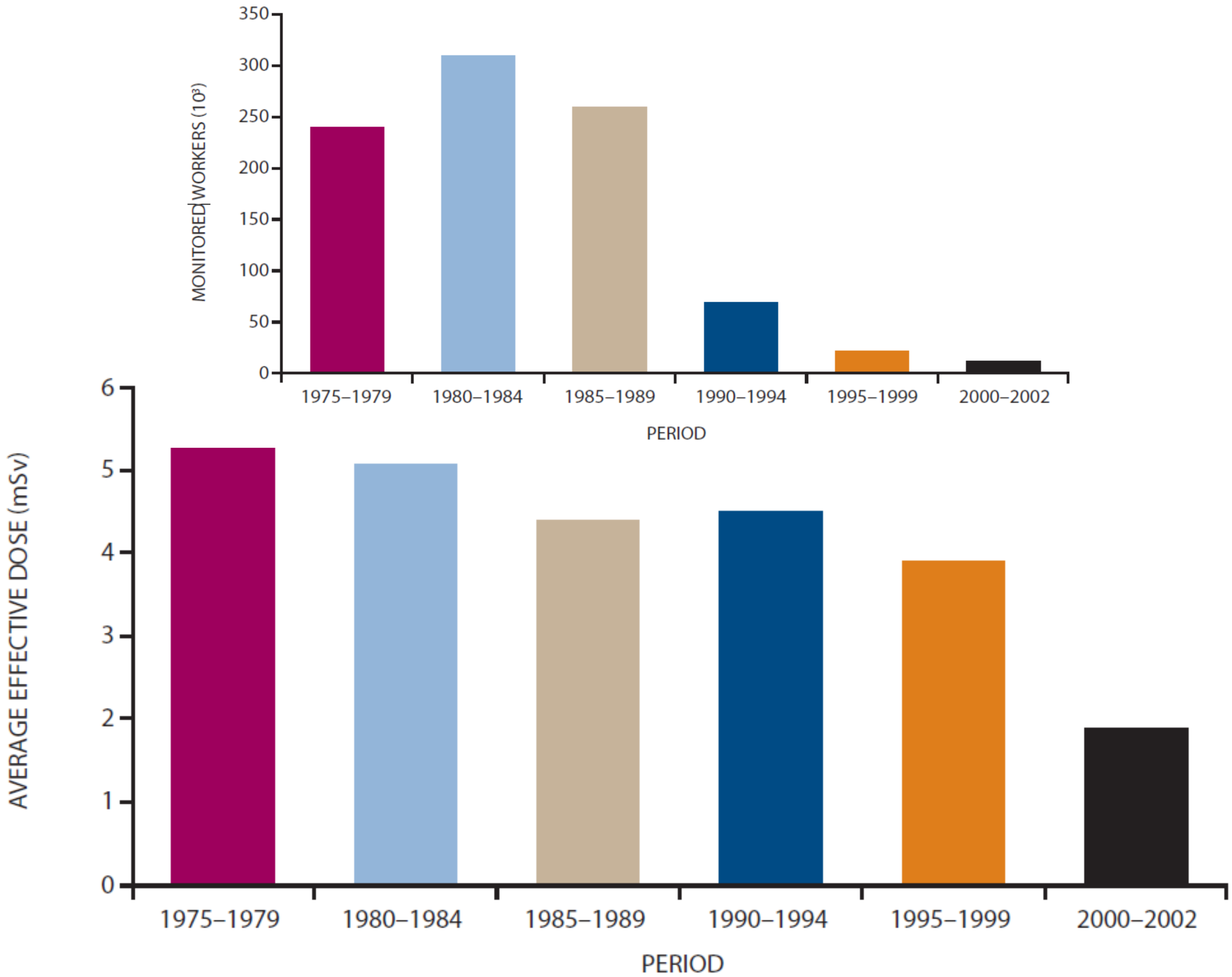


Source of natural gamma radiation exposure surrounds you in underground mine + dust + Rn-222. Gamma background is likely enhanced due to mineral content of bedrock.

Occupational Exposure in Uranium Mining



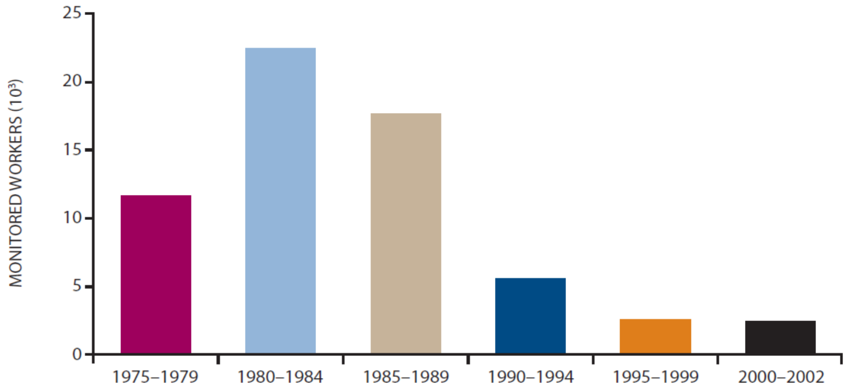
25 years of data on occupational dose from uranium mining

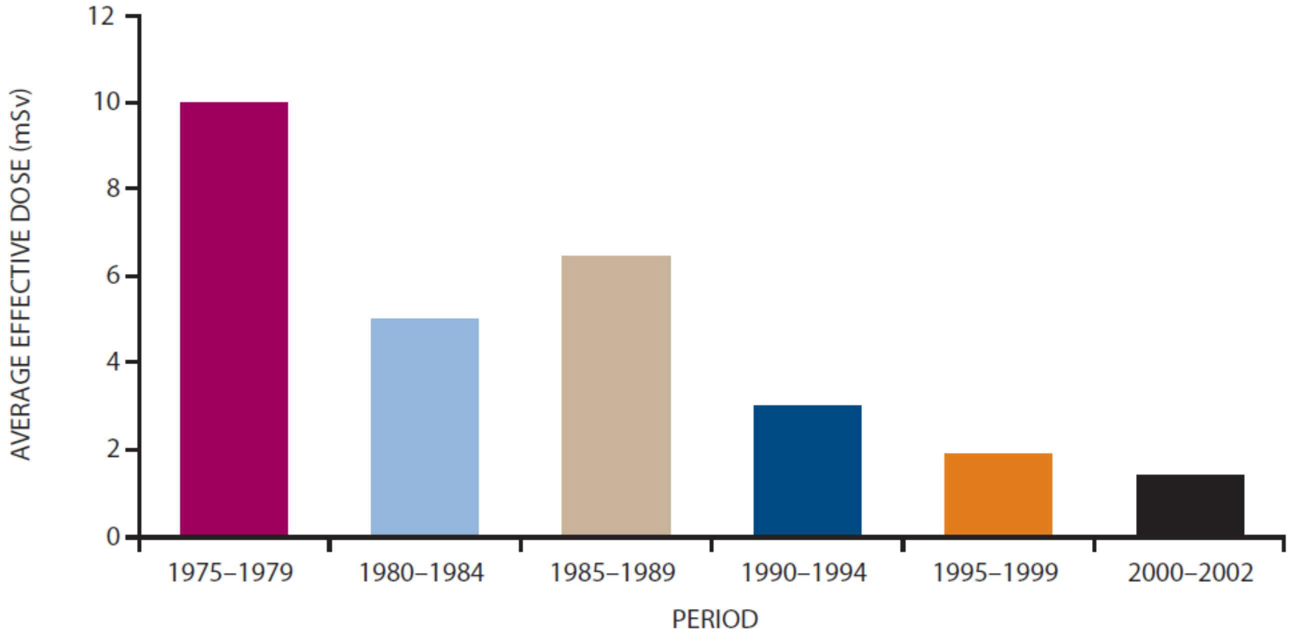


Source: UNSCEAR 2000

Occupational Exposure in Uranium Milling

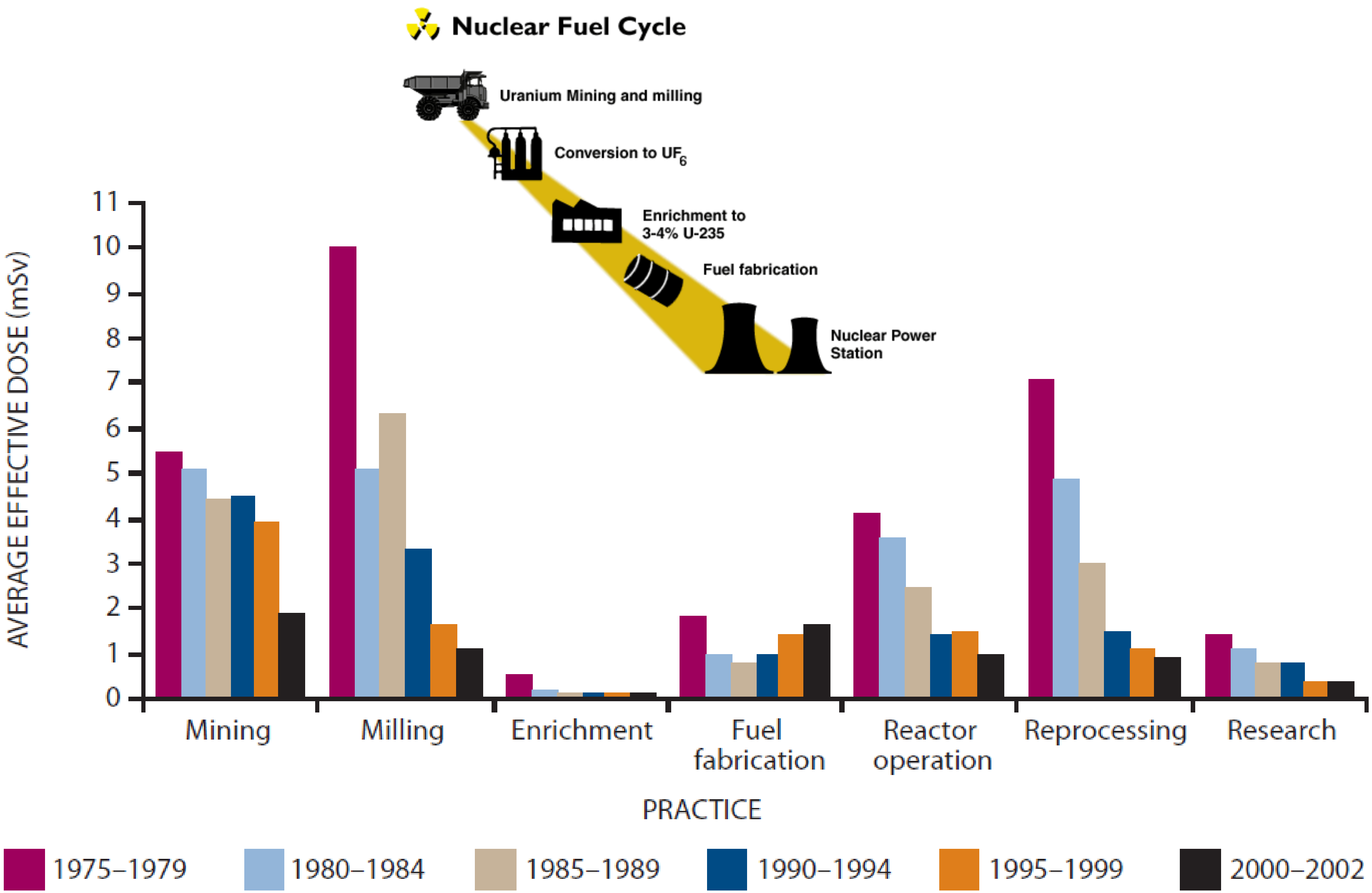
25 years of data on occupational dose from uranium milling





Source: UNSCEAR 2000

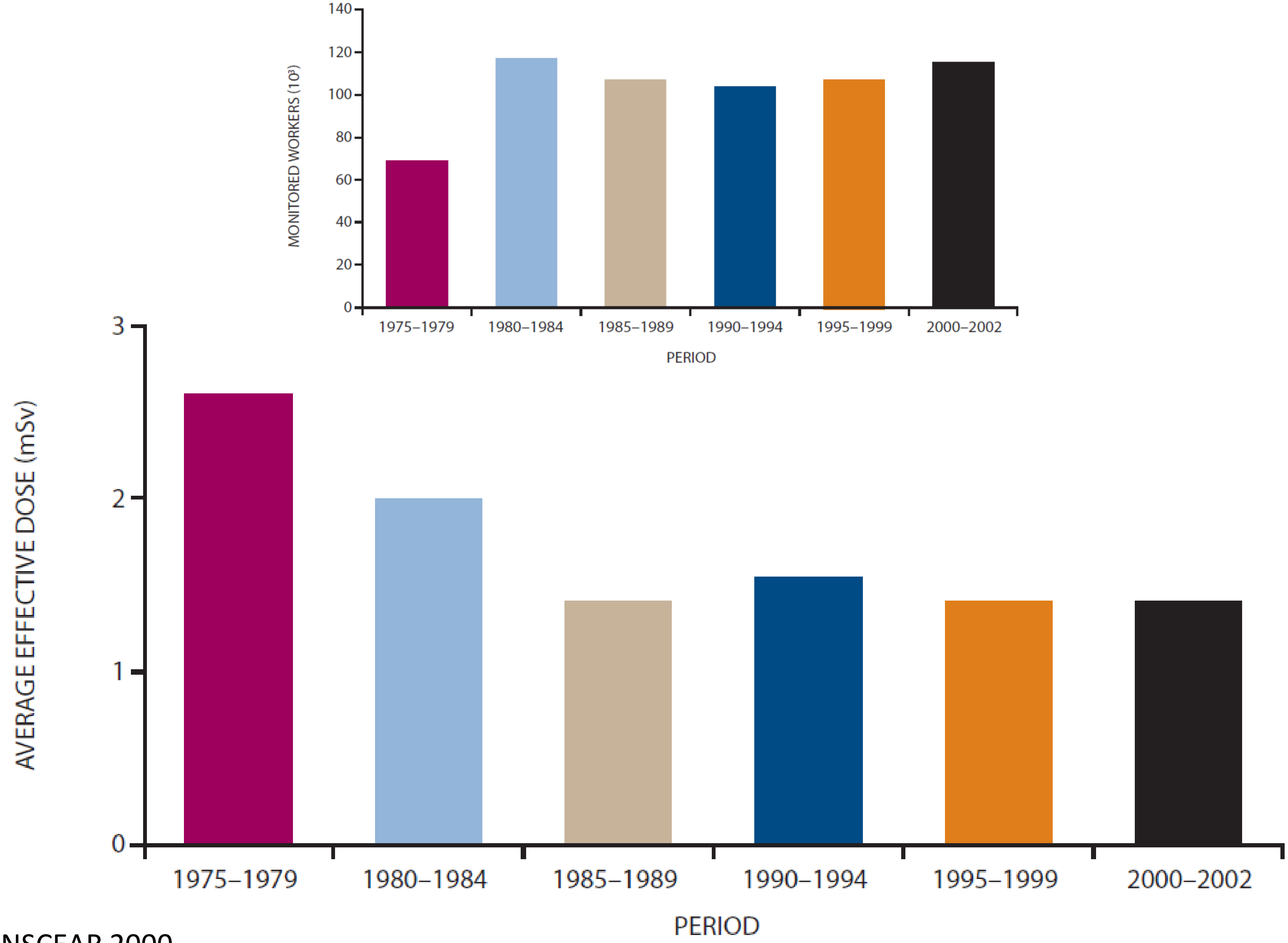
25 years of data on occupational dose from complete nuclear fuel cycle



Source: UNSCEAR 2000

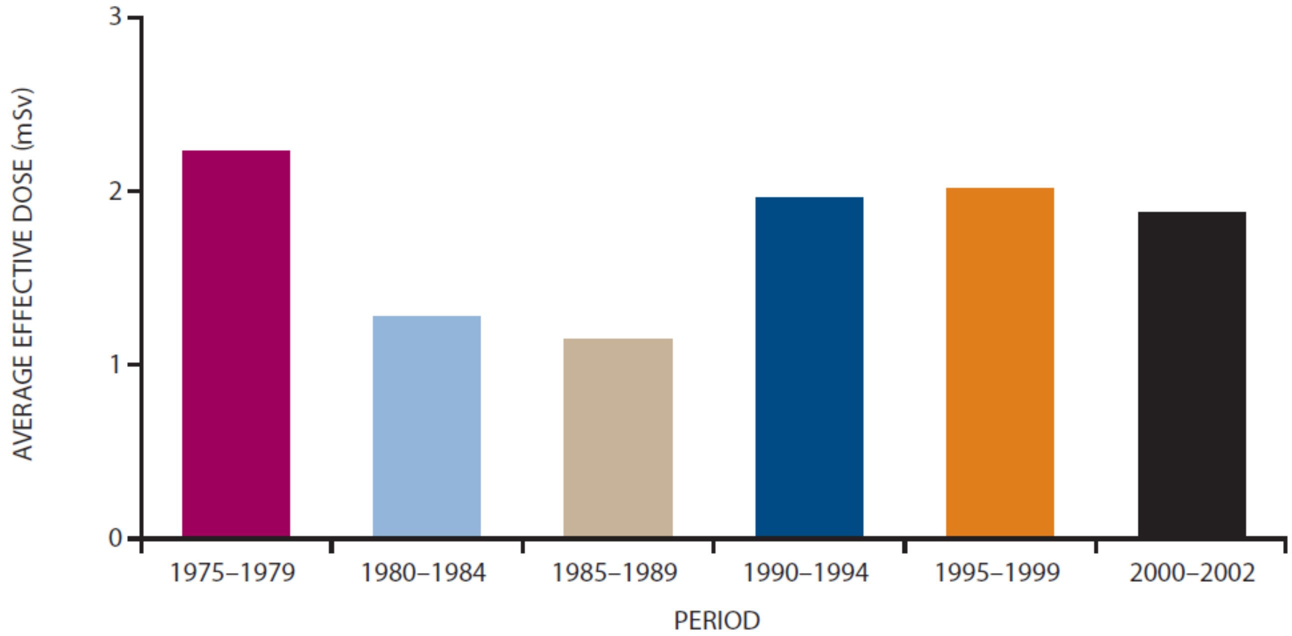
Occupational Exposure in Industry

Occupational Exposure in Industrial Radiography



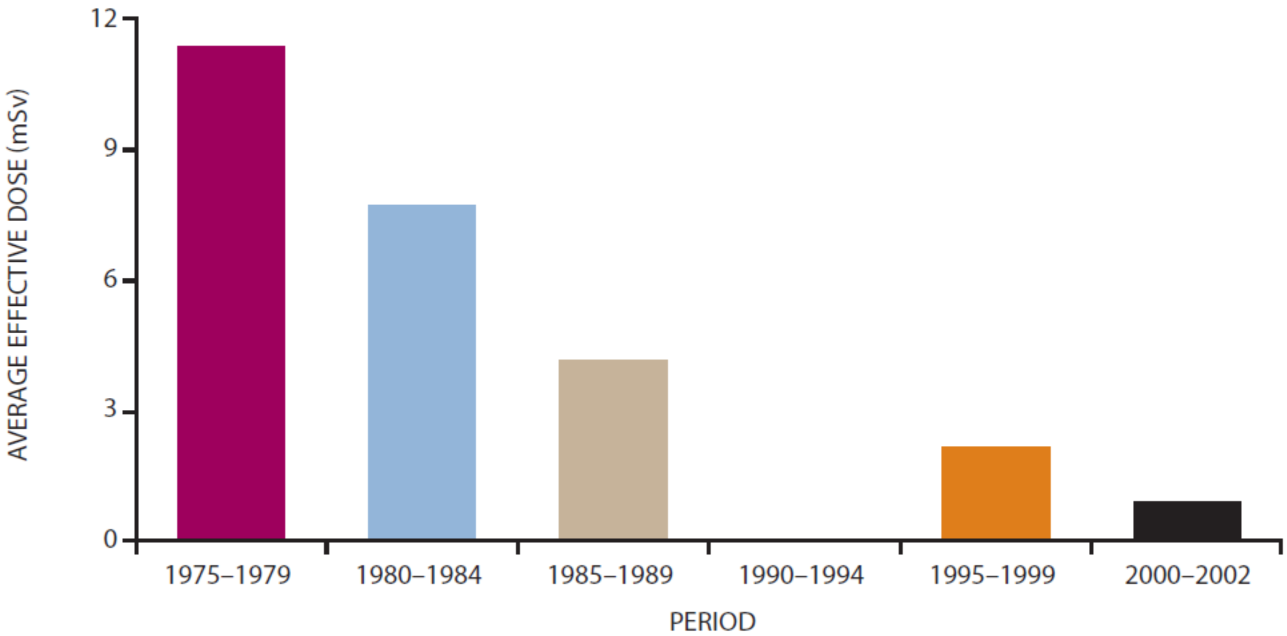
Source: UNSCEAR 2000

Occupational Exposure in Radioisotope Production



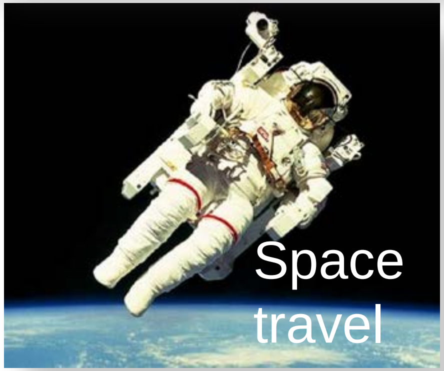
Source: UNSCEAR 2000

Occupational Exposure in Luminizing Industry in Switzerland



Source: UNSCEAR 2000

Occupational Exposure in Commercial and Military Air Travel and Space Research



Occupational exposure of aircrews (the forgotten radiation worker?)

Country	Number of workers	Collective Dose (person-Sv)	Average annual effective dose (mSv)
United States	**150,000**	**~ 30 to 750**	**0.2 – 5**
United Kingdom	40,000	80	2.0
Germany	31,000	60	2.0
Netherlands	12,500	17	1.3

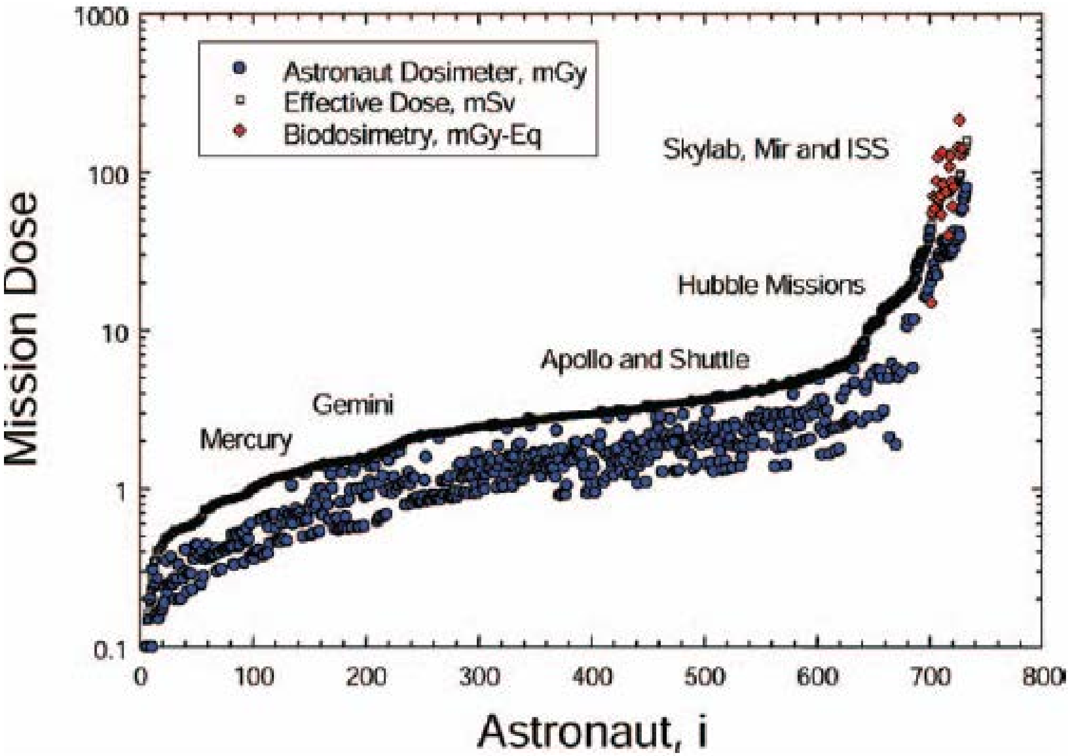
Source: UNSCEAR (2008)

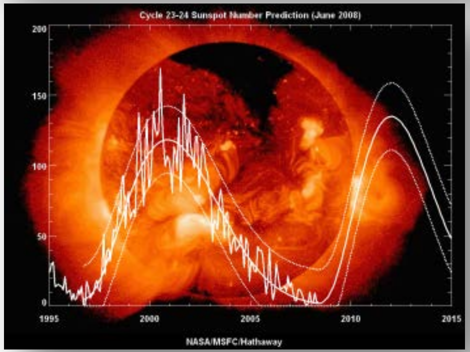
ASTRONAUTS: An occupation with many risks (besides radiation)

As of mid-2011, 529 people qualify as having reached space, above 50 miles (80 km) altitude.

Space travelers have spent over 30,400 man-days (83 man-years) in space, including over 100 astronaut-days of spacewalks.

Longest cumulative time in space by a man or woman was 803 days and 377 days, respectively.

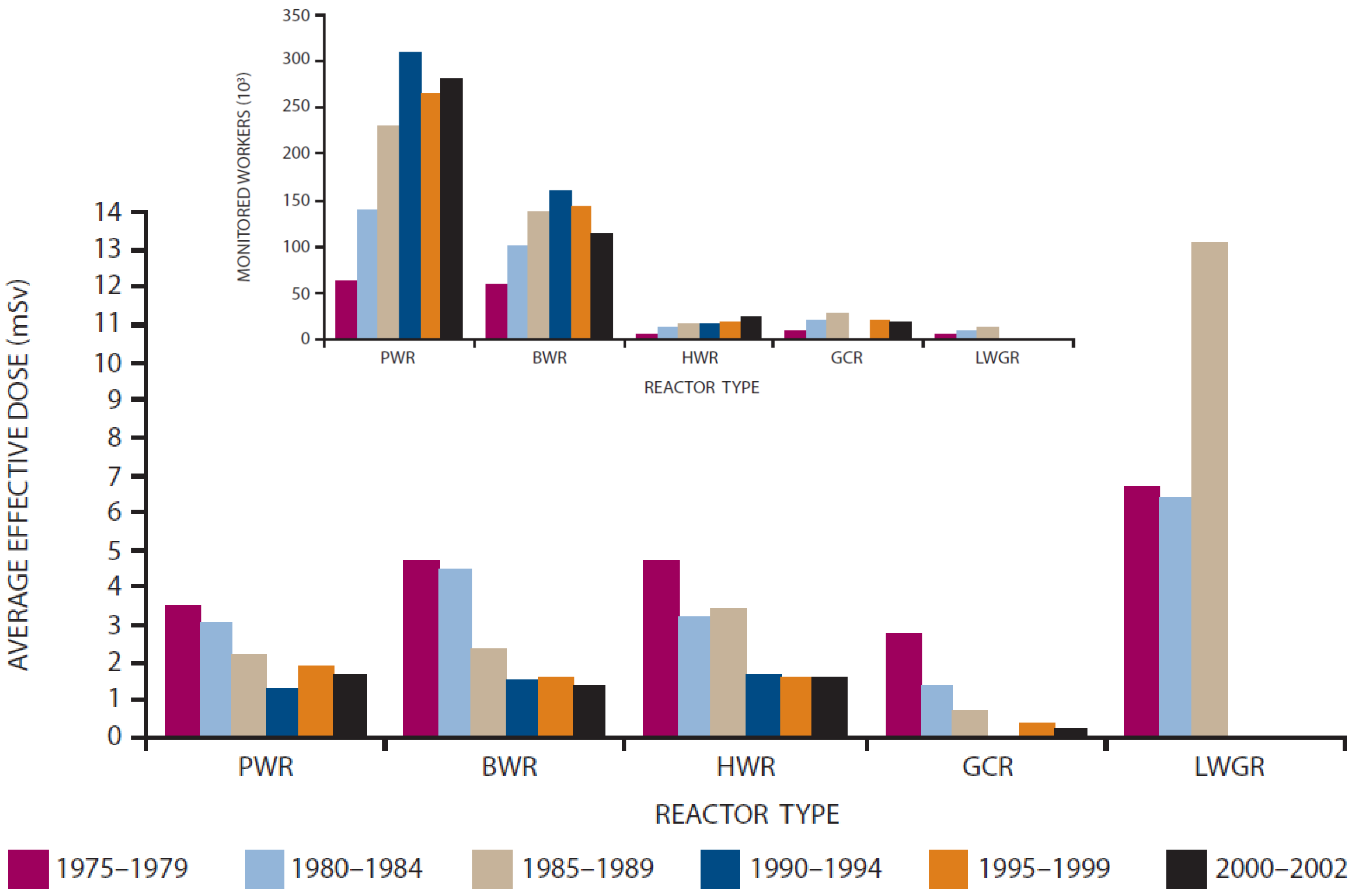




Data from Cucinotta et al. Radiation Research 2008

Occupational Exposure in Normal Reactor Operations

Occupational Exposure in Reactor Operations



Source: UNSCEAR 2000

Occupational Exposure in Reactor & Industrial Accidents

Occupational exposure of reactor clean-up workers

	Fukushima	Chernobyl
Number of workers	6,800	86,000
Period of work	March-July 2011	April-December 1986
Mean dose (mSv) due to		
- external irradiation	9	100
- internal irradiation	5	210 (thyroid dose (mGy) due to ^{131}I intakes in 620 early liquidators)
Number of workers with external doses:		
100-250 mSv	105	32,500
250+ mSv	6	15,300

Occupational Exposure in the Military

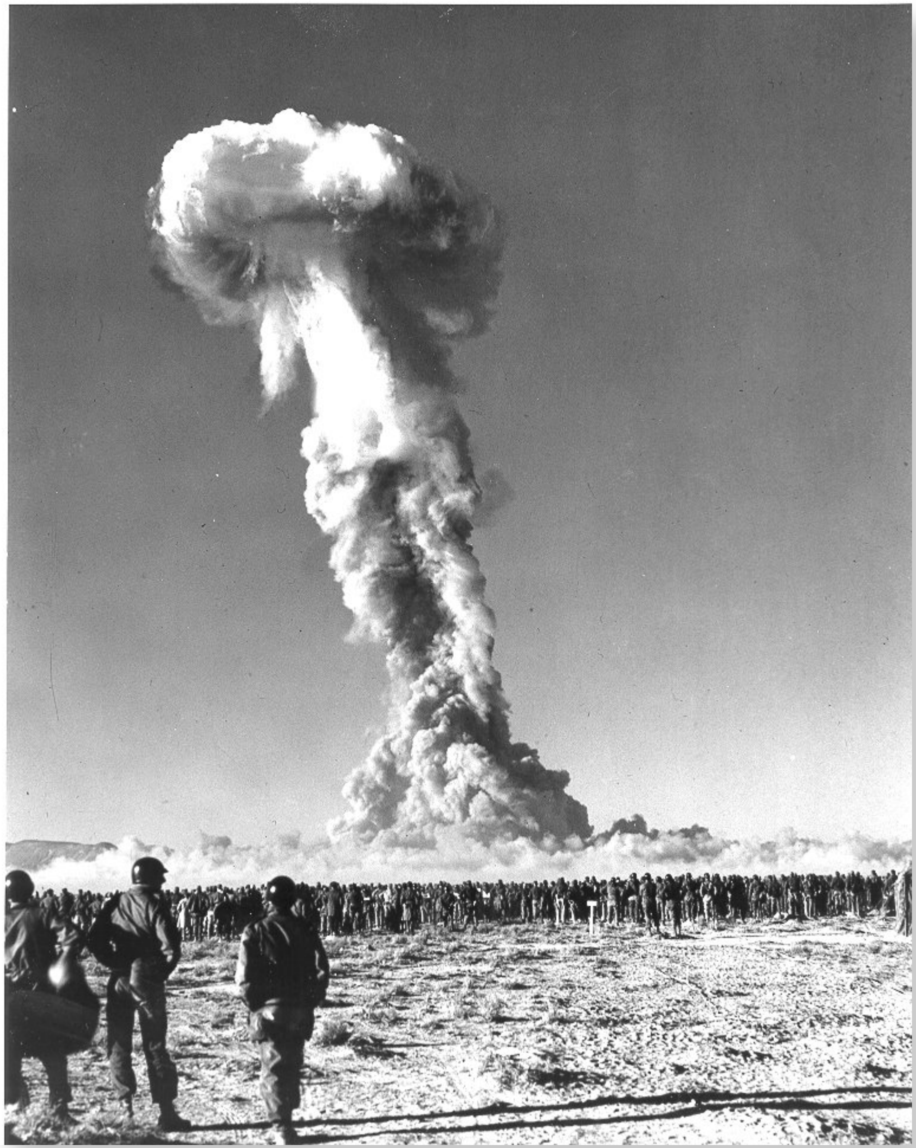
Atomic veterans: Who are they?

- US military who were potentially exposed to ionizing radiation while stationed in Hiroshima and Nagasaki during the American occupation of Japan before 1946,

- US military took part in atmos-pheric nuclear tests (1945-1962) in the U.S. and the Pacific.

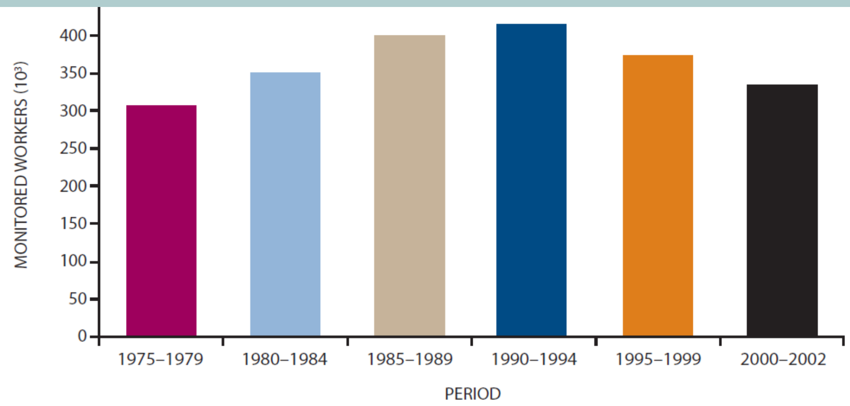
- Number more than 125,000.

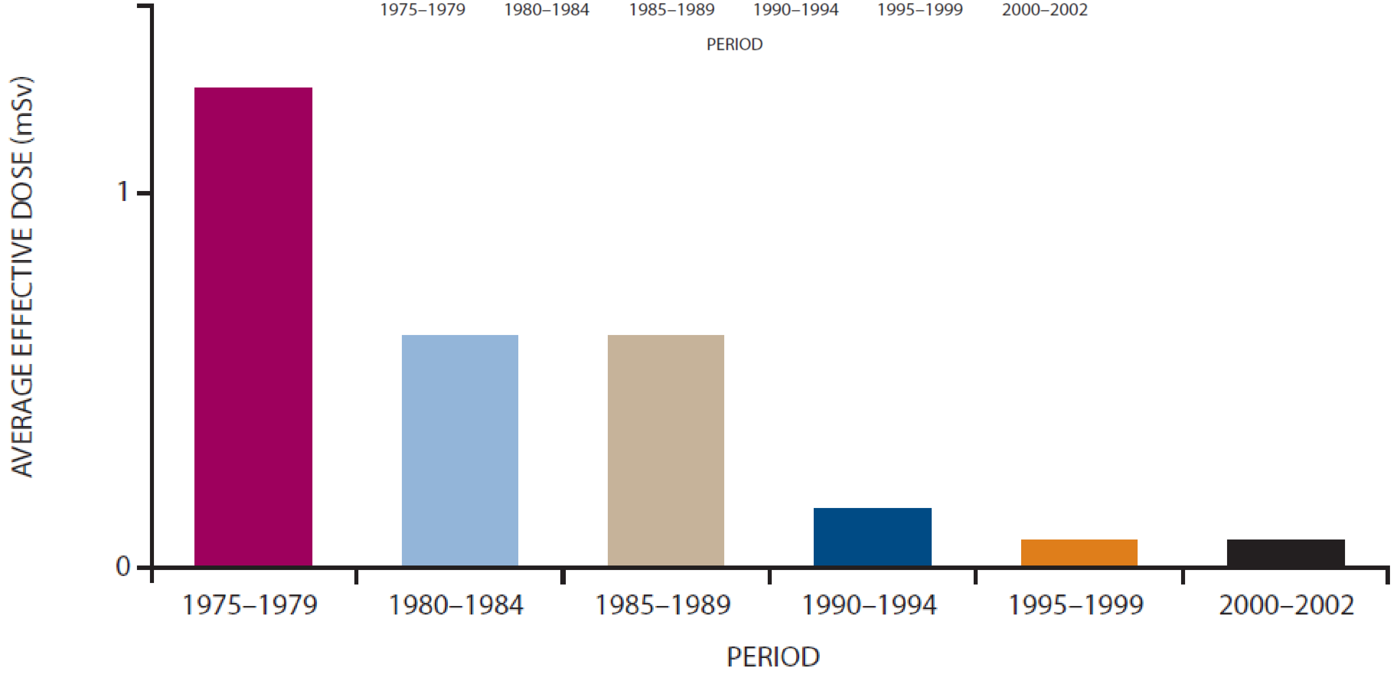
- Wide range of doses depending on activities conducted.



Source: Boice, J. Health Physics, 100(1), 2011

25 years of data on occupational dose in the military





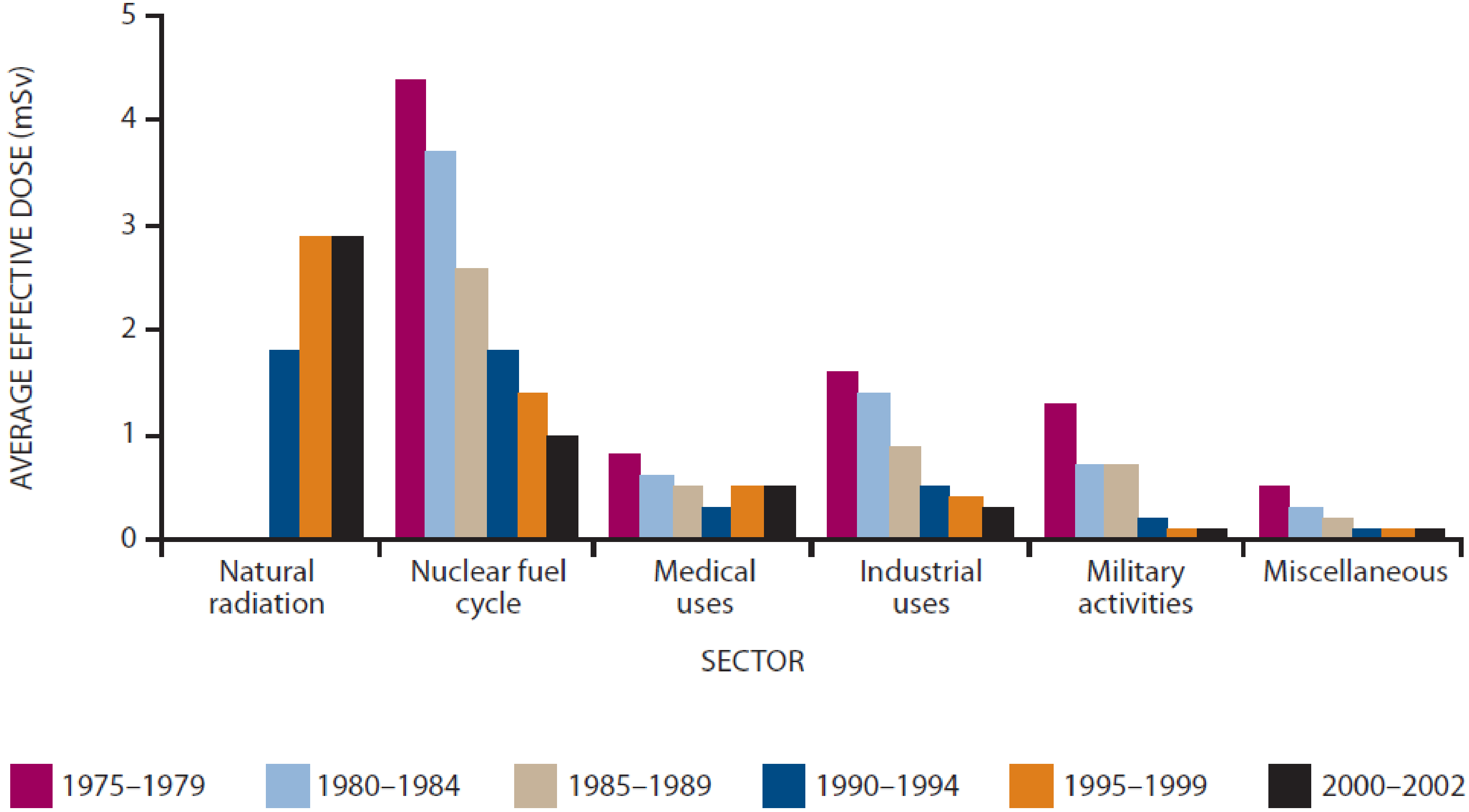
Source: UNSCEAR 2000

High-altitude lifestyles and occupations

Some 140 million people live permanently at high altitudes (>2,500 m or 8,200 ft).

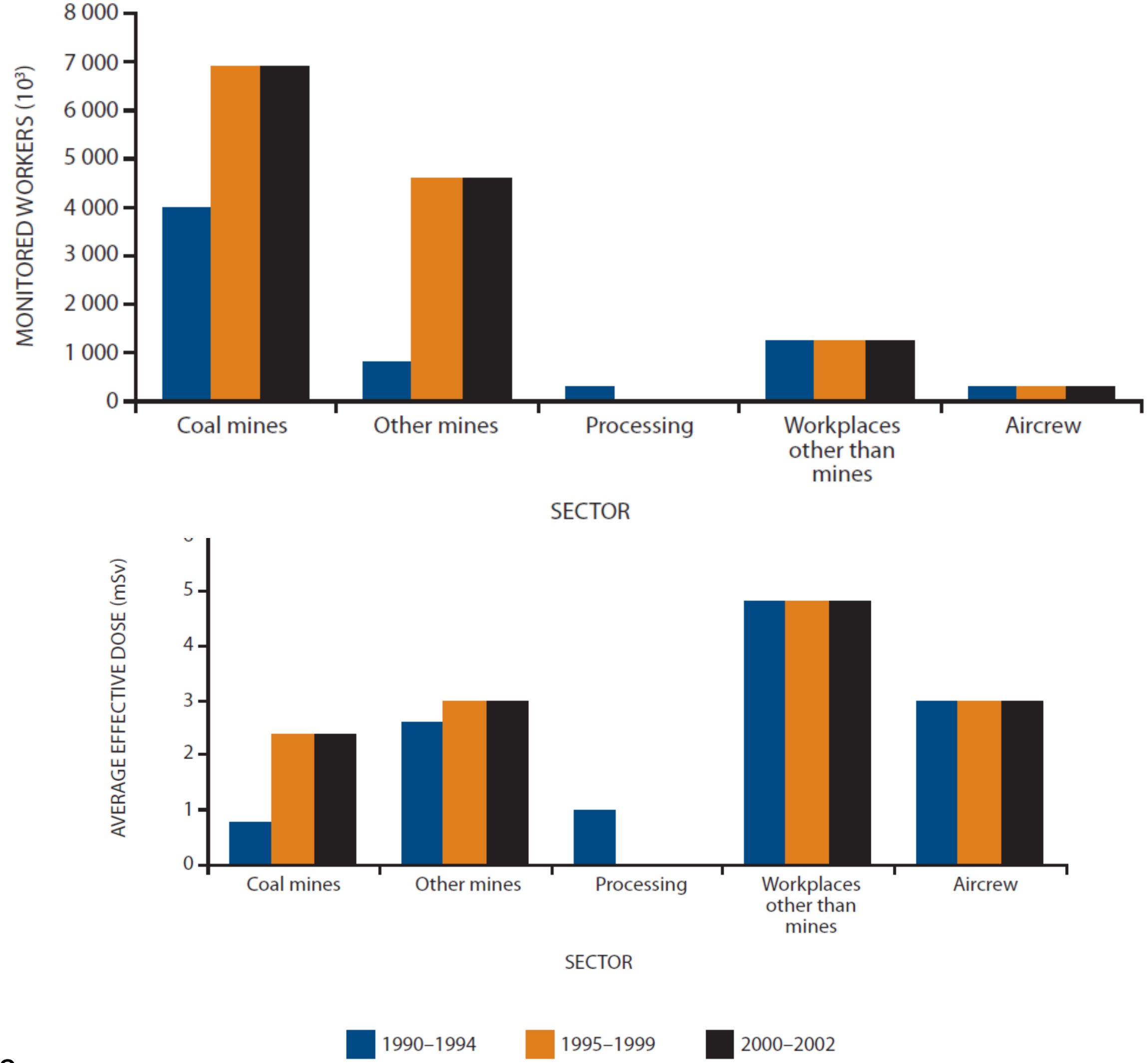
Ionizing radiation strongly depends on altitude. The absorbed dose rate at 2,500 m altitude is about 1 mSv/y compared to about 0.25 mSv/y at sea level.

Occupational Exposure – All Monitored Workers (normal, non-accident conditions)



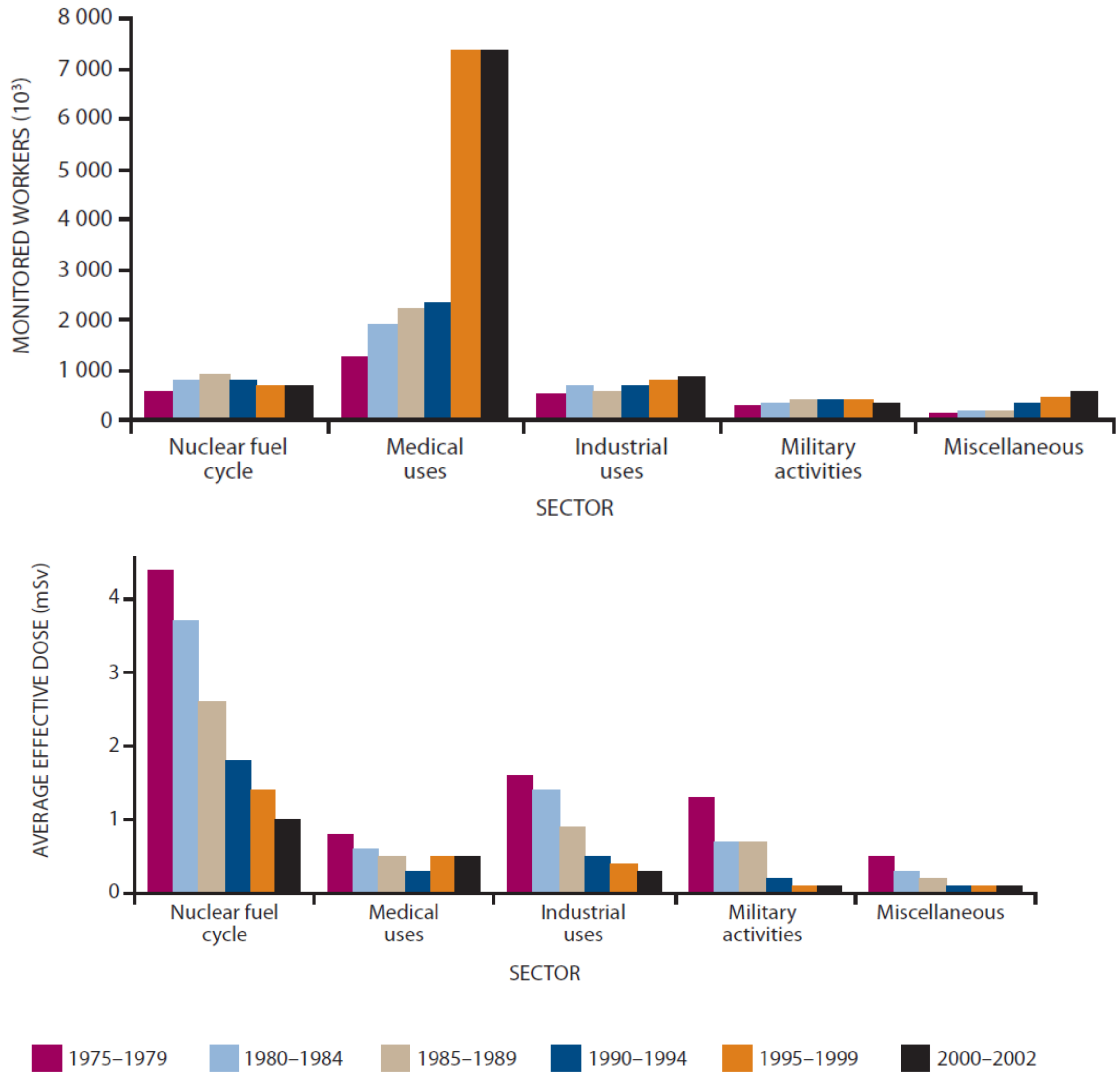
Source: UNSCEAR 2000

Worldwide Trends in Occupational Exposure to Natural Sources of Radiation



Source: UNSCEAR 2000

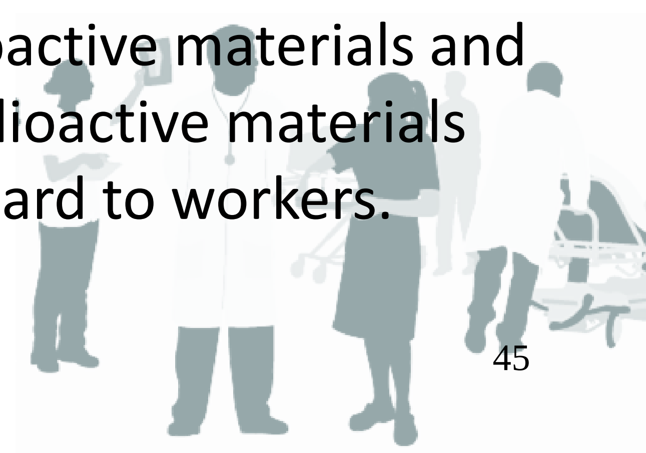
Worldwide Trends in Exposure to Man-made Radiation



Source: UNSCEAR 2000

Who regulates occupational radiation exposure in the U.S.? (1/9)

- **The NCR (Nuclear Regulatory Commission) has statutory authority for licensing and regulating nuclear facilities and materials** as mandated by the Atomic Energy Act of 1954, the Energy Reorganization Act of 1974, the Nuclear Nonproliferation Act of 1978, and other applicable statutes.
- Specifically, the NRC has the authority to regulate source, by-product and certain special nuclear materials (e.g., nuclear reactor fuel). This authority covers radiation hazards in NRC-licensed nuclear facilities produced by radioactive materials and plant conditions that affect the safety of radioactive materials and thus present an increased radiation hazard to workers.



Who regulates occupational radiation exposure in the U.S.? (2/9)

- **The Occupational and Safety and Health Administration (OSHA) has authority to regulate occupational ionizing radiation sources not regulated by NRC.** Examples of non-NRC regulated radiation sources include X- ray equipment, accelerators, accelerator-produced materials, electron microscopes, betatrons, and some naturally occurring radiation sources and sources of technologically-enhanced naturally occurring radioactive materials (TENORM).

Who regulates occupational radiation exposure in the U.S.? (3/9)

- In addition to Federal regulation of ionizing radiation exposure, **States have radiation control programs** for sources of exposure within their state.
- NRC has 33 Agreement State Programs. OSHA has 26 State Plan States, of which 13 are Agreement States. A number of other states have some radiation protection program but are neither NRC Agreement States nor OSHA State Plan States.

Who regulates occupational radiation exposure in the U.S.? (4/9)

- **EPA** sets Environmental Radiation Protection Standards for Nuclear Power Operations (40 CFR 190) to limit the radiation releases and doses to the public from the normal operation of nuclear power plants and other uranium fuel cycle facilities.
- The standards apply to facilities involved in the milling, conversion, fabrication, use and processing of uranium fuel for generating electrical power.

Who regulates occupational radiation exposure in the U.S.? (5/9)

- **EPA** also regulates the Management and Storage of Spent Fuel, High Level and Transuranic Wastes (40 CFR 191) sets dose standards for public protection from the radiation from spent nuclear fuel, high-level wastes and wastes that contain elements with atomic numbers higher than uranium (transuranic wastes).
- The standards apply to the management, storage and disposal of spent nuclear fuel, and include provisions to protect groundwater from radioactive contamination.

Who regulates occupational radiation exposure in the U.S.? (6/9)

- The **EPA** also regulates radionuclides in drinking water to protect public health. The National Primary Drinking Water Regulations for radionuclides became effective in 1977 and were last revised in 2000 to include uranium. The Safe Drinking Water Act requires EPA to periodically review the regulation for each contaminant and revise it, if appropriate. EPA may review the radionuclides regulation again in 2015.

Who regulates occupational radiation exposure in the U.S.? (7/9)

- **U.S. Department of Energy (DOE) is responsible for regulating its nuclear activities** to ensure protection of its workers (and the public from radiation from DOE facilities and activities).
- **DOE is also responsible for disposing of spent nuclear fuel and high-level radioactive waste** from the nation's nuclear power plants and for the management and disposal of radioactive waste and other radioactive materials associated with its nuclear weapons production and research and development activities.

Who regulates occupational radiation exposure in the U.S.? (8/9)

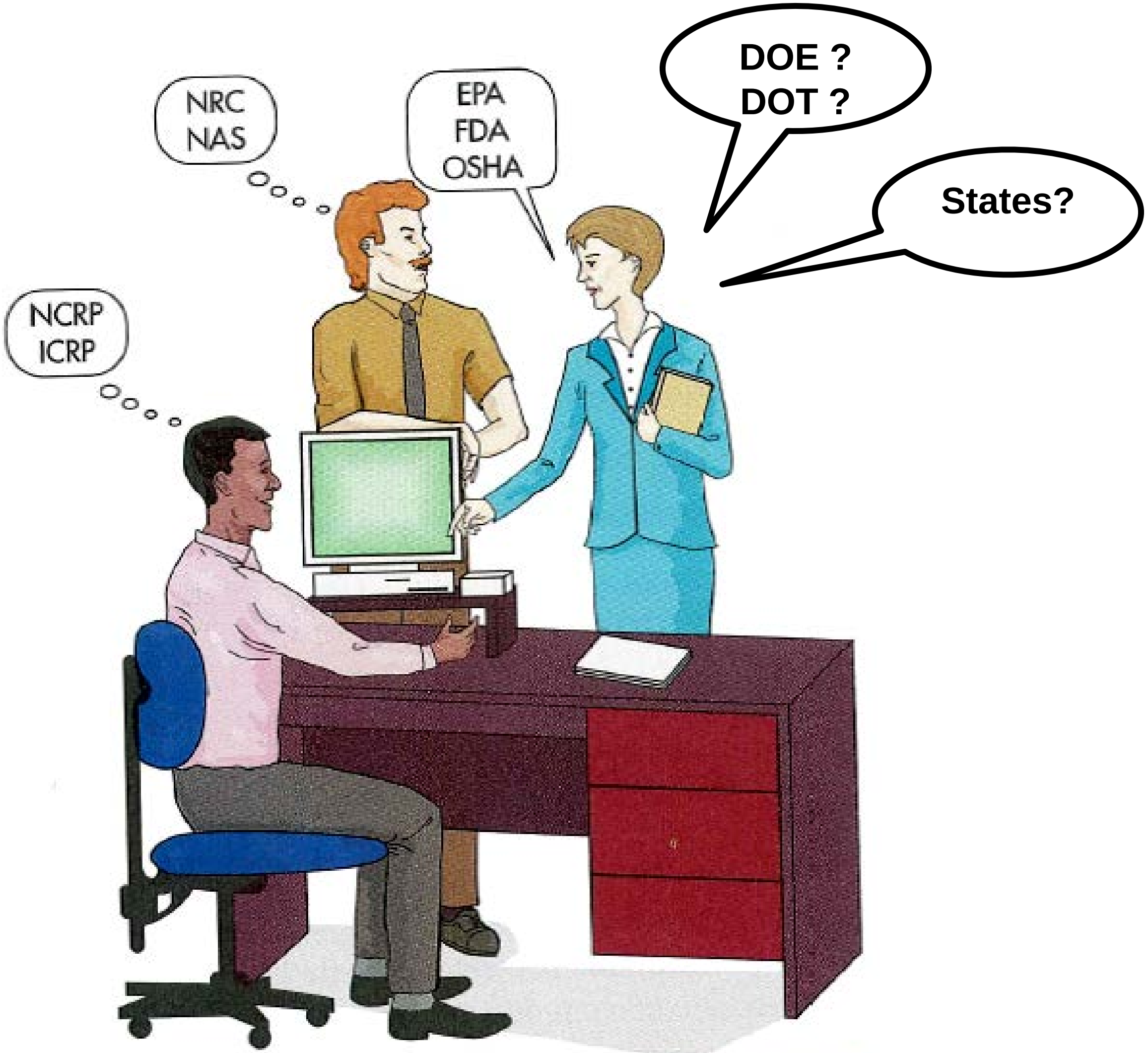
- **The U.S. Department of Transportation (DOT)** in cooperation with Nuclear Regulatory Commission and the states, governs the packaging and transport of commercial radioactive materials.

Who regulates occupational radiation exposure in the U.S.? (9/9)

- Finally, **States** have agencies /offices responsible for **regulating the use of radiation** and radioactive emissions.

  Some states operate under an agreement with the NRC to license and regulate certain types of radioactive materials.

So…who regulates occupational radiation exposure in the U.S.?



Understanding who regulates radiation exposure in the U.S. is simple and without ambiguity.

Occupational Dose Limits (simple version)

Nuclear Regulatory Commission (NRC) occupational dose to individuals are presented as a good example.

(1) An annual limit, which is the more limiting of:

(i) The total effective dose equivalent being equal to 50 mSv (5 rem); or

(ii) The sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye being equal to 500 mSv (50 rem).

(2) The annual limits to the lens of the eye, to the skin of the whole body, and to the skin of the extremities, which are:

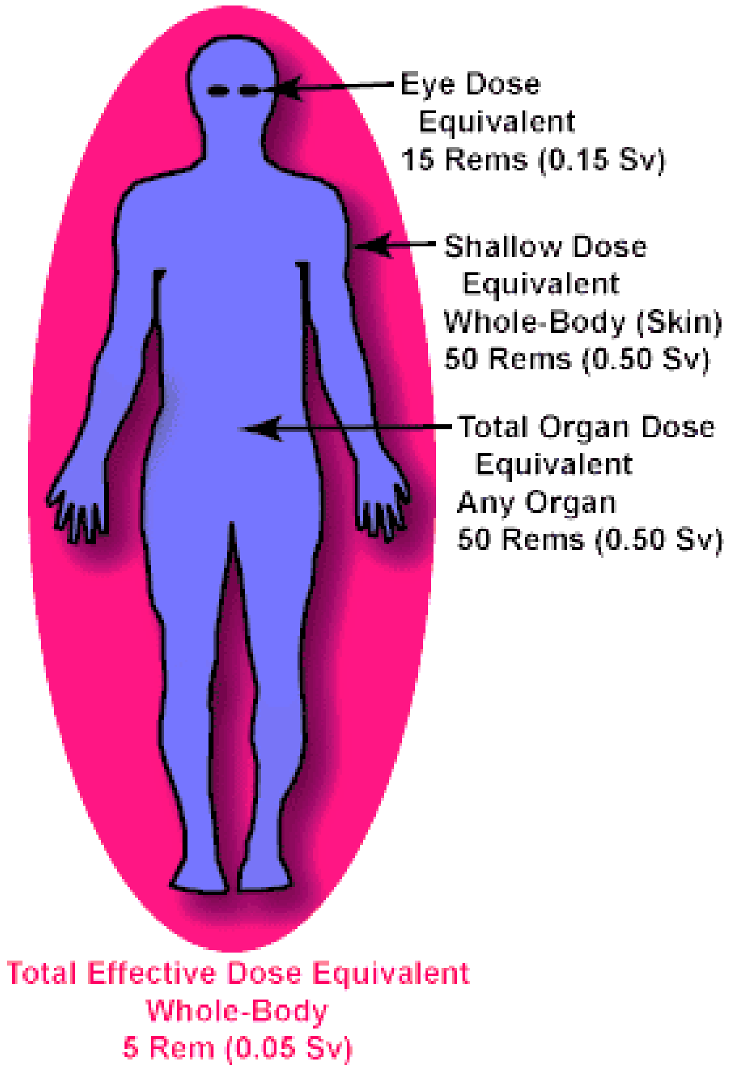
(i) A lens dose equivalent of 0.15 Sv (15 rem), and

(ii) A shallow-dose equivalent of 0.5 Sv (50 rem) to the skin of the whole body or to the skin of any extremity.

When the external exposure is determined by measurement with an external personal monitoring device, the deep-dose equivalent must be used in place of the effective dose equivalent. **The assigned deep-dose equivalent must be for the part of the body receiving the highest exposure.**

Occupational Dose Limits (simple version)

Graphical depiction of limits.



https://www.ndeed.org/EducationResources/CommunityCollege/RadiationSafety/safe_use/exposure.htm

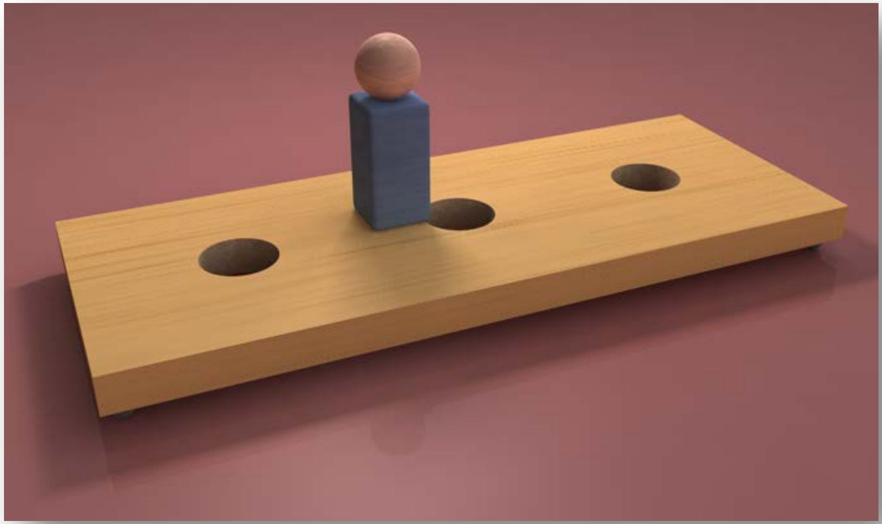
Occupational Dose Limits for minors

Occupational dose limits for minors.
The NRC annual occupational **dose limits for minors are 10 percent** of the annual dose limits specified for adult workers.

Occupational Dose Limits to embryo/fetus

Occupational Dose Limits to embryo/fetus
The NRC licensee shall ensure that the dose equivalent to the embryo/fetus during the entire pregnancy, due to the occupational exposure of a declared pregnant woman, **does not exceed 5 mSv (0.5 rem)** dose equivalent.

Limitations of Dose Monitoring Records



Dose monitoring records can often be useful for reconstructing, or to help reconstruct, doses needed for health risk studies. The data, however, usually has significant limitations that need to be recognized.

Limitations of Dose Monitoring Records (1/3)

The accuracy of dose estimates derived from occupational monitoring records depends largely on the quality of available data and an understanding of the following 4 factors:

(1) **The applied external dosimetry technology**, which includes the capabilities of the measurement system (*e.g*., sensitivity, energy response, and angular dependence of personal dosimeters) and factors affecting performance (*e.g*., temporal variations, environmental conditions, and human factors);

Limitations of Dose Monitoring Records (2/3)

(2) **The applied internal dosimetry technology**, which includes the processes used to collect bioassay samples and the analytical methods used to process them;

(3) **The radiation characteristics of the work environment** (including mixed radiation types, varying exposure geometries for external sources, air-borne radionuclide mixtures composed of several forms of solubility class and particle size distributions, or severe environmental conditions), and

Limitations of Dose Monitoring Records (3/3)

(4) The procedures, practices and policies adopted by the work facilities:

- to calibrate dosimetry systems;
- to issue, wear and process personal monitoring devices;
- to collect, store and process bioassay samples.

Dose Reconstruction Steps

Steps in dose reconstruction for occupational exposures are <u>not</u> unique compared to other exposure situations, except that the degree of control of the exposure is greater for occupations than for non-routine exposure situations.

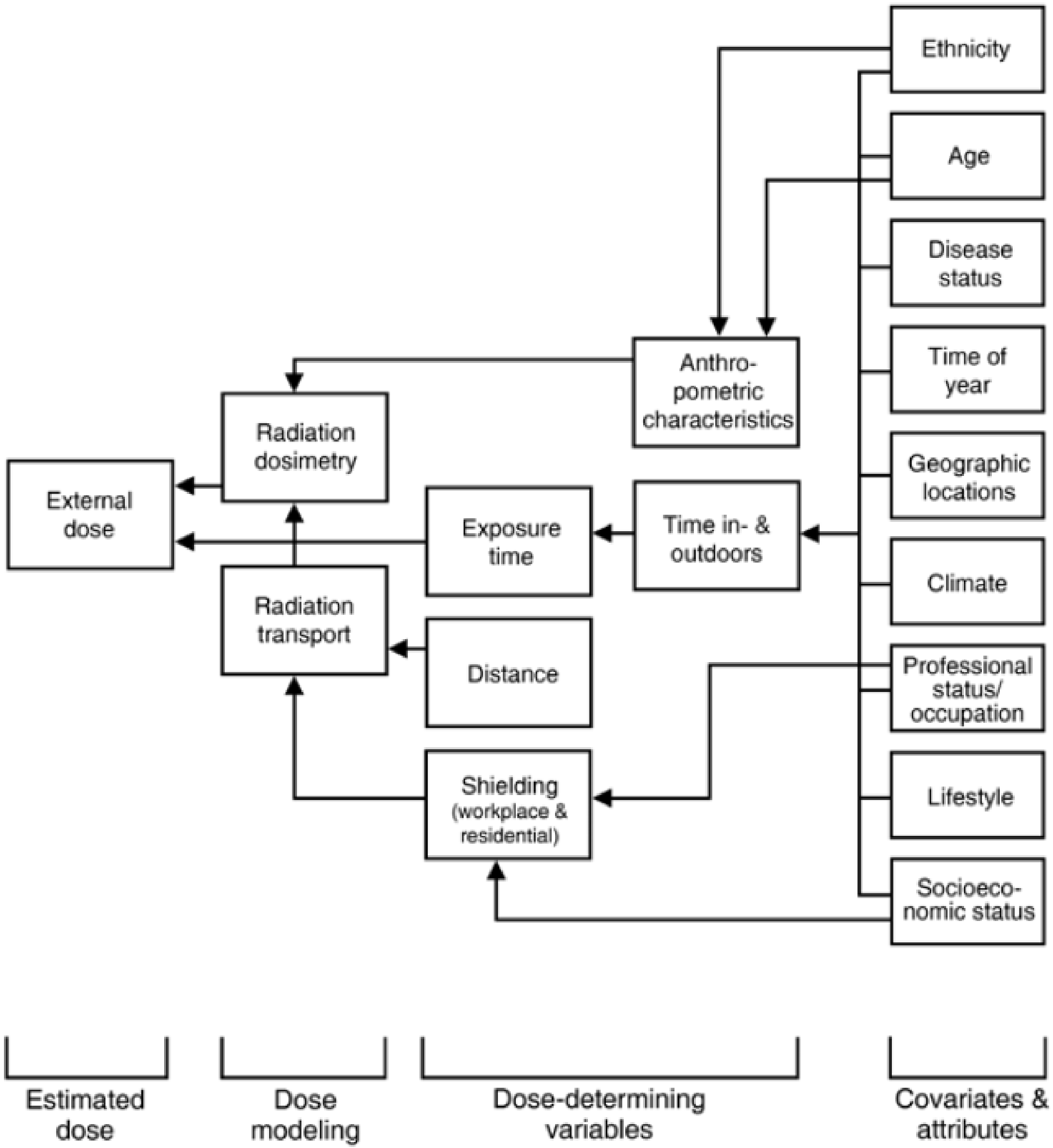
The main components of dose reconstruction include:

- Exposure scenario definition (radiation source, conditions, geometry)
- Exposure pathway definition (external, internal, etc.)
- Development of method (exposure assessment model)
- Dose estimation
- Model validation
- Evaluation of uncertainties
- Interpretation of results

See NCRP 163 (2009).

Strategies for Dose Reconstruction (example of external dose)

Inter-relationships of external dose with dose-determining variables and potentially-important attributes or covariates.



Source: NCRP 163 (2009)

Sources of Uncertainties in Estimates of Occupational Doses

1) Compliance-driven **differential monitoring and reporting requirements**, such as established monitoring thresholds or the assignment of notional doses;

2) Uncertainty in recorded values from varying and limited measurement processes, including random and systematic measurement error and uncertainties associated with exposures below limits of detection (*i.e.*, missed dose);

Sources of Uncertainties in Estimated Occupational Doses

3) Doses associated with **unmonitored occupational exposure**

4) **Exposures prior and subsequent to the employment period** under study, and from additional **radiation exposure not associated with employment** (*e.g*., medical exposure).

5) **Dose reconstruction** parameters, models, and input data.

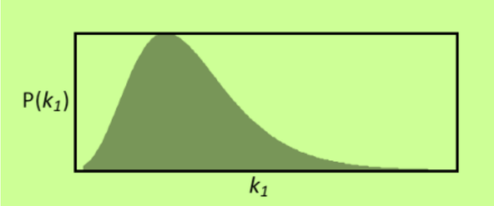
Combining Uncertainties

Strategies for combining uncertainties in occupational exposure studies are the same as in other types of studies:

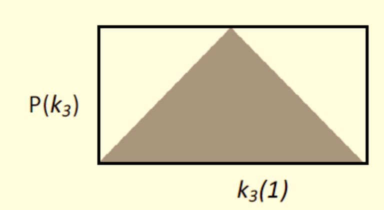
1)Analytical error propagation – low tech, quick and uncomplicated, limited flexibility
2)Monte Carlo analysis – more flexible, can handle any type of probability distribution, best simulates complex equations and relationships.

Monte Carlo–based uncertainty analysis samples from probability density functions (PDFs) describing **uncertainty** or **variability** of exposure-related parameters.

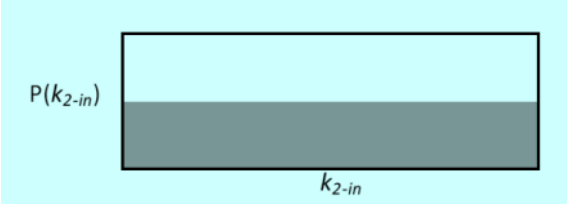
Lognormal PDF



Triangular PDF

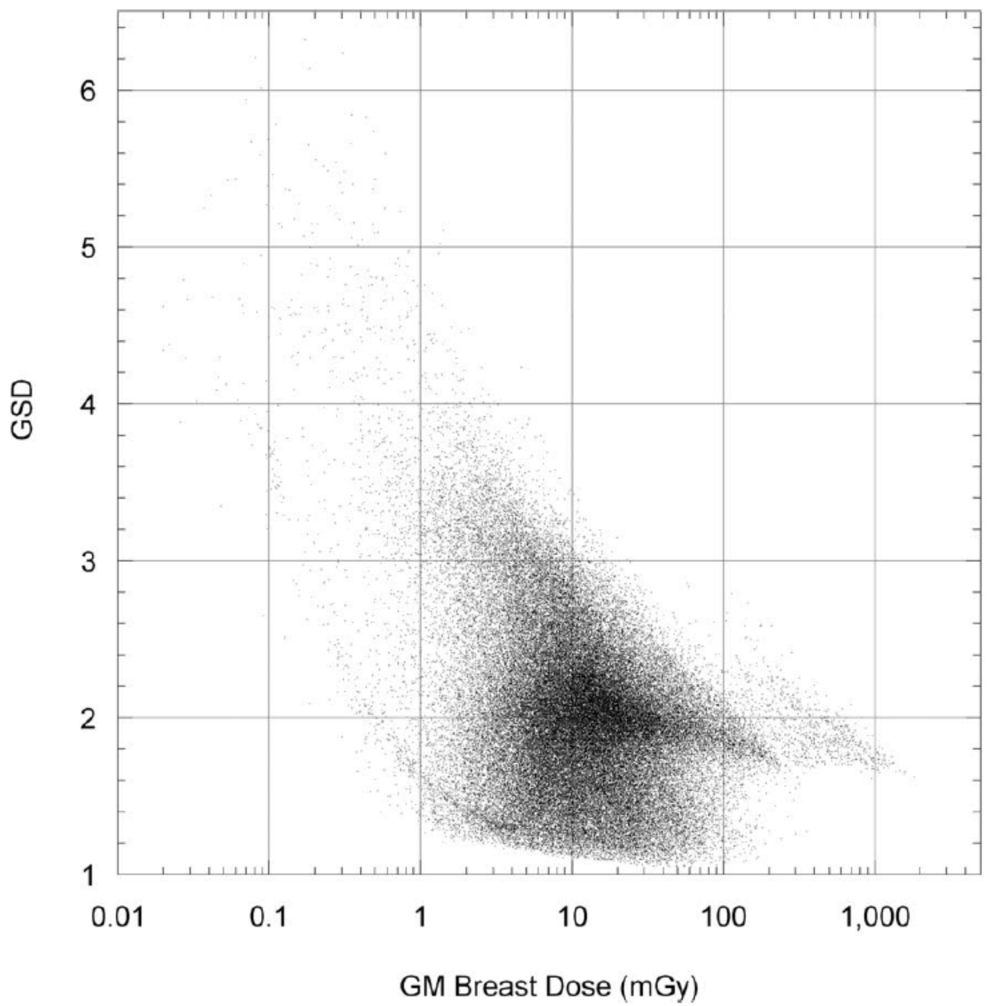


Uniform PDF



Example PDFs of Exposure Parameters

Example of uncertainties in USRT study of radiologic technologists – typical of many dose reconstructions



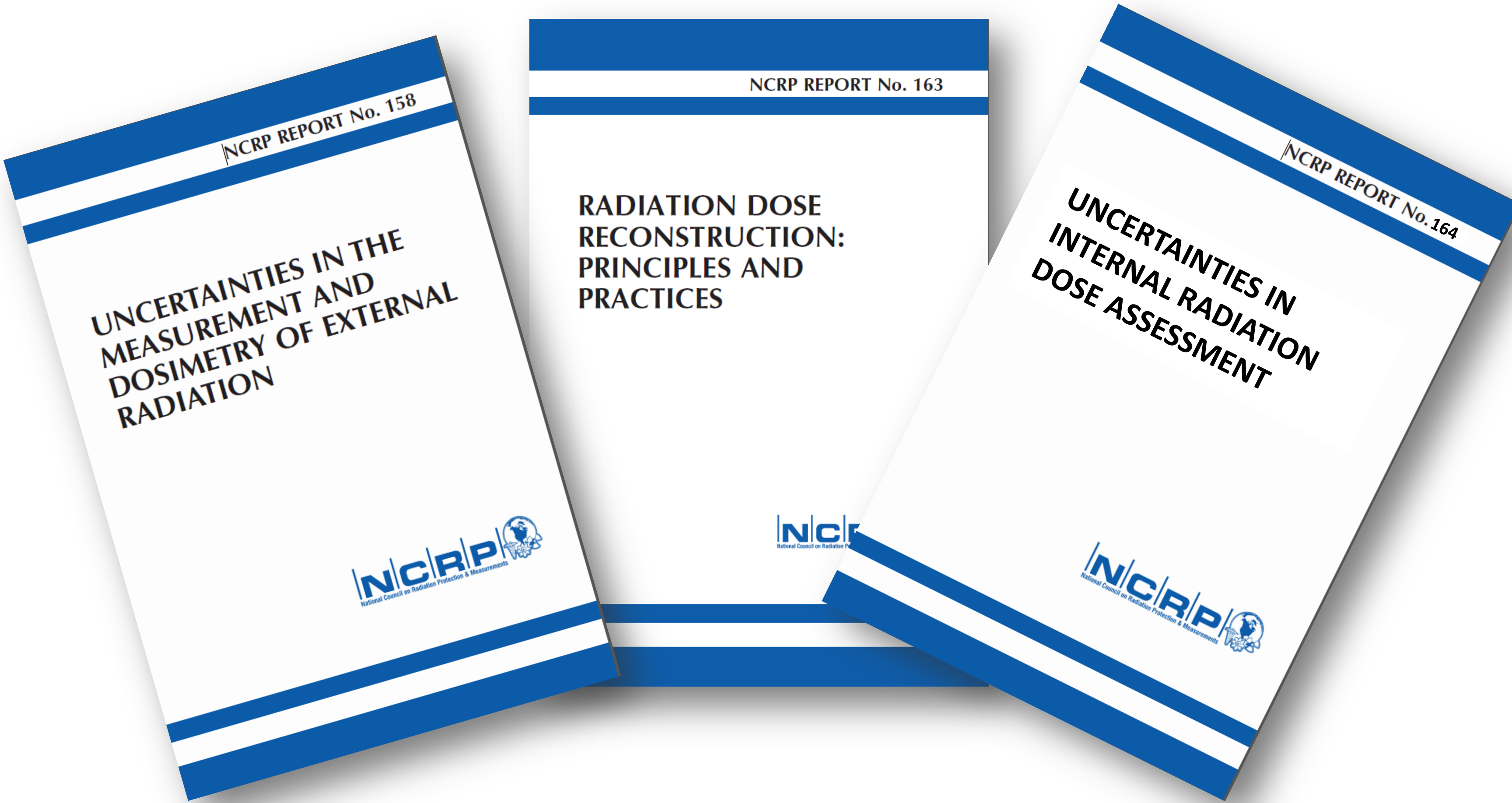
95% CI is defined from $1/GSD^2$ to GSD^2

GSD of 1.5 implies an uncertainty range of almost 5x.

GSD of 2.5 implies an uncertainty range of almost 40x.

GSD of 3 implies an uncertainty range of 81x.

NCRP Reports Useful for Understanding Uncertainties



Also, see http://physics.nist.gov/cgi-bin/cuu/Info/Uncertainty/index.html

Concluding Points (1/3)

- In occupational radiation health studies, identifying the potentially exposed populations is the first step. A study may want to eventually identify the actual exposed individuals.
- On an individual level, the difficulty in answering the question, "Who is exposed?", may vary from simple to great depending on the availability of individual monitoring information.
- In some cases, "exposure" may be based on well-substantiated individual records, e.g., medical or occupational records.
- More generally, answering "Who is exposed?" may depend on the definition of exposure or on the estimation method used to estimation exposure.
- Aside from occupational exposure records, some measurement-based strategies (e.g., biodosimetry) can be used to identify persons exposed, with the caveat that the exposure is above the threshold of the measurement technique.

Concluding Points (2/3)

- Generally, health risk studies identify a target population for "exposure assessment" and do not try and answer the questions "Who?" or "How many?".
- Because of the difficulties mentioned in defining or determining exposure on an individual basis, the "true" number of exposed persons in an "exposed population" may never be known (it may not be important to study, though possibly useful for public health reasons).
- Occupationally exposed populations may be distinguished based on one or more attributes, e.g.:
    - Monitoring records,
    - Working in a particular place at a particular time
    - A particular occupation,
    - A particular gender, age group, ethnic group,
    - Proximity to an event or source of radiation,

Concluding Points (3/3)

- For the most part, radiation protection in the U.S. and elsewhere works most of the time.
- Evidence for success of radiation protection programs are the predominantly low annual exposures seen in personnel monitoring.
- Non-routine events, accidents, and purposeful neglect of personal dosimeters can sometimes lead to exposures approaching (over possibly exceeding) dose limits.
- New occupations and/or new uses of radiation require careful surveillance to ensure that occupational exposures stay low.
- Occupational dosimetry may benefit radiation epidemiology the most by focusing on historical exposures which were generally were larger.
- Historical doses are difficult to reconstruct and their uncertainties need to be quantified and recognized.

Occupational dosimetry – at least in epidemiology - doesn’t have to be a boring subject! The variety of populations that have and continue to be exposed is fascinating in and of itself.

Occupational Dosimetry

Questions and Answers

U.S. Department of Health and Human Services
National Institutes of Health | National Cancer Institute
www.dceg.cancer.gov/RadEpiCourse
1-800-4-CANCER
Produced May 2015