“He had no idea of the journey we were about to take.”
—Henry Lawson in “Journey to the Center of the Earth” by Jules Verne.
Website for NPME 442

http://wiki.cites.illinois.edu/wiki/display/NPR
E442sp12/Home
Radioactive Waste Management in the 21st Century

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Draft Textbook for NPRE 442, Radioactive Waste Management

2016
Nuclear energy in the past

In the 1950s, “atomic energy” was regarded as the key to the future.

1957. First large-scale commercial power plant in the US (PA)

1960. Dresden-1 Nuclear Power Station, Unit 1 (Illinois) the first privately-financed nuclear power plant built in the U.S. (shut down in 1978 and is currently in SAFSTOR. Decontamination and dismantlement take place from 2029 through 2031).
Atomic Suit Inflated with Conditioned Air

The girl at the right, wearing an anti-radiation suit, is ready for her atomic job. Handling a Geiger counter and protected by the inflated plastic garment, she can detect floating radioactive particles without danger of contamination. Goodyear-made, the suit is air-conditioned for comfort.

Robot Halts Waste

When waste collected by this tape shows plutonium, the machine signals control engineers at the Hanford atomic plant. Prompt “leak” plugging saves GE $250,000 a year in lost nuclear fuel.
Atomic energy for youth
ATOMIC ENERGY LAB

- ATOMIC CLOUD CHAMBER with PROJECTOR ILLUMINATOR
  - See the vapor trails of alpha and beta particles, and of cosmic rays.
- SPINTHARISCOPE — Shows exploding atoms.
- ELECTROSCOPE — Measures background radiation and tests sample sources.
- SAFE RADIOACTIVE MATERIALS — Alpha source in handy container and Uranium Ore.

FULL INSTRUCTIONS COVER USE AND THEORY

FUN EASY EXCITING
But, in the decades that followed. . .

Economic difficulties.

Widespread public fear.

Chernobyl in 1986.
“radiophobia”
Since the late 1980s, there has been a defacto moratorium on building new nuclear power plants in the US.

Until now . . .

In about 2000, the concept of global warming was gaining acceptance.
Is global warming real?

Warmest 11 years:
The concentration of CO$_2$ is increasing
Greenhouse gases warm the earth

The Greenhouse effect

Solar radiation passes through the clear atmosphere.
Incoming solar radiation: 343 Watt per m²

Some solar radiation is reflected by the atmosphere and earth’s surface.
Outgoing solar radiation: 105 Watt per m²

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules. The direct effect is the warming of the earth’s surface and the troposphere.

Surface gains more heat and infrared radiation is emitted again

Solar energy is absorbed by the earth’s surface and warms it...
168 Watt per m²

... and is converted into heat causing the emission of longwave (infrared) radiation back to the atmosphere

Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington, Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.
To reduce the emissions of greenhouse gases by fossil fuels. . .

Many advocate greater use of alternative sources of energy:

Wind, hydroelectric, geothermal, wave energy, solar, and

Nuclear! Yes, nuclear is considered by some as a “green energy source” because it does not contribute to global warming.
A nuclear energy renaissance was born because of global climate change.

The NRC received 17 applications for 25 new reactors by 2010. First one arrived Oct. 2007. Some applications have not gone forward.

As of January, 2017:

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Expected on-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts Bar 2</td>
<td>Tennessee</td>
<td>2017 first in 20 years!</td>
</tr>
<tr>
<td>Vogtle 3</td>
<td>Georgia</td>
<td>2019</td>
</tr>
<tr>
<td>Vogtle 4</td>
<td>Georgia</td>
<td>2020</td>
</tr>
<tr>
<td>Summer 2</td>
<td>South Carolina</td>
<td>2019</td>
</tr>
<tr>
<td>Summer 3</td>
<td>South Carolina</td>
<td>2020</td>
</tr>
</tbody>
</table>
Planned or proposed

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Expected on-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellefonte 1</td>
<td>Alabama</td>
<td>2028</td>
</tr>
<tr>
<td>William States Lee</td>
<td>South Carolina</td>
<td>2024</td>
</tr>
<tr>
<td>Fermi</td>
<td>Michigan</td>
<td>?</td>
</tr>
<tr>
<td>North Anna</td>
<td>Virginia</td>
<td>2022</td>
</tr>
<tr>
<td>South Texas Project</td>
<td>Texas</td>
<td>2020s</td>
</tr>
<tr>
<td>UAMPS</td>
<td>Idaho</td>
<td>2024</td>
</tr>
<tr>
<td>Clinch River</td>
<td>Tennessee</td>
<td>2020s</td>
</tr>
<tr>
<td>Green River</td>
<td>Utah</td>
<td>?</td>
</tr>
<tr>
<td>Fresno</td>
<td>California</td>
<td>?</td>
</tr>
<tr>
<td>Amarillo</td>
<td>Texas</td>
<td>?</td>
</tr>
</tbody>
</table>
On a global scale

“With 70 reactors being built around the world today, another 150 or more planned to come online during the next 10 years, and over two hundred further back in the pipeline, the global nuclear industry is clearly going forward strongly.” “56 countries operate a total of about 240 research reactors and . . . 180 nuclear reactors power some 150 ships and submarines.”

WNA (http://www.world-nuclear.org/info)
Illinois has most nuclear power plants in the US

Illinois’ Electricity Generation

<table>
<thead>
<tr>
<th>Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>48.7%</td>
</tr>
<tr>
<td>Coal</td>
<td>47.1%</td>
</tr>
<tr>
<td>Oil</td>
<td>0.1%</td>
</tr>
<tr>
<td>Gas</td>
<td>2.3%</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.1%</td>
</tr>
<tr>
<td>Renewable and Other</td>
<td>1.9%</td>
</tr>
</tbody>
</table>
2011, Fukushima

The events at the Fukushima plant in Japan are a public relations nightmare.

New safety reviews and studies have been launched on a global scale. Concerns about nuclear plants in earthquake zones.

At the same time, it highlighted the lack of a national policy for managing used nuclear fuel.
The U.S. nuclear energy renaissance has slowed down

Why?
Cheap natural gas prices.
Economic issues.
Premature shutdown of some reactors.

Unsolved issues with respect to the management of radioactive wastes!
But what about radioactive wastes?

If world goes nuclear, where will waste go?

Inching forward on nuclear waste disposal issue

Don’t rush back into nuclear power

LETTERS TO THE EDITOR

May 5, 2008

Exelon’s plan for early decommissioning of its Zion nuclear site has renewed the controversy over nuclear waste and power. Rep. John D. Dingell (D-Mich.), who has been a staunch advocate of nuclear power, has been critical of the plan, saying it would not address the issue of permanent disposal. He has called for a moratorium on new nuclear power plants until a permanent disposal solution is found.

May 4, 2008

Nuclear waste issue still unsolved

In response to your story in the May 3 edition of the American Energy Association, we would like to clarify a few points. The issue of nuclear waste disposal is complex and multifaceted. While there have been some recent advances, such as the Yucca Mountain site, there are still many concerns and obstacles to be overcome.

May 3, 2008

Inching forward on nuclear waste disposal issue

Last week’s delivery of the long-awaited Yucca Mountain repository application to the Environmental Protection Agency is a significant milestone for the nation’s nuclear power industry. The Yucca Mountain site has been proposed as a repository for high-level radioactive waste from nuclear power plants. However, there are still many issues to be addressed, including public concerns and environmental impacts.

June 11, 2008

If world goes nuclear, where will waste go?

By ANGELA CHARLTON

As the United States moves towards a nuclear energy future, the issue of waste disposal becomes increasingly pressing. The current approach, which involves storing waste in underground repositories, has faced numerous challenges and controversies. It is essential that we find a sustainable and safe solution to this problem.
JIM NOWLAN:

Where to store nuclear waste

The Economist magazine reported recently that Illinois is home to more radioactive, spent nuclear fuel than any state in the nation.

Should that concern us? Why else would this highly respected magazine have carried a story about it? The problem is that the 9,000 tons of radioactive nuclear waste stored, supposedly temporarily, at reactor sites across our state have no place to go.

The nuclear industry and its ardent opponents agree on this much, if nothing else — all that waste should be moved to a permanent site. Ultimately this site will likely be somewhere in a sparsely populated location in the West, where some of the waste will continue to be lethally radioactive for at least 10,000 years.

I asked representatives of Exelon, our state’s nuclear energy generator, as well as skeptics and opponents of nuclear power, what level of concern Prairie State residents should have for their safety on this matter: none, little, some, a great deal.

I could have written the scripts in advance.

Pam Cowan of Exelon, a nuclear engineer, declares that the pools and casks are extremely secure, with enough engineering, steel and concrete, and multiple safety system redundancies to protect against accidents from earthquakes, terrorists and any kind of mayhem that can be imagined.

(Lochbaum of the concerned scientists, also a nuclear engineer, thinks that casks are safer than the pools, but Cowan disputes this, noting the Nuclear Regulatory Commission has found the two storage systems equally safe.)

Nuclear opponent Kraft says the unimaginable has happened in the past, as at the Fukushima nuclear accident in Japan in 2011. All agree that a central permanent site is needed.

Two counties in Texas and New Mexico have offered to create “centralized interim storage sites,” but even these would be decades away from receiving spent fuel.

Clearly, the nuclear power community should have resolved the permanent storage issue decades ago, at the front end of the nuclear power era, before creating all this spent fuel.

I think we should reinstate the moratorium on licensing any new nuclear reactors until a permanent site is approved. Second, interim sites should be established.

In addition, the nation must put even more resources into increasing the efficiency of renewable sources of energy such as wind and solar.

As for the stored nuclear waste in Illinois, I think it is safely secured, but I would feel even better if it were stored permanently elsewhere. But that is decades away.

Jim Nowlan is a retired senior fellow with the University of Illinois Institute of Government and Public Affairs. His email is jnowlan3@gmail.com.
A Nuclear Renaissance without Disposal?

All countries that use nuclear energy now, or that wish to do so in the future, must have a credible waste disposal strategy that will lead to safe disposal when this becomes necessary. In addition, this strategy must be accepted by a sufficiently large fraction of the population.
The bottom line
Regardless of the future of nuclear energy in the US and the world, there are radioactive wastes from a number of sources that need to be managed today, and well into the future in a manner that is protective of human health and the environment.

Do we as engineers and scientists know how to manage these wastes?
Radioactive Decay and Measurement

A curie (Ci) is \(3.7 \times 10^{10}\) disintegrations per second.
A pico is \(10^{-12}\)
pCi/L and pCi/g are often used in radiochemical/radiological studies.

The SI unit (International System of Units) of radioactivity is the becquerel (Bq). One Bq is 1.0 disintegration per second. One pCi = 0.037 Bq
One tera is \(10^{12}\)
One terabecquerel (TBq) = 27 Ci
Modes of decay: $\alpha$

During radioactive decay, charged particles are emitted:

Alpha radiation is two protons and two neutrons (He$^{2+}$).

Polonium-210:

$^{210}\text{Po}_{84} \rightarrow ^{206}\text{Pb}_{82} + \alpha$
Modes of decay: $\beta^-$

Beta radiation consists of electrons or positrons.

An unstable atomic nucleus with an excess of neutrons may undergo $\beta^-$ decay, where a neutron is converted into a proton, an electron, and an antineutrino:

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Beryllium-10:

\[ ^{10}\text{Be}_4 \rightarrow ^{10}\text{B}_5 + e^- \]
Modes of decay: $\beta^+$

An unstable atomic nucleus with an excess of protons may undergo $\beta^+$ decay, where a proton converted into a neutron, a positron, and a neutrino:

\[ p \rightarrow \eta + e^+ + \nu_e \]

Rubidium-82:

\[ ^{82}\text{Rb}_{37} \rightarrow ^{82}\text{Kr}_{36} + e^+ \]
Modes of decay: electron capture

An atomic nucleus absorbs an inner electron, changing a proton into a neutron yielding a neutrino, and in some cases photons and electrons.

\[ p + e^- \rightarrow \eta + \nu_e \]

Iron-55:

\[ {^{55}}\text{Fe}_{26} + e^- \rightarrow {^{55}}\text{Mn}_{25} \]
Modes of decay: $\gamma$

Unstable nucleus releases high-level electromagnetic energy. Gamma ray emission frequently follows beta decay, alpha decay, and other nuclear decay processes.

Cobalt-60:

$^{60}\text{Co}_{27} \rightarrow ^{60}\text{Ni}_{28} + e^- + \gamma$
Modes of decay:

**isomeric transition**

Nucleus in an excited, metastable state emits a gamma ray. No change in number or protons or neutrons.

Technitium-99m: $^{99m}\text{Tc}_{93} \rightarrow ^{99}\text{Tc}_{93} + \gamma$

**spontaneous fission**

Characteristic of very heavy isotopes (atomic numbers greater than 93).

Curium-250: 11% $\alpha$ ($^{246}\text{Pu}$), 9% $\beta^-$ ($^{250}\text{Bk}$, and 80% SF (various daughters)
Sources of background radiation (about 620 mrem/year or 6.2 mSv/year)

- Radon and thoron, 228
- Nuclear medicine, 77
- Computed tomography, 147
- Interventional fluoroscopy, 43
- Conventional radiography, 33
- Consumer, 13
- Space, 33
- Internal, 29
- Terrestrial, 21
Increase in background

Increased applications of X-ray computed tomography (CT scans), conventional radiography and fluoroscopy since the 1990s account for the largest increase in background exposure: previous estimated effective dose was 360 mrem/year.
Consumer products
(13 mrem/year or 0.13 mSv/year)

Older (c. 1930s) Fiesta ware (U)
Antique glass (U)
Bathroom tile (U)
Jewelry (U)
Camera lens (Th)
Smoke detectors (Am)
Fertilizer ($^{40}$K, U, Th, Ra)
Consumer products
(13 mrem/year or 0.13 mSv/year)

Watches and clocks ($^3$H, $^{226}$Ra)
Bricks
Cement blocks
Granite counter tops (U, Th, Ra)
Kitty litter ($^{40}$K, Th, U)
Food and water
Radioactivity in food

Carrots contain 2.4 pCi of uranium per pound (196 mBq/kg)

Beef contains about 4.3 pCi U/pound (350 mBq/kg)

Table salt: 12 pCi U/pound (979 mBq/kg)
Radioactivity in food

Bananas (1,140 pCi/lb) [93 Bq/kg]
Potatoes (1,955 pCi/lb) [159 Bq/kg]
Chicken (955 pCi/lb) [78 Bq/kg]
Orange juice (1,800 pCi/L) [67 Bq/L]

All contain $^{40}\text{K}$

Why? Because 0.012\% of all potassium is radioactive $^{40}\text{K}$.

$^{40}\text{K} \rightarrow ^{40}\text{Ca} + \text{beta radiation}$

Half-life $= 1.3$ billion years.
### Natural Radioactivity in the body

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Total Mass of Nuclide</th>
<th>Total Activity of Nuclide</th>
<th>Daily Intake of Nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>90 μg</td>
<td>30 pCi (1.1 Bq)</td>
<td>1.9 μg</td>
</tr>
<tr>
<td>Thorium</td>
<td>30 μg</td>
<td>3 pCi (0.11 Bq)</td>
<td>3 μg</td>
</tr>
<tr>
<td>Potassium 40</td>
<td>17 mg</td>
<td>120 nCi (4.4 kBq)</td>
<td>0.39 mg</td>
</tr>
<tr>
<td>Radium</td>
<td>31 pg</td>
<td>30 pCi (1.1 Bq)</td>
<td>2.3 pg</td>
</tr>
<tr>
<td>Carbon 14</td>
<td>95 μg</td>
<td>0.4 μCi (15 kBq)</td>
<td>1.8 μg</td>
</tr>
<tr>
<td>Tritium</td>
<td>0.06 pg</td>
<td>0.6 nCi (23 Bq)</td>
<td>0.003 pg</td>
</tr>
<tr>
<td>Polonium</td>
<td>0.2 pg</td>
<td>1 nCi (37 Bq)</td>
<td>~0.6 μg</td>
</tr>
</tbody>
</table>

It would be reasonable to assume that all of the radionuclides found in your environment would exist in the body in some small amount. The internally deposited radionuclides contribute about 11% of the total annual dose.
Nuclear medicine (77 mrem/year or 0.77 mSv/year)

Using radionuclides in diagnosis and treatment of cancers.

Injections of $^{99m}$Tc for cancers.
Injection of tracers.
Nuclear medicine (77 mrem/year)

Radioactive pellets (seeds) containing $^{125}\text{I}$ and $^{89}\text{Sr}$ for breast, prostate and bone cancer.
Diagnostic X-rays

Radiographs Effective Dose (mrem)
Skull  3
Chest  2
Thoracic spine 40
Abdomen 70
Dental film 0.4
Limbs and joints 6
Coronary angiogram 460-1,580
Mammogram 13
  Lumbar spine series 180
  Thoracic spine series 140
  Cervical spine series 27
http://hps.org/hpspublications/articles/dosesfrommedicalradiation.html
Internal radiation in the human body (29 mrem/year or 0.29 mSv/year)

From food: $^{40}\text{K}$, U, Th, $^{14}\text{C}$

Water: $^{40}\text{K}$, Rn, U, Th, $^{3}\text{H}$

Air: Rn

$^{40}\text{K}$ has a biological half-life of 30 days.

The $^{40}\text{K}$ content in the body is constant, with an adult male having about 100,000 pCi. This isotope yields a dose of about 18 mrem to soft tissues of the body and 14 mrem to bone per year.
Radon and Thoron
(228 mrem/year or 0.23 mSv/year)

Radon ($^{222}\text{Rn}$)
A naturally occurring radioactive gas.
A decay product from $^{226}\text{Ra}$
Causes lung cancer.

Thoron ($^{220}\text{Rn}$)
Radon in Illinois

Radon gas can diffuse from the ground and accumulate in homes.

Can move as a gas through the foundation.

Enter as a dissolved gas in water.
We are in an area of “high potential” for radon (> 4 pCi/L)

Zone 1  Highest Potential (greater than 4 pCi/L)

Zone 2  Moderate Potential (from 2 to 4 pCi/L)

Zone 3  Low Potential (less than 2 pCi/L)
Radon (cont)

Greater than 4 pCi/L is about 8.9 counts/min.  
A high potential? Why? 
Soils in this area contain 1 to 3 mg/kg uranium which is decaying to yield radon. 
Because homes are built to be energy efficient, we might detect up to 6 pCi/L in a home in Urbana. 
Is this a concern?
How to interpret a radon test

The accuracy of the testing devices commonly used is $6 \pm 2 \text{ pCi/L}$.

If we think of the worst case (8 pCi/L), the level of radioactivity means that if you breath this air for 70 years and do not smoke, your chances of having cancer are 10 times the chance of dying in an airplane crash.
Terrestrial Radiation
(21 mrem/year or 0.21 mSv/year)

The naturally occurring radioactive elements in rocks, soil, fresh water, and sea water.

Crustal abundance of $^{238}\text{U}$: 1 pCi/g [37 mBq/g]
Carbonate rocks: 0.7 pCi $^{238}\text{U}$/g [26 mBq/g]
U.S. soils: 0.6 pCi $^{238}\text{U}$/g [22 mBq/g]

Surface water in U.S.
0.01 to 582 pCi/L U [0.4 to 21,534 mBq/L]
0.1 to 0.5 pCi/L $^{226}\text{Ra}$ [0.4 to 18.5 mBq/L]
Terrestrial radiation example

A NPRE 397 (Independent Study in Radioactive Waste Management) research project by Chris Demetriou

Atmospheric testing of nuclear weapon from 1945 to 1962 created radioactive fallout.

Could $^{137}\text{Cs}$ still be detected in undisturbed, surface soil samples in Champaign County?
Experimental Procedure

- After the soil samples dried:
  - Samples were sifted to separate out organic matter
  - 100 grams were placed into specialized beaker for radiation detection
  - A high purity Germanium Semiconductor Detector was used to detect any radioactivity within the sample over a two day time span
  - The detector was encased in lead bricks to shield from background radiation, but a background test was also taken
Results – Depth of the Cesium-137

Woodlawn Cemetery

Depth Interval (cm)
- 0-5
- 5-10
- 10-15

137Cs (mBq/g)

Blackberry School

Depth Interval (cm)
- 0-5
- 5-10
- 10-15

137Cs (mBq/g)

Clements Cemetery

Depth Interval (cm)
- 0-5
- 5-10
- 10-15

137Cs (mBq/g)
Cosmic Radiation
(33 mrem/year or 0.33 mSv/year)

High-energy particles (up to $10^{18}$ eV), and are mostly protons, with photons, and muons.

The amount of radiation depends on altitude: flying increase dose.

Cosmic radiation permeates all of space, the source being primarily outside of our solar system. The upper atmosphere interacts with many of the cosmic radiations, and produces radioactive nuclides (cosmogenic).
Cosmic Radiation
(33 mrem/year)

They can have long half-lives, but the majority have shorter half-lives than the primordial nuclides, and include $^{14}$C, $^{3}$H, $^{7}$Be, $^{10}$Be, $^{26}$Al, $^{36}$Cl, $^{80}$Kr, $^{32}$Si, $^{39}$Ar, $^{22}$Na, $^{35}$S, $^{37}$Ar, $^{33}$P, $^{32}$P, $^{38}$Mg, $^{24}$Na, $^{38}$S, $^{31}$Si, $^{18}$F, $^{39}$Cl, $^{38}$Cl, $^{34m}$Cl.
Half-Life Calculations

Chemical kinetics—the rate by which a chemical reaction occurs.

Zero-order reactions—the reaction rate is independent of concentration (adding more reactant will not speed up the reaction). These are rare. Often catalytic surfaces containing the reactant.
Half-Life Calculations

In a first-order reaction, the reaction rate depends on the concentration of only one reactant.

That is, the more reactant, the faster the reaction.

Radioactive decay is a first-order reaction.
Radioactive decay can be written as

\[-\frac{dC}{dt} = kC\]

where

- \(C\) = concentration of the reactant
- \(t\) = time
- \(k\) = rate constant
Half-Life Calculations

\[-(dC/C) = k \, dt\]

\[-\int \frac{dC}{C} = k \int dt \quad \text{from } C = C_0 \text{ to } C, \quad \text{and } t = t_0 \text{ to } t, \quad \text{and we have}\]

\[-\ln \left(\frac{C}{C_0}\right) = k \left(t - t_0\right)\]

\[K = \frac{(2.303/t) \log \left(\frac{C_0}{C}\right)}{t_0 = 0}\]
If we let \( C_0 = 1.0 \) and \( C = 0.5 \) at \( t_{1/2} \) then

\[
k = \frac{(2.303/t_{1/2}) \log(1/0.5)}{t_{1/2}}
\]

\[
= \frac{(2.303 \times 0.3010)}{t_{1/2}}
\]

\[
k = \frac{0.693}{t_{1/2}}
\]

And thus, \( t_{1/2} = \frac{0.693}{k} \)
Half-Life Calculations

Keep in mind:

Other environmental contaminants such as lead, cadmium, and mercury do not degrade.

We must remind people that radionuclides do decay with time in a quantitative manner.

Some organic chemicals decay (chemical and biochemical), but the rate is uncertain and system-specific.
Half-Life Calculations

A biological half-life ($T_{bio}$) is the time required for the sum of all the available biological processes to eliminate one-half of the retained radionuclide.

The effective half-life ($T_{eff}$) is the time required for the activity of a radionuclide to be halved as a result of both radioactive decay and biological elimination.

$$T_{eff} = \frac{(T_{bio} \times t_{1/2})}{(T_{bio} + t_{1/2})}$$
### Effective Half-Life

**Table 2-2. Effective Half-Lives of Selected Radionuclides in Major Adult Body Organs**

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Critical organ</th>
<th>Physical</th>
<th>Biological</th>
<th>Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium ($^3$H)</td>
<td>Whole body</td>
<td>12.3 yr</td>
<td>12 d</td>
<td>12d</td>
</tr>
<tr>
<td>Iodine-131 ($^{131}$I)</td>
<td>Thyroid</td>
<td>8 d</td>
<td>138 d</td>
<td>7.6 d</td>
</tr>
<tr>
<td>Strontium-90 ($^{90}$Sr)</td>
<td>Bone</td>
<td>28 yr</td>
<td>50 yr</td>
<td>18 yr</td>
</tr>
<tr>
<td>Plutonium-239 ($^{239}$Pu)</td>
<td>Bone</td>
<td>24,400 yr</td>
<td>200 yr</td>
<td>198 yr</td>
</tr>
<tr>
<td></td>
<td>Lung</td>
<td>24,400 yr</td>
<td>500 yr</td>
<td>500</td>
</tr>
<tr>
<td>Cobalt-60 ($^{60}$Co)</td>
<td>Whole body</td>
<td>5.3 yr</td>
<td>9.5 d</td>
<td>9.5 d</td>
</tr>
<tr>
<td>Iron-55 ($^{55}$Fe)</td>
<td>Spleen</td>
<td>2.7 yr</td>
<td>600 d</td>
<td>388 d</td>
</tr>
<tr>
<td>Iron-59 ($^{59}$Fe)</td>
<td>Spleen</td>
<td>45.1 d</td>
<td>600 d</td>
<td>41.9 d</td>
</tr>
<tr>
<td>Manganese-54 ($^{54}$Mn)</td>
<td>Liver</td>
<td>303 d</td>
<td>25 d</td>
<td>23 d</td>
</tr>
<tr>
<td>Cesium-137 ($^{137}$Cs)</td>
<td>Whole body</td>
<td>30 yr</td>
<td>70 d</td>
<td>$\approx$70 d</td>
</tr>
</tbody>
</table>

* Mixed in body water as tritiated water

\(d = \text{days; yr = years}\)
In a poll of 15 European countries, 16,000 participants were asked:

True or false? “All radioactive waste is very dangerous.”

14% said “false”
11% “don’t know”
75% said “true”
Exposure and Risk

Where do the data come from?
1. Survivors of Hiroshima and Nagasaki.
2. Patients exposed to medical radiation.
3. Occupational exposure in the nuclear industry.
Exposure and Risk

Linear non-threshold model

Response

Dose

Control
Exposure and Risk

Linear model with a threshold
(No observed adverse effect level)
Exposure and Risk

Hormesis

NOAEL

Control

Dose

Response
Exposure and Risk

The linear, no threshold model (LNT) is used by the US EPA, FDA, and NRC. Has been called “a regulatory convenience.”

The LNT model is most radiologically conservative.

The use of the LNT model implies that any exposure to radiation poses some health risk, i.e. there is no safe dose.
Limitations in using the LNT model

The relation between risk and dose at small levels of radiation is not well understood.

Most of the data based on large levels of exposure. “Hiroshima should not be the gold standard.”

If 1,000 aspirin kills one person (taken all at once), then does it follow that 1 aspirin should kill one person out of 1,000?
Limitations in using the LNT model

Background cancer rate is 0.20 (1 in 5).

At small levels of radiation, difficult to differentiate noise from signal. Smallest dose the epidemiologist can measure risk reliably is about 10 rem.

Cancer development is complicated.

Not all cancers are diseases. Cells become damaged everyday and repair themselves; a normal process of life.
Limitations in using the LNT model

People often have cancerous cells, but progression to full malignancy is rare.

Non-target cells (not hit by radiation) can “communicate” with impacted cells.

Cancers appear years after exposure (long latent period).
Limitations in using the LNT model

Linearity is in question: may depend on the organ.

Breast cancer is thought to be linear.

Bone cancer from radium exhibits a threshold dose response.
Deterministic Model

- Cells undamaged
- Cells damaged but repair and operate normally
- Cells damaged, repair the damage, but operate abnormally
- Cells die because of damage

Fig. 2.2 Deterministic effects of radiation