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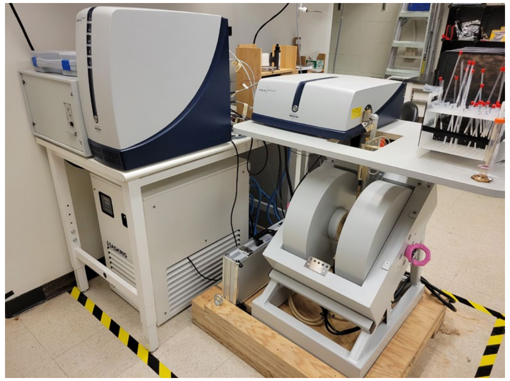
Radiological Risk in Perspective

Robert B. Hayes, PhD, CHP, PE Associate Professor
Fellow of the Health Physics Society
Fellow of the American Physical Society
Associate Editor *Radiation Physics and Chemistry*
Savannah River National Laboratory Joint Faculty Appointment

Nuclear Engineering Department
North Carolina State University
2500 Stinson Drive, Raleigh, NC 27695-7909
Office: (919) 515-2321, Fax: (919) 515-5115

RB Hayes



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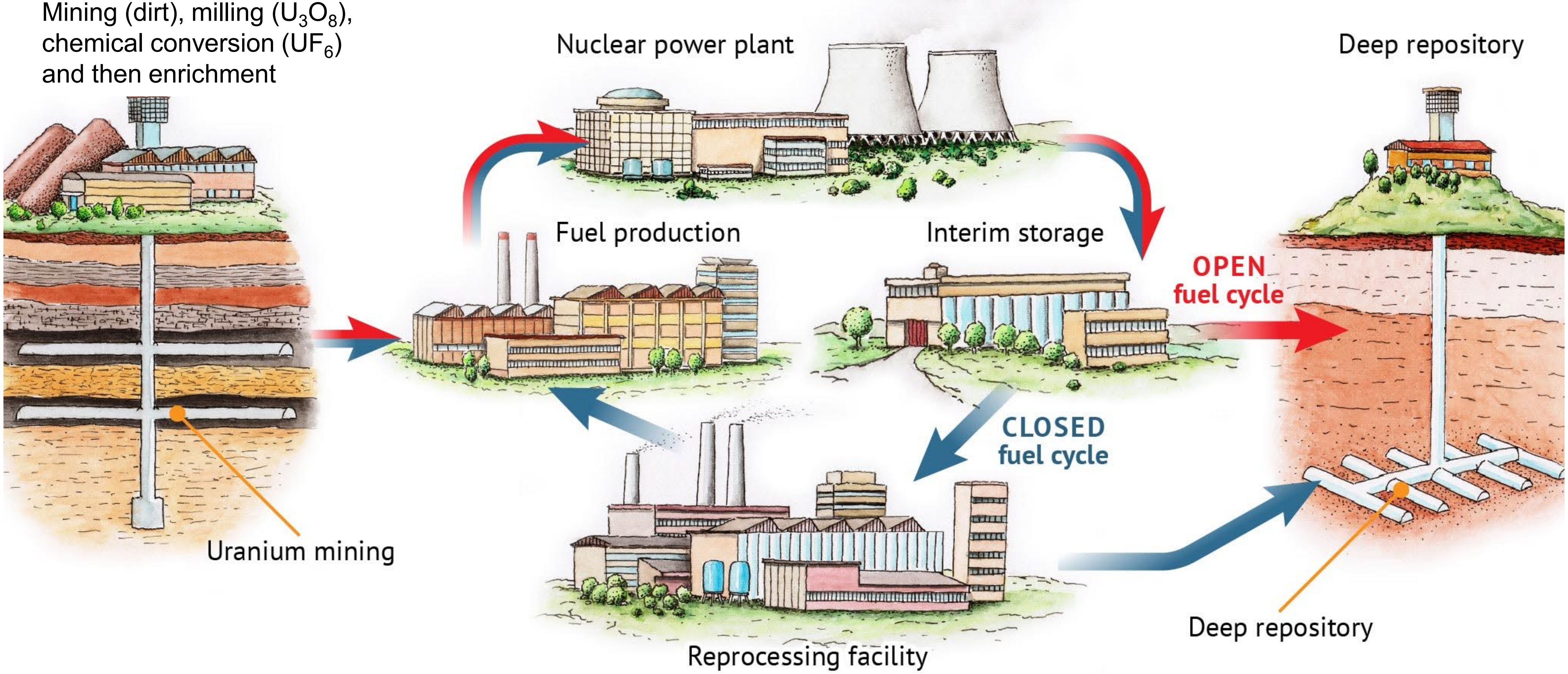
What are we going to cover?

- Nuclear fuel cycle
- Nuclear Waste
  - Interim storage
  - Scale of the problem
  - Transportation safety
  - Permanent disposal
- Radiation risk in context
  - What are the risks associated with radiation dose
  - Where do we normally get radiation dose?
- Environmental impact
  - Why renewables are so important
  - Why nuclear is so complimentary
- Nuclear Accidents
  - Three Mile Island
  - Fukushima
  - Chernobyl
  - Safety (transportation and industrial)
- Questions

The nuclear fuel cycle

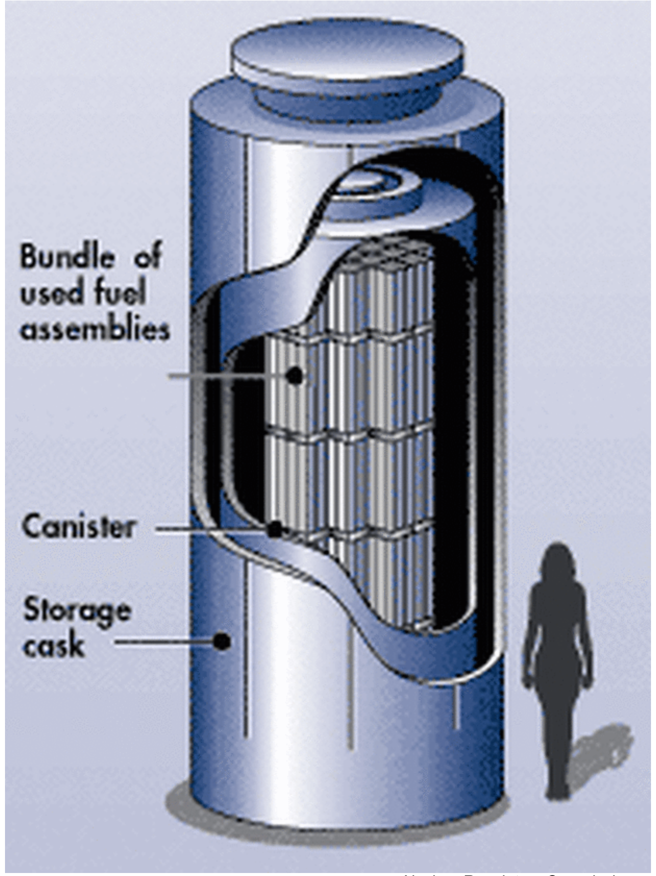
Mining (dirt), milling (U_3O_8), chemical conversion (UF_6) and then enrichment



Credit: EnergyEncyclopedia.com https://www.energyencyclopedia.com/en/free-downloads

Used nuclear fuel

- We have used nuclear fuel whether we like it or not
- We will have more used nuclear fuel than we do now
- We need to find a solution whether we support nuclear energy or not



Nuclear Regulatory Commission https://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html

Dry casks used to store nuclear waste. Photo from the Nuclear Regulatory Commission.

Interim storage

Nuclear Regulatory Commission

Scale of the problem

- The US has received almost 20% of its electrical supply for over 50 years.
- Despite this, according to the US Department of Energy,‡ “In fact, the U.S. has produced roughly 83,000 metric tons of used fuel since the 1950s—and all of it could fit on a single football field at a depth of less than 10 yards.”

‡ Accessed May 30, 2020 https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel

U.S. Department of Energy

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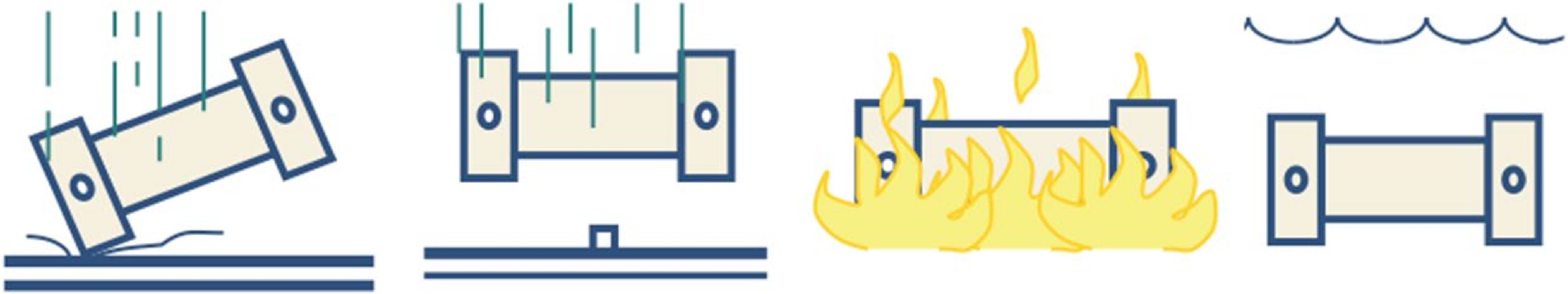
Transportation Safety



1. 30 ft drop onto unyielding surface
2. 40 inch drop onto steel bar
3. 1475^{o} F for 30 min
4. 50 ft water for 8 hrs

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

As of July 2018

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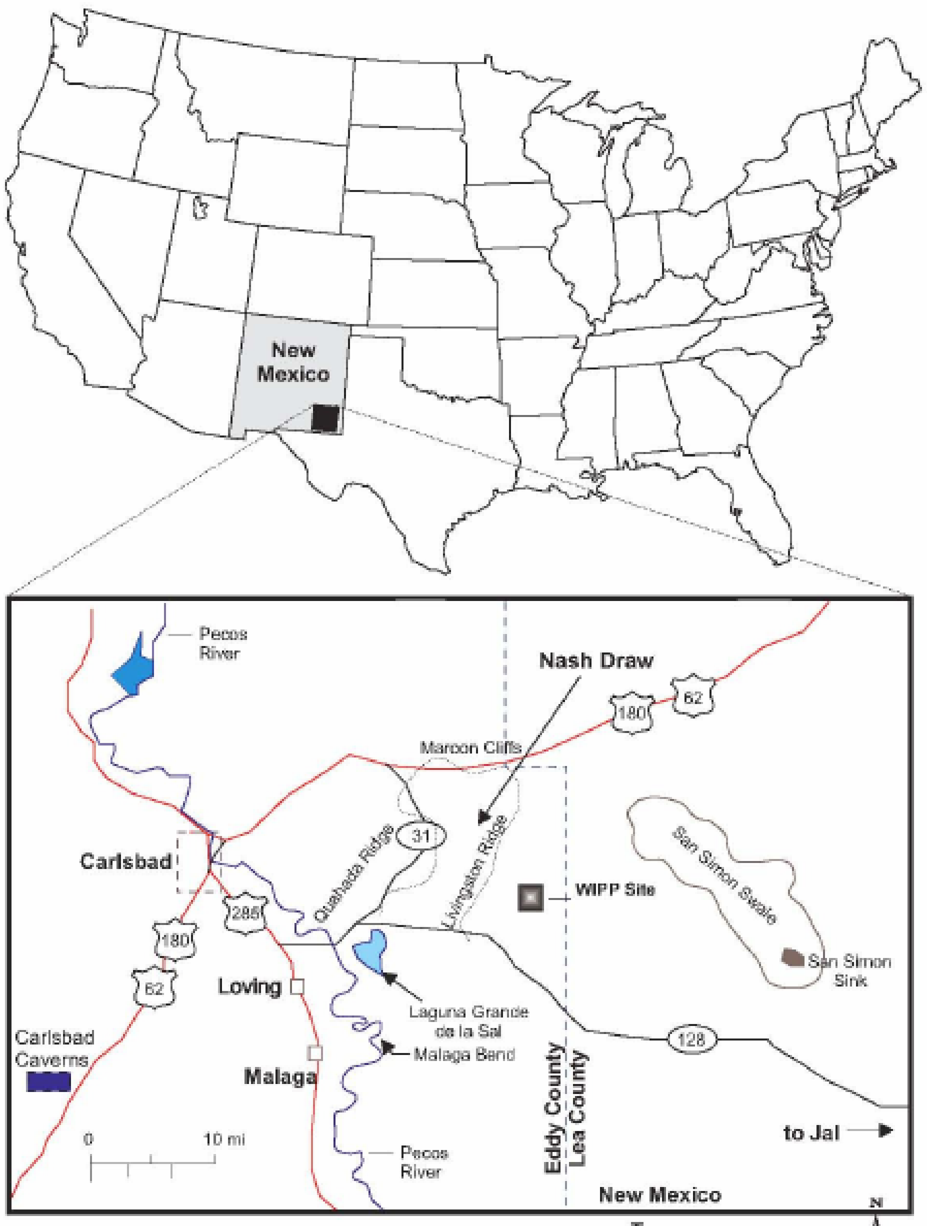
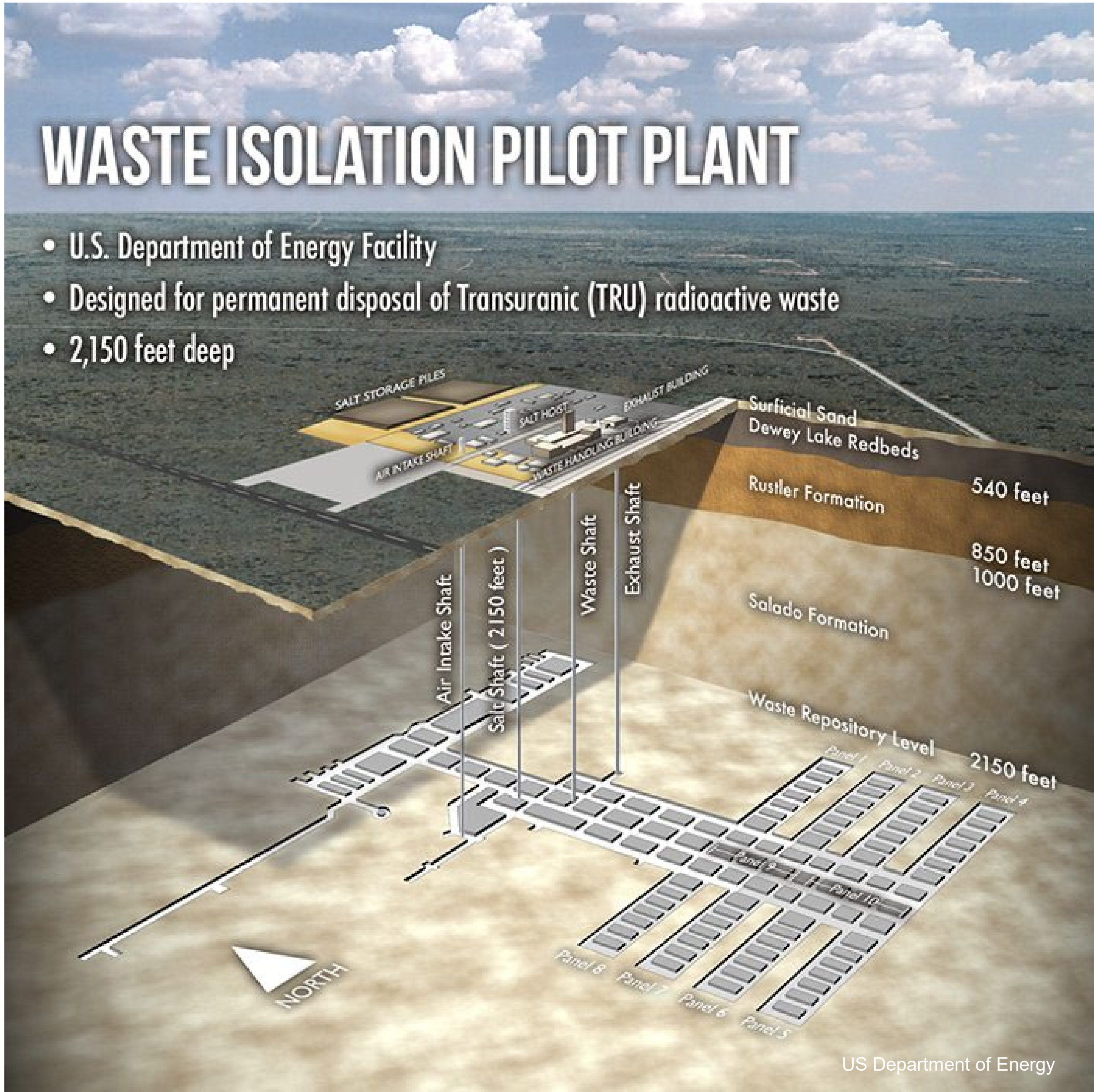
Permanent Disposal



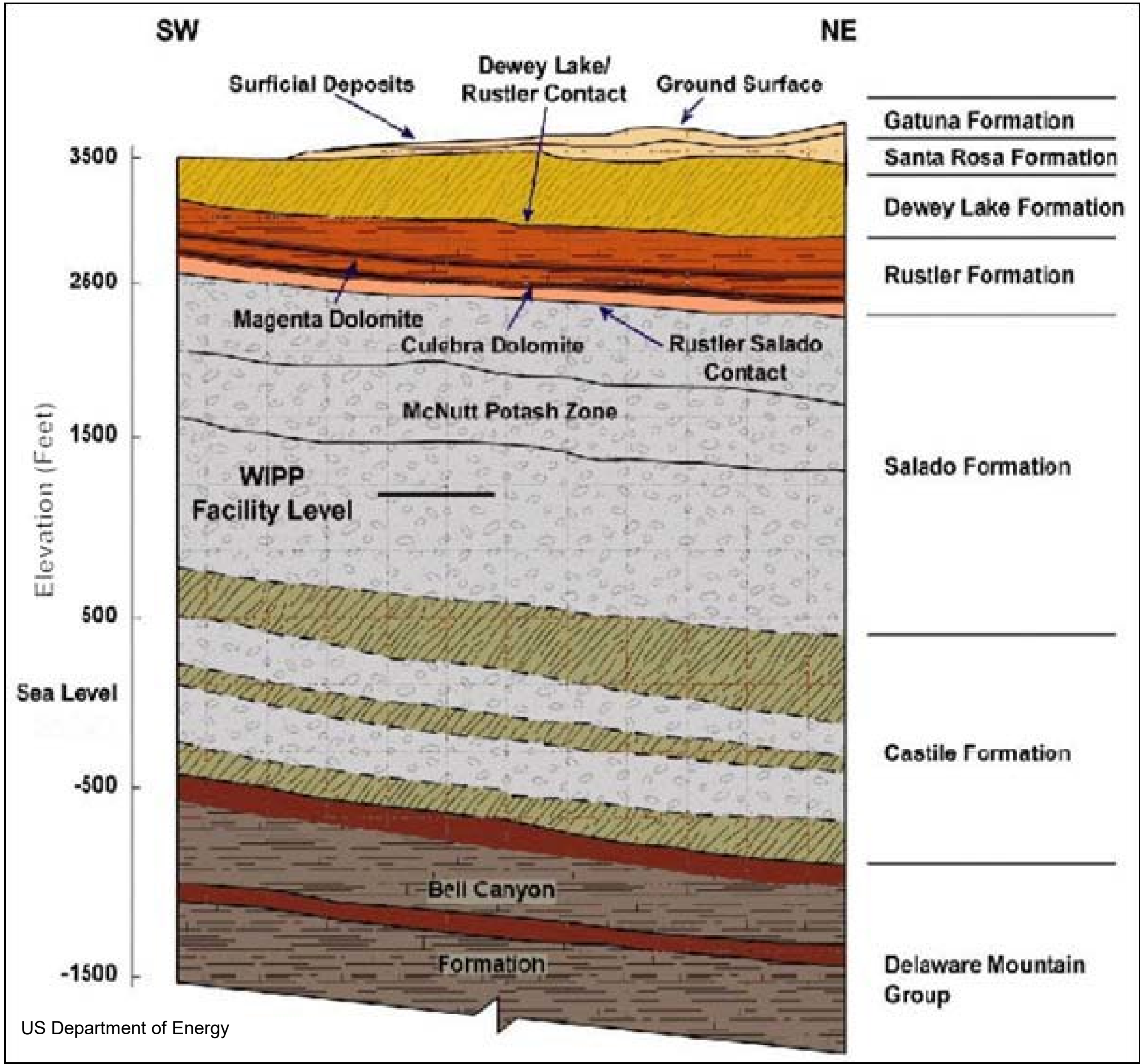
Office of Scientific and Technical Information



US Department of Energy

Waste Isolation Pilot Plant (WIPP)

International Atomic Energy Agency



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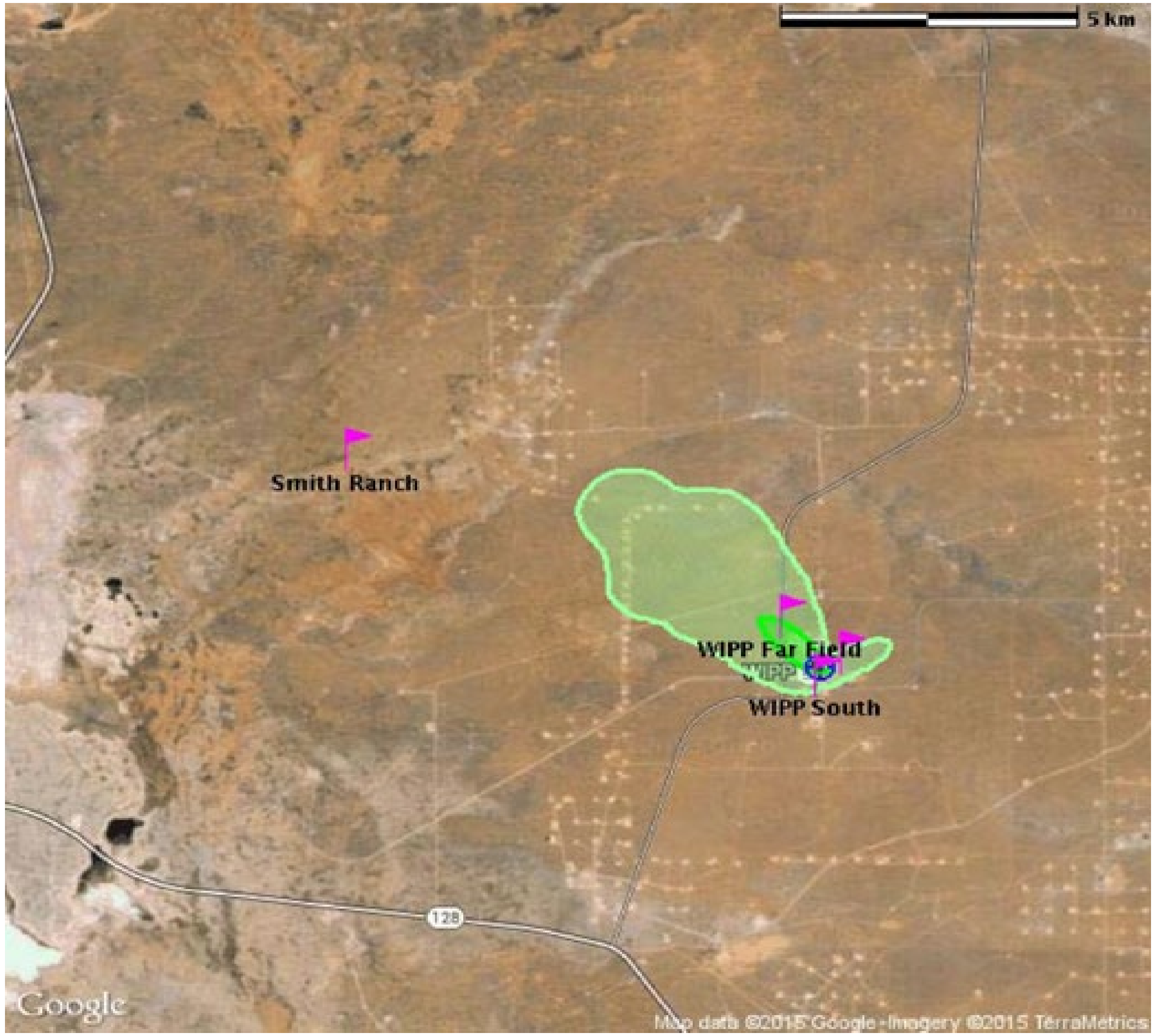
The 2014 WIPP release event

Hayes R. B. (2016) Consequence assessment of the WIPP radiological release from February 2014. *Health Phys*. **110**(4), 342-360.



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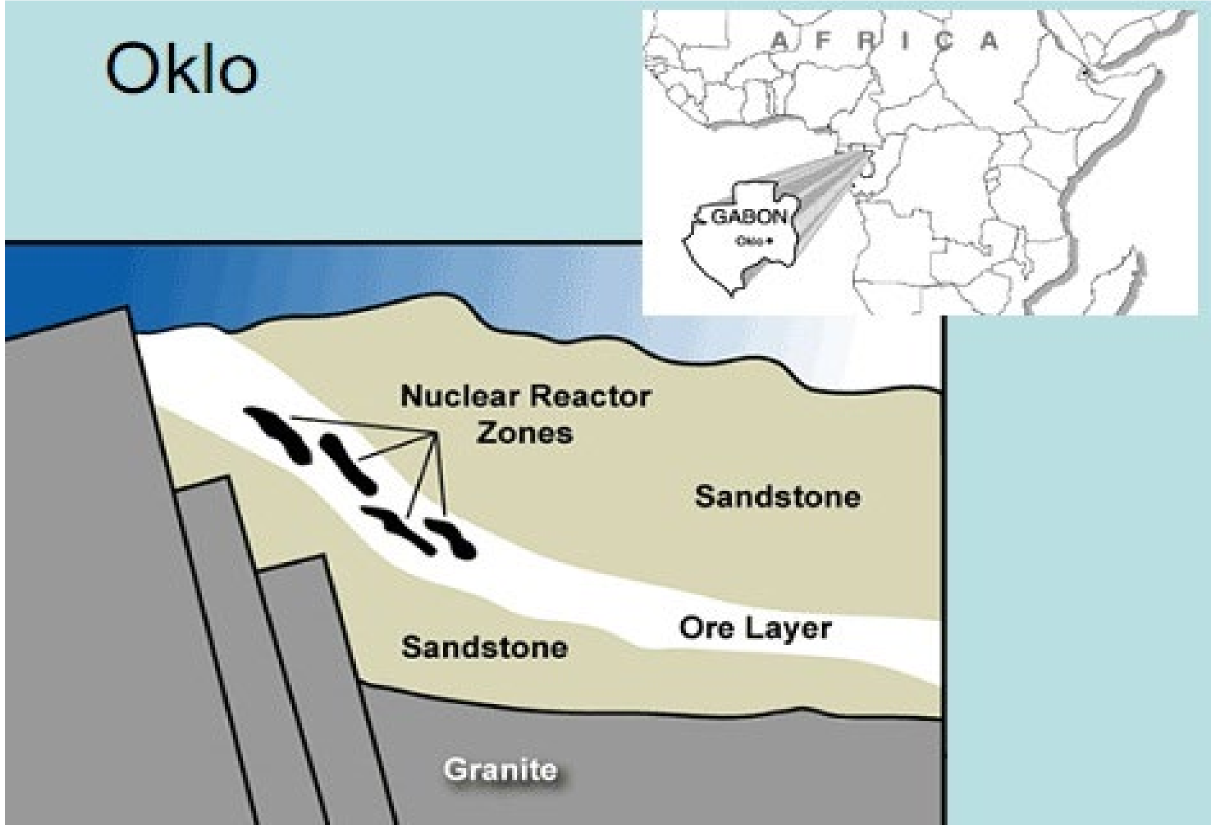
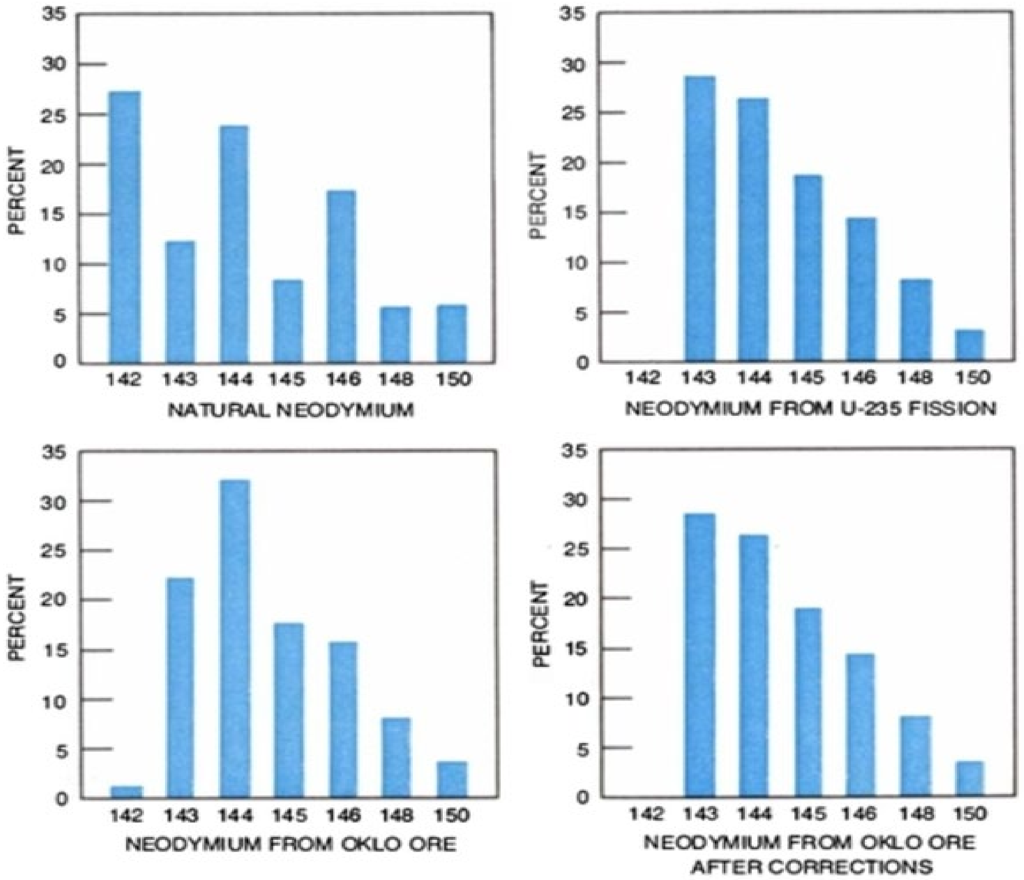
Mother natures example of geological disposal for used nuclear fuel



Cowan, G. A. (1976). A natural fission reactor*Scientific American, 235*(1), 36-47. doi:10.1038/scientificamerican0776-36



Hayes RB. (2022) The ubiquity of nuclear fission reactors throughout time and space. *Physics and Chemistry of the Earth, Parts A/B/C* **125**, 103083

Radiation Risk in Context

- **1 mrem** = daily background

123RF.com

Radiation Risk in Context

- 1 mrem 
  - **5 mrem,** coast to coast round trip, EPA annual drinking water standard

EPA

Radiation Risk in Context

- 1 mrem
  - 5 mrem

- **10 mrem** = EPA annual limit for offsite airborne effluent release

EPA

^{40}K

Freepik.com

Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - **40 mrem**, maximum internal dose from natural potassium

EPA

^{40}K

R.B. Hayes

R.B. Hayes

Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- **100 mrem** public dose limit from any nuclear facility or a pelvis X-ray

EPA

^{40}K

Shutterstock

Pixabay: Mingo123

Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem,
- 100 mrem
  - **320 mrem** average annual natural background



EPA




^{40}K

NASA

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Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- **1,000 mrem,** minimum EPA evacuation guideline or nuclear medicine stress test or head, chest or hip CT scan







^{40}K

Dr. James Heilman, CC SA

NUCLEAR EMERGENCY SUPPORT TEAM

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Radiation Risk in Context



EPA


- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - **5,000 mrem** maximum radiation worker legal dose




^{40}K

NEST
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Naval Medical Center San Diego

R.B. Hayes

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Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- **10,000 mrem** is potentially a 0.5% cancer probability
  - Typical cancer probability from all sources is 40%

EPA

^{40}K

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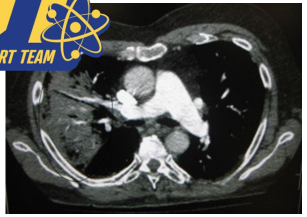

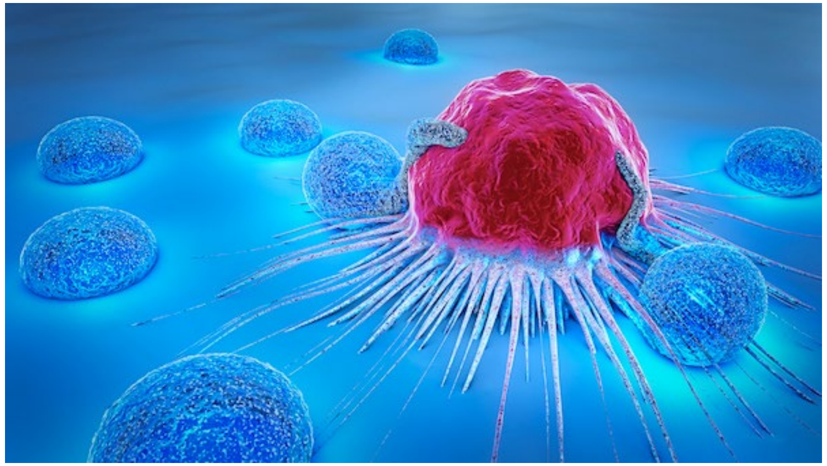

Adobe Stock

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Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- **100,000 mrem** gives a 5% increase in cancer probability



EPA




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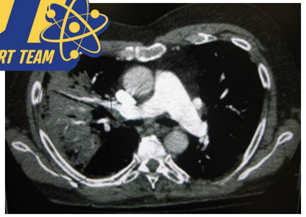
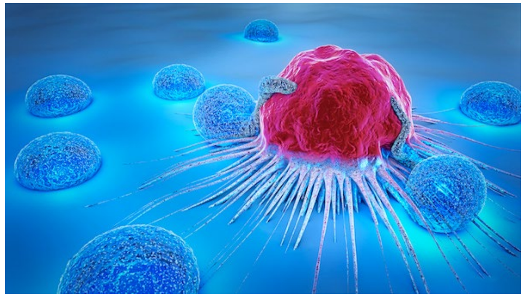


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Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- 100,000 mrem
  - **500,000 mrem** is around the LD30/50 dose (lethality)



EPA





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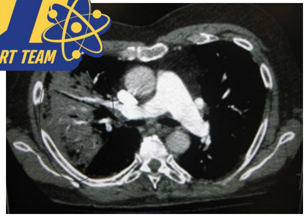


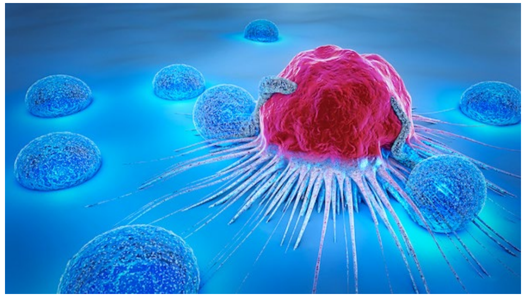


AP Photos: Public domain

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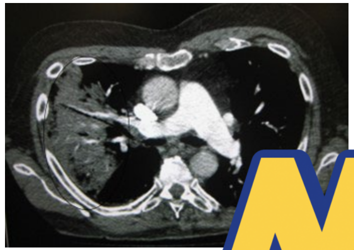
Radiation Risk in Context

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- 100,000 mrem
  - 500,000 mrem
- **1000,000 rem** likely death acute radiation syndrome







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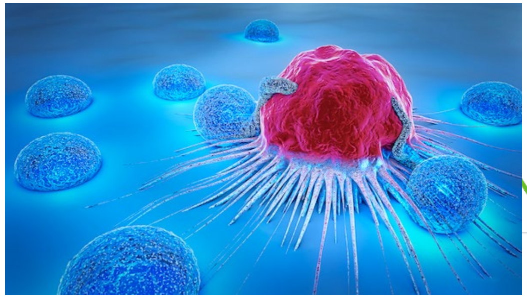
Ministry of Health and Family Welfare (India)

Radiation Risk in Context

- 1 mrem = daily background
  - 5 mrem, coast to coast round trip
- 10 mrem = EPA annual limit for offsite airborne effluent release
  - 40 mrem, maximum internal dose from natural potassium
- 100 mrem public dose limit from any nuclear facility or a pelvis X-ray
  - 320 mrem average annual natural background
- 1 rem minimum EPA evacuation guideline or nuclear medicine stress test or head, chest or hip CT scan
  - 5 rem maximum radiation worker legal dose
- 10 rem is potentially a 0.5% cancer probability increase
  - Typical cancer probability from all sources is 40%
- 100 rem gives a 5% increase in cancer probability
  - 500 rem is around the LD30/50 dose (lethality)
- 1000 rem expected death and acute radiation syndrome

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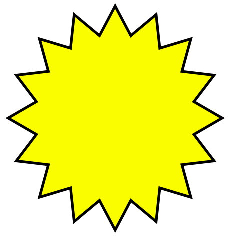
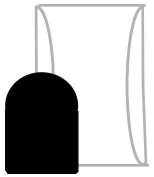
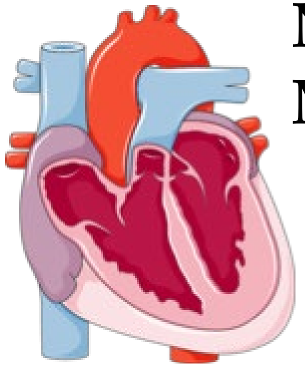
Where do we get dose?



Solar Radiation



Nuclear Energy

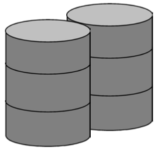


Servier.com

Nuclear Medicine

CT scans & X-rays

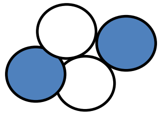
Radioactive Waste



Terrestrial Radiation

$^{4}_{2}\alpha^{++}$

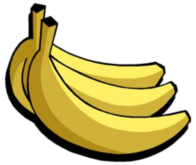
Radon



Consumer Products

Each Other

Food & Drink



Cosmic Rays

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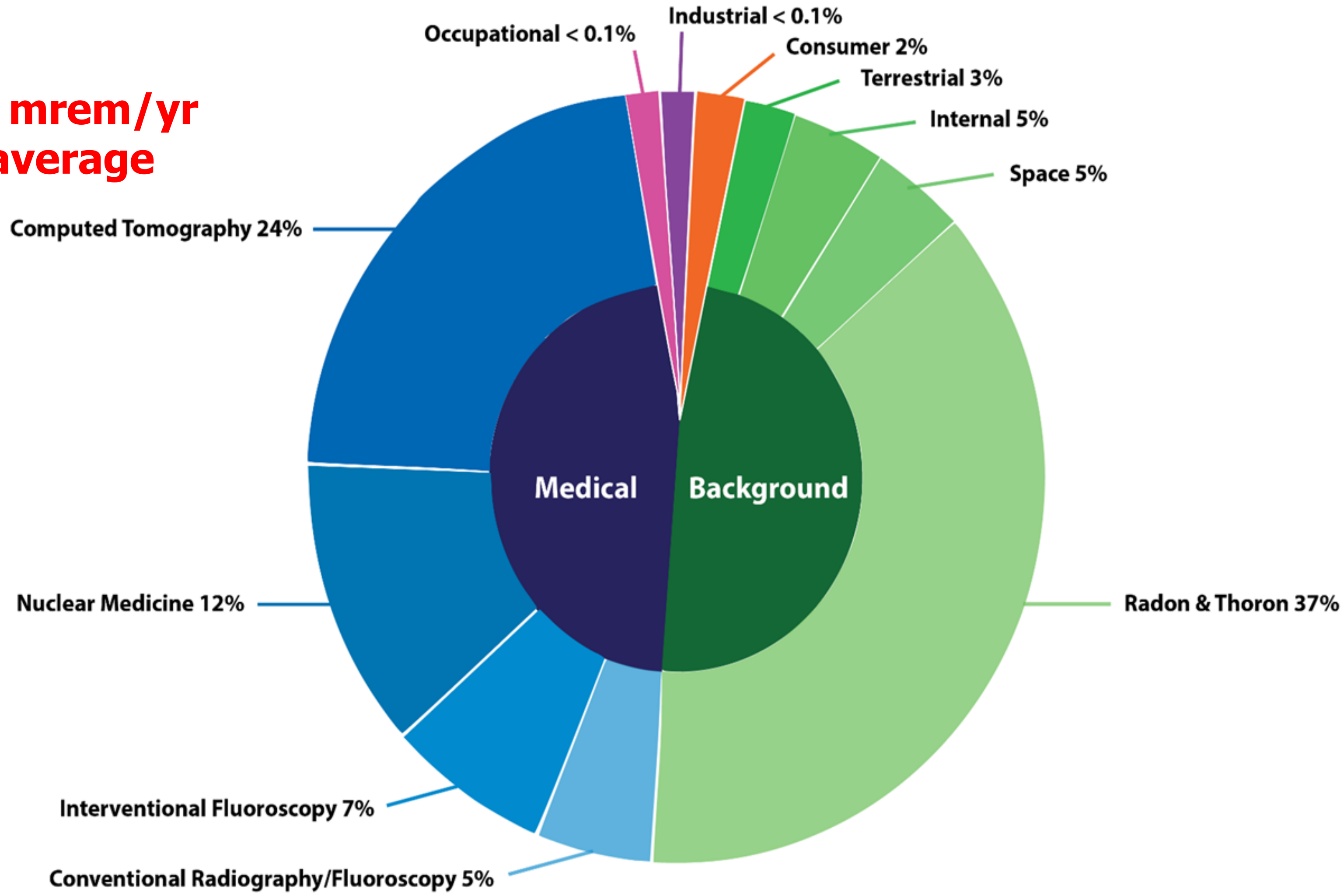
Sources of Radiation Exposure

625 mrem/yr
US average



Average Annual Radiation Dose

Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/ Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
Units mrem (United States) mSv (International)	228 mrem 2.28 mSv	147 mrem 1.47 mSv	77 mrem 0.77 mSv	43 mrem 0.43 mSv	33 mrem 0.33 mSv	33 mrem 0.33mSv	29 mrem 0.29 mSv	21 mrem 0.21 mSv	13 mrem 0.13 mSv	0.5 mrem 0.005 mSv	0.3 mrem 0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

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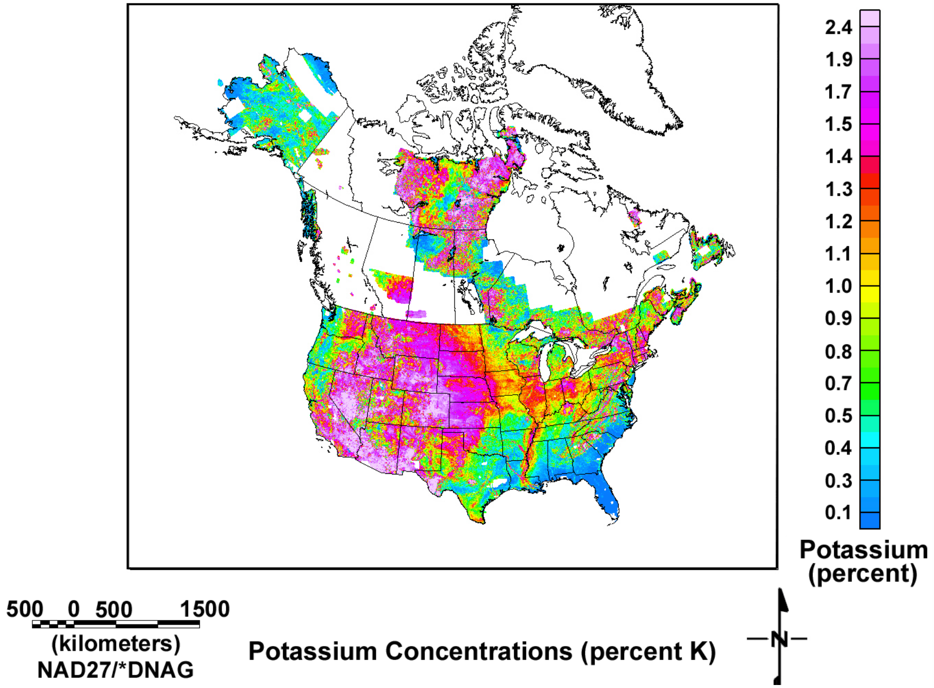
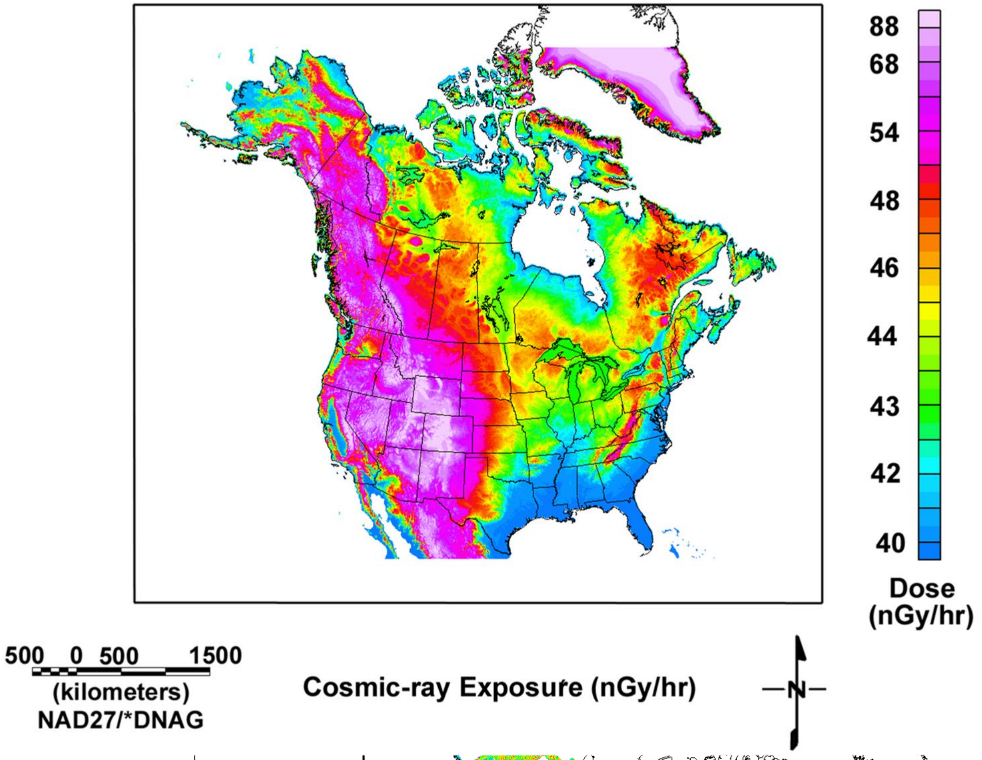
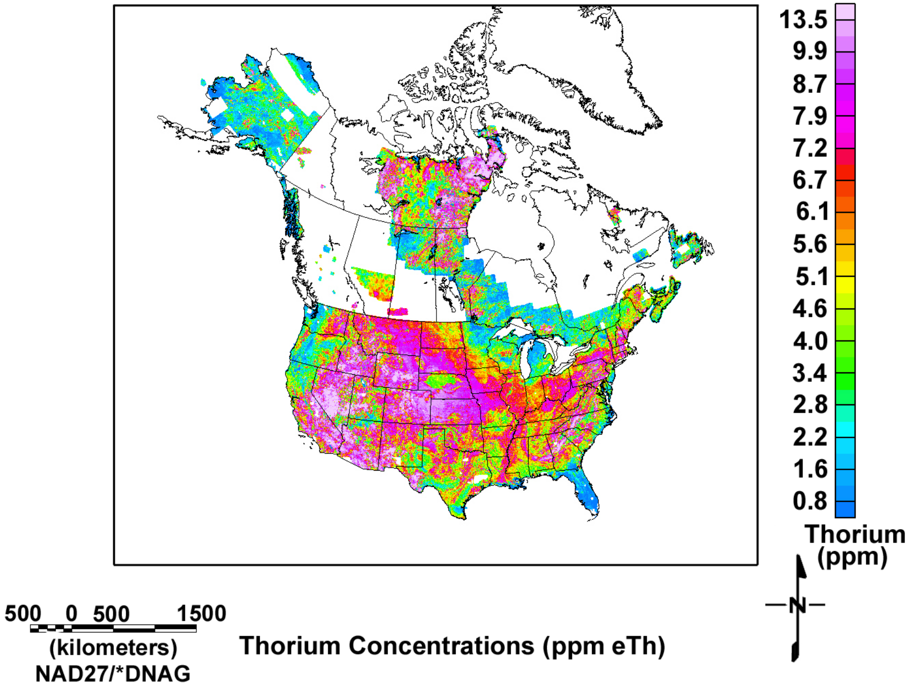
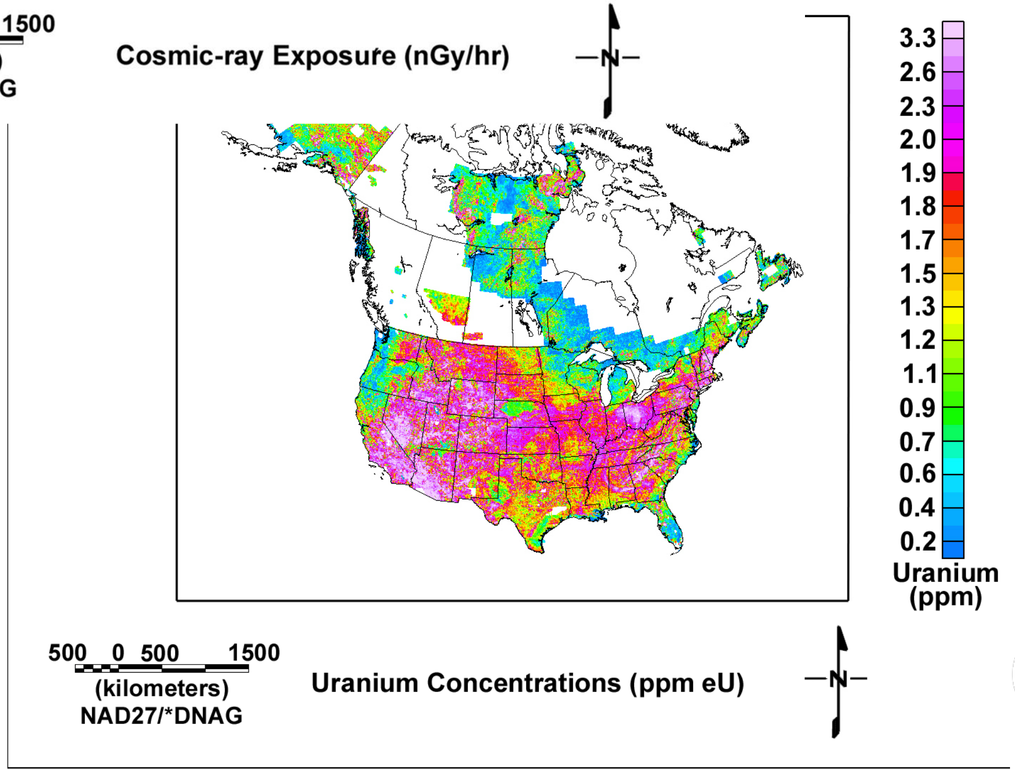




https://pubs.usgs.gov/of/2005/1413/NAMrad_U_let.gif





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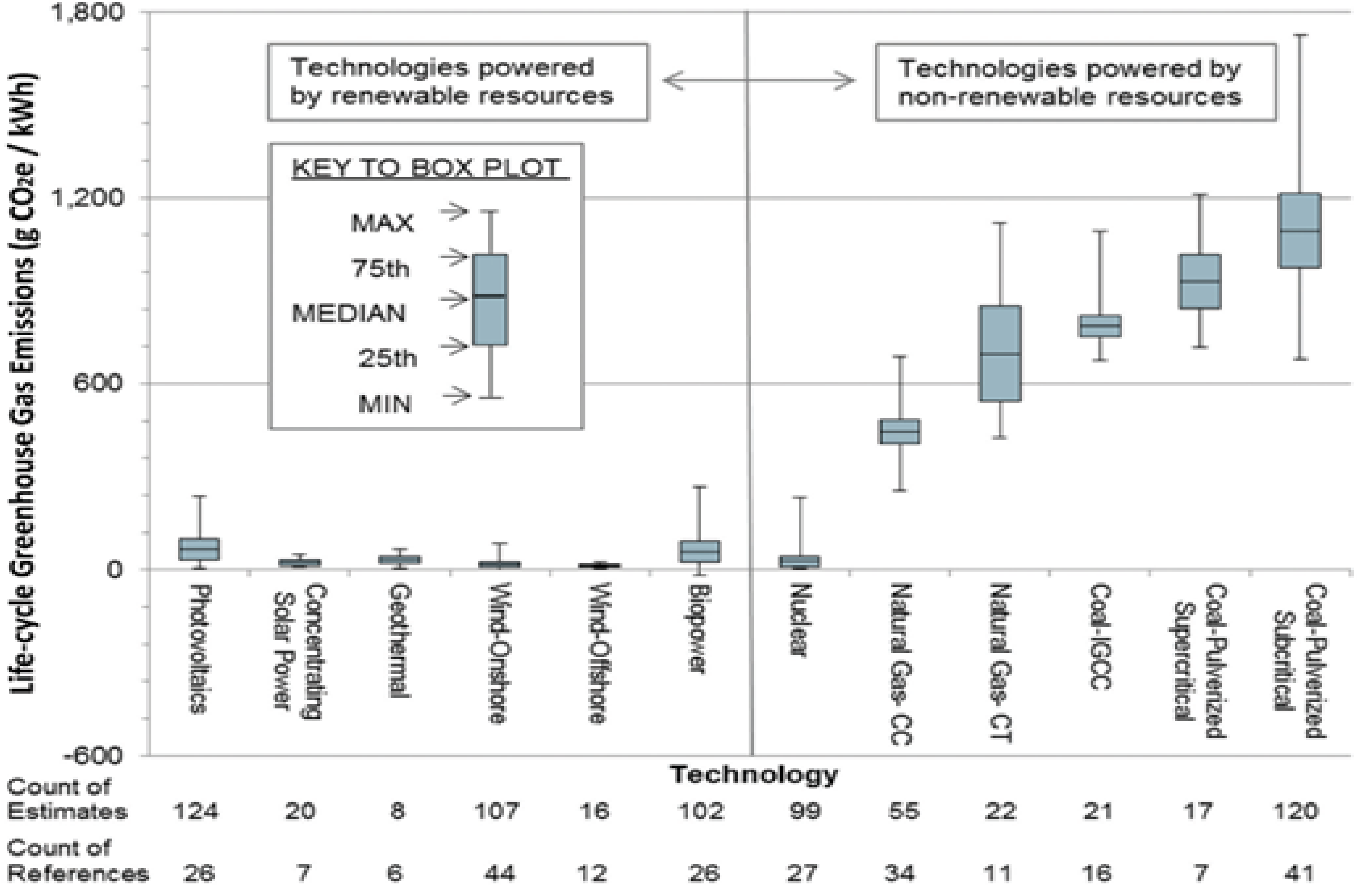
Environmental impact

- Why renewables are so important
- Materials requirements
- Land and materials requirements
- Safety is important too

Imgflip.com

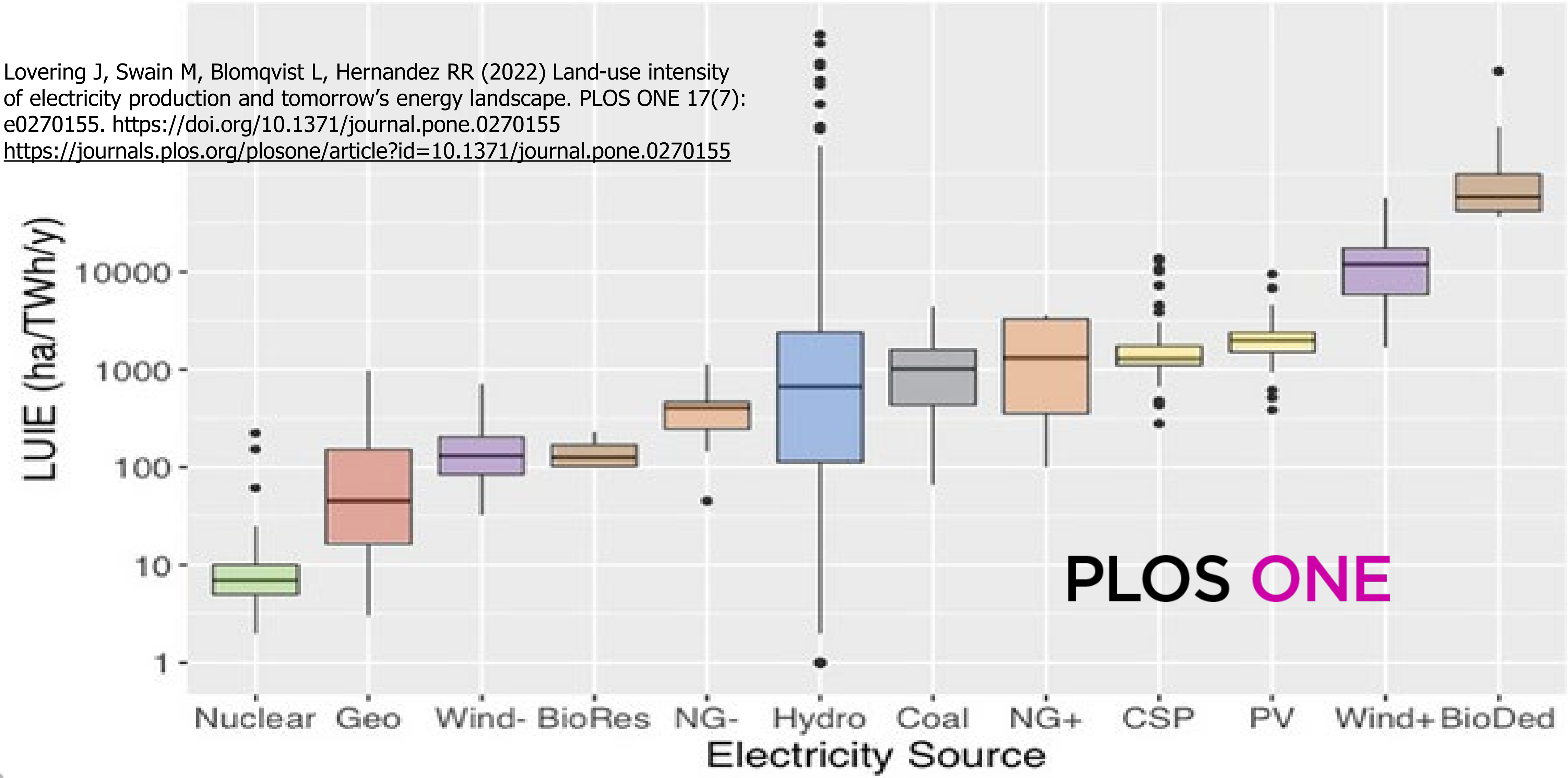
Why renewables are so important

- Life-cycle greenhouse gas emissions per kWh generated from all energy sources.
- *Quadrennial Technology Review An Assessment of Energy Technologies and Research Opportunities*, US Department of Energy, Washington DC, Sept 2015



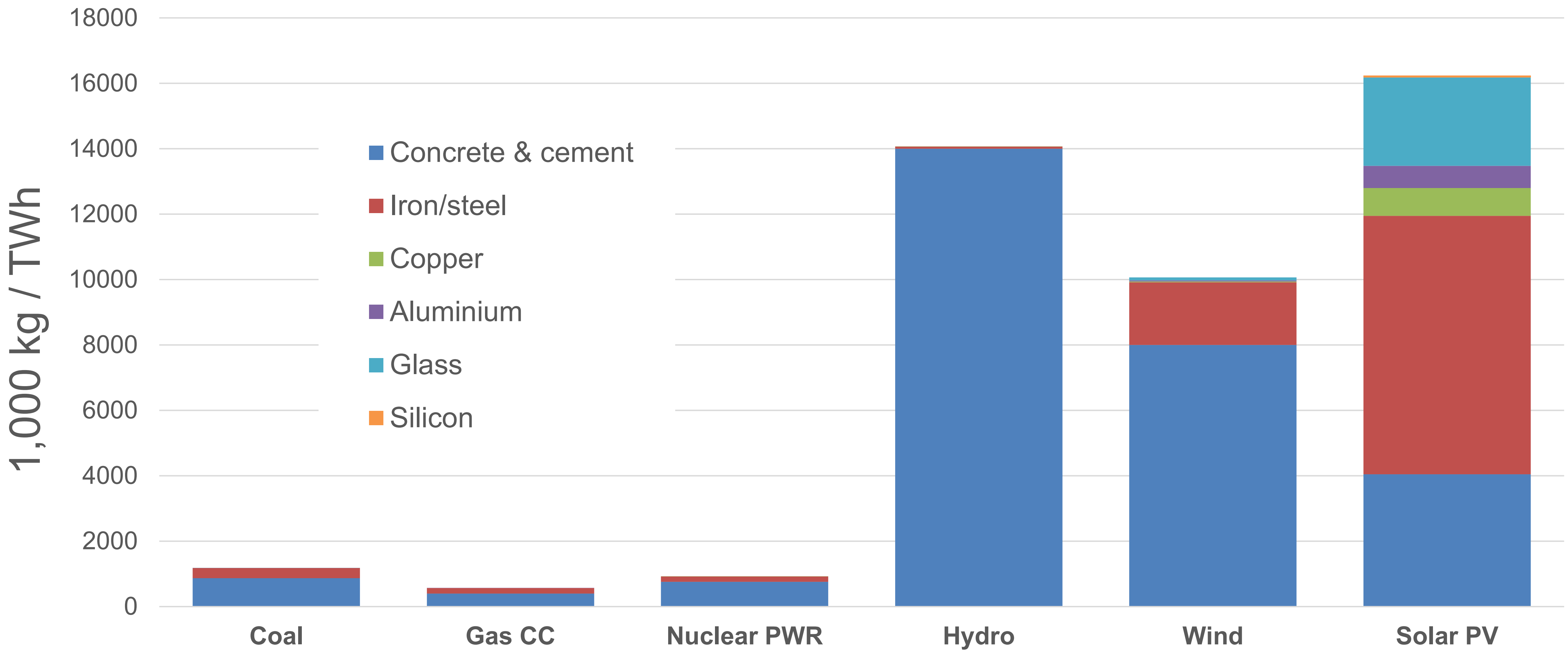
Land requirements

Lovering J, Swain M, Blomqvist L, Hernandez RR (2022) Land-use intensity of electricity production and tomorrow's energy landscape. PLOS ONE 17(7): e0270155. https://doi.org/10.1371/journal.pone.0270155
https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0270155



Land use intensity of electricity (LUIE: ha/TWh/y), shown on log scale.

Material requirements



US Department of Energy, 2015. Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities.

https://www.world-nuclear.org/information-library/energy-and-the-environment/mineral-requirements-for-electricity-generation.aspx accessed on 1/15/2024

Nuclear Accidents

- Three mile island
- Fukushima
- Chernobyl

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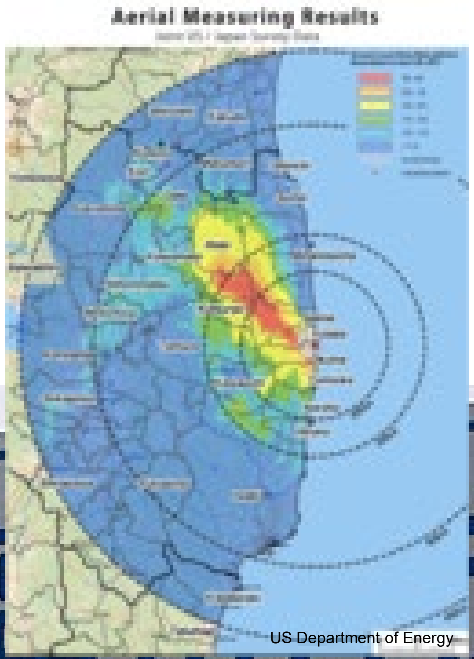
Wikimedia Commons CC-SA



US Department of Energy

Aircraft (NPP) & similar events?

Wikimedia, CC BY, https://commons.wikimedia.org/wiki/File:Another_Airplane!_(4676723312).jpg

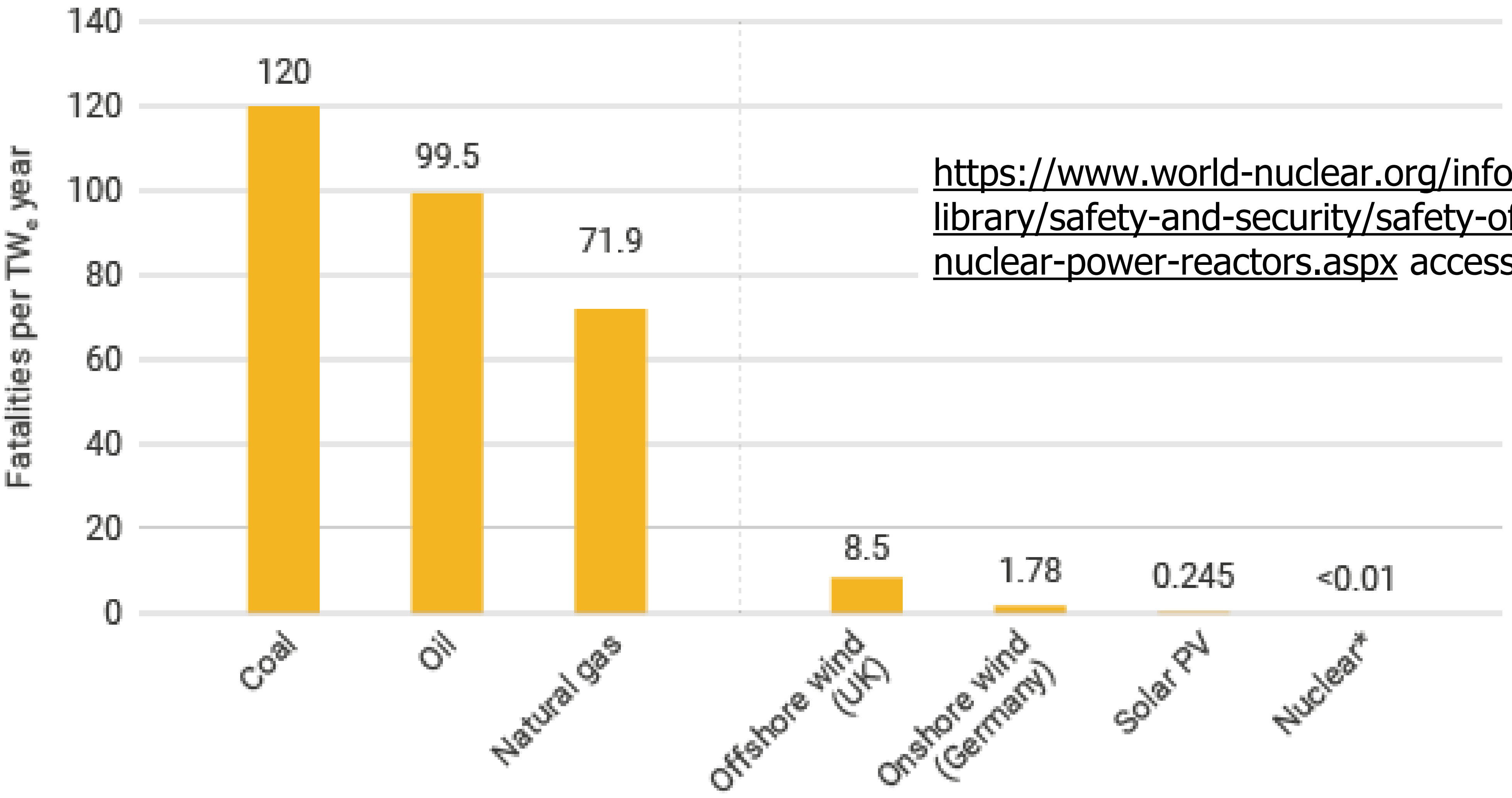
Kevin Koske, CC SA, https://en.m.wikipedia.org/wiki/File:United_Airlines_B777-222_N780UA.jpg

- **10 CFR 50.150 Aircraft impact assessment.**
- (a) *Assessment requirements*. (1) *Assessment*. … the effects on the facility of the impact of a large, commercial aircraft. Using realistic analyses,…
- (i) The reactor core remains cooled, or the containment remains intact; and
- … based on the beyond-design-basis impact of a large, commercial aircraft used for long distance flights in the United States, …

https://www.energy.gov/ne/articles/new-railcar-designed-transport-spent-nuclear-fuel-completes-final-testing

Custom train design

General safety



https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx accessed 8/26/2023

**Gen II PWR, Swiss.*
Source: Paul Scherrer Institut. Data for nuclear accidents modified to reflect UNSCEAR findings/recommendations 2012 and NRC SOARCA study 2015

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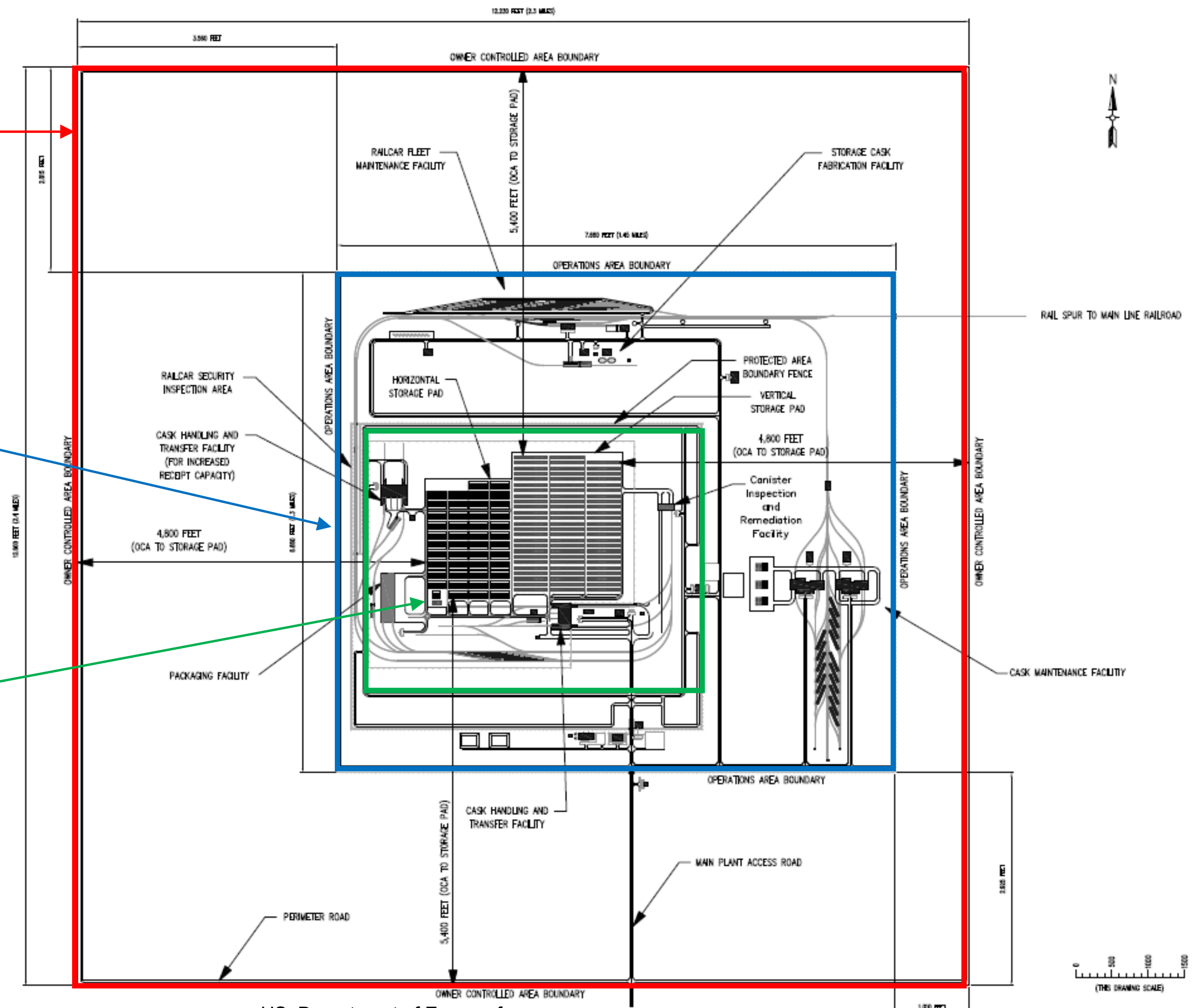
Reference Concept – Site Plan

Consolidated Interim Fuel Site

- **owner controlled area (OCA)**
  - 5.5 sq-miles (3,540 acres)
  - 4,800+ feet stand-off distance from edge of storage pad edge to OCA
- **operations area (OA)**
  - 1.9 sq-miles (1,210 acres)
  - fence boundary and perimeter road
  - includes administration and maintenance structures, Storage Cask Fabrication Facility, and OA railyard
- **protected area (PA)**
  - includes security and inspection structures, Cask Handling and Transfer Facility, dry storage pad, and PA railyard

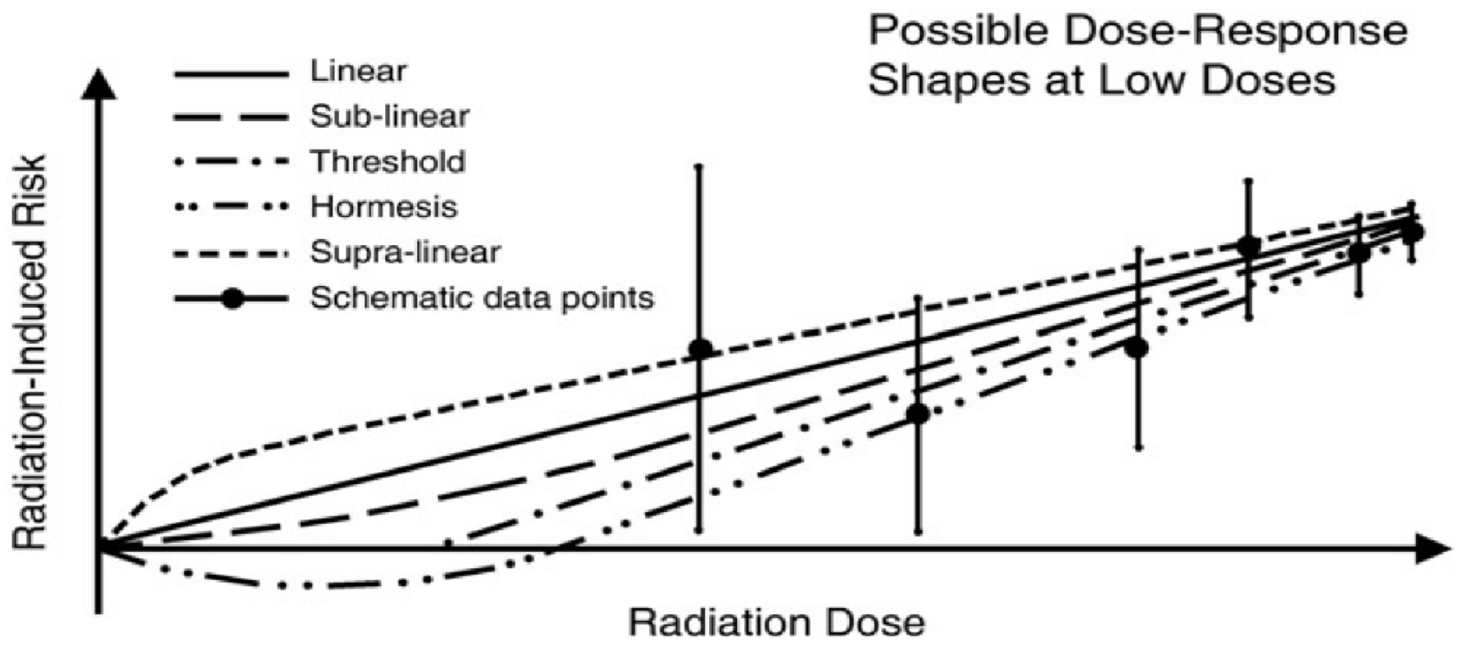


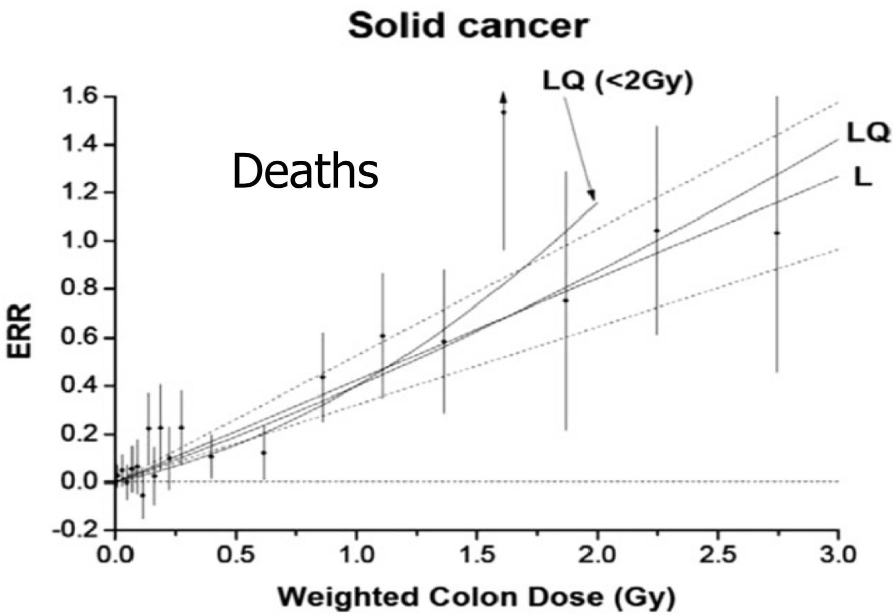
US. Department of Energy, from https://cdn.ymaws.com/inmm.org/resource/resmgr/gerard_jackson_-_transportat.pdf

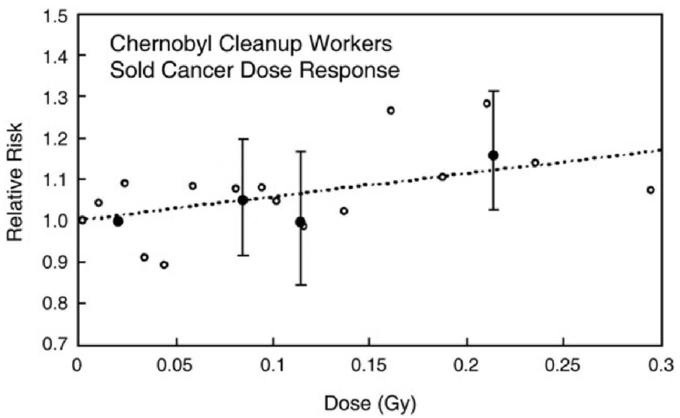
Questions?

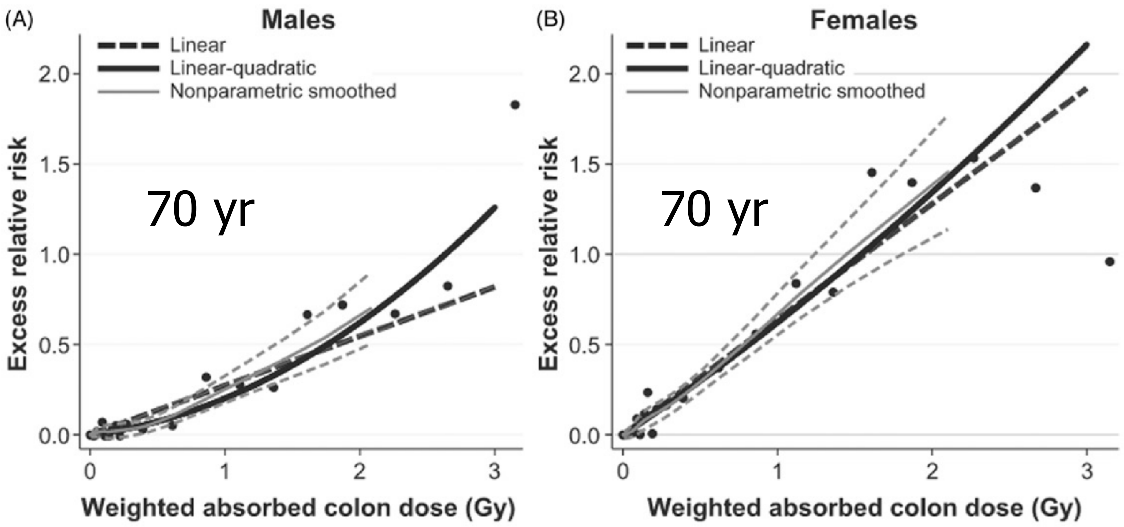
Spare slides for anticipated questions

Linear no-threshold theory









INTERNATIONAL JOURNAL OF RADIATION BIOLOGY,
2017 VOL. 93, NO. 10, 1079–1092
https://doi.org/10.1080/09553002.2017.1328750

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Fear, stress and cancer

- Fitzgerald, Devon M., P. J. Hastings, and Susan M. Rosenberg. "Stress-induced mutagenesis: implications in cancer and drug resistance." *Annual Review of Cancer Biology* 1 (2017): 119-140.
- Reiche, Edna Maria Vissoci, Sandra Odebrecht Vargas Nunes, and Helena Kaminami Morimoto. "Stress, depression, the immune system, and cancer." *The lancet oncology* 5, no. 10 (2004): 617-625.
- Sklar, L. S., & Anisman, H. (1981). Stress and cancer. *Psychological bulletin*, *89*(3), 369.
- Soung, Nak Kyun, and Bo Yeon Kim. "Psychological stress and cancer." *Journal of Analytical Science and Technology* 6 (2015): 1-6.
- Jin Shin, Kyeong, Yu Jin Lee, Yong Ryoul Yang, Seorim Park, Pann-Ghill Suh, Matilde Yung Follo, Lucio Cocco, and Sung Ho Ryu. "Molecular mechanisms underlying psychological stress and cancer." *Current pharmaceutical design* 22, no. 16 (2016): 2389-2402.

https://www.cancer.gov/about-cancer/coping/feelings/stress-fact-sheet

- Even when stress appears to be linked to cancer risk, the relationship could be indirect.
- For example, people under chronic stress may develop certain unhealthy behaviors, such as smoking, overeating, becoming less active, or drinking alcohol, that are themselves associated with increased risks of some cancers

Accessed 8/22/2023

Risk, what is risk, is it minimized?

$$\boldsymbol{Risk} = \sum_i \boldsymbol{Consequences}_{\,i} \times \boldsymbol{Probability}_{\,i} = \sum_i \boldsymbol{B_i} \times$$

In a generic sense, this would be to say that if risks from N outcomes have energy risk metrics of B_1 through B_N, then if each of these risks can be reduced by amounts C_1 through C_N per $ (Note C_i is a risk reduction per $), then the optimal fraction of the monetary distribution K_D for option A_D in reducing all the risks would be found from the weighted average $\boldsymbol{K_D} = (\boldsymbol{B_D} \cdot \boldsymbol{C_D})/\sum_{i=1}^{N}(\boldsymbol{B_i}\boldsymbol{C_i})$. If the total budget for risk reduction is then some value F, then the optimized $ to be spent on outcome A_D is then $F \times K_D$.

Hayes, RB. (2022) Nuclear energy myths versus facts support it's expanded use - a review. **Vol. 2,** *Cleaner Energy Systems* 100009, ISSN 2772-7831.

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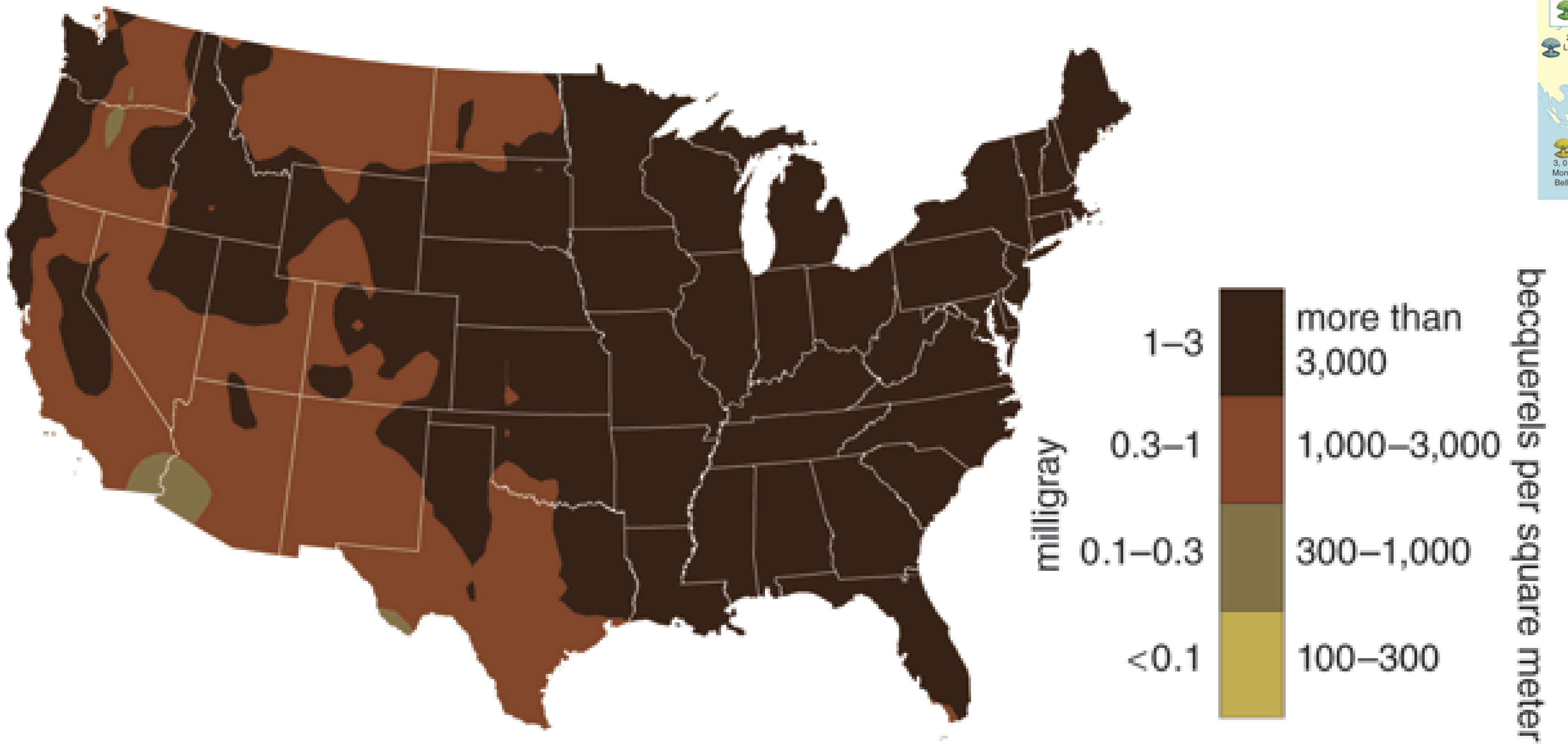
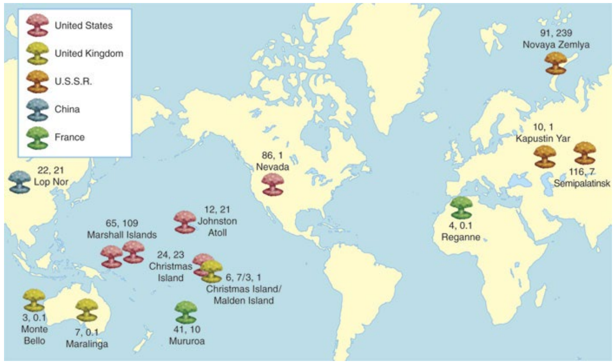
Nuclear weapons background doses

Dose to red bone marrow from global fallout for persons born on January 1, 1951,





3 mGy = 300 mrem
(less than natural
annual background)

Simon, Steven L., André Bouville, and Charles E. Land. "Fallout from nuclear weapons tests and cancer risks: exposures 50 years ago still have health implications today that will continue into the future." *American Scientist* 94, no. 1 (2006): 48-57.

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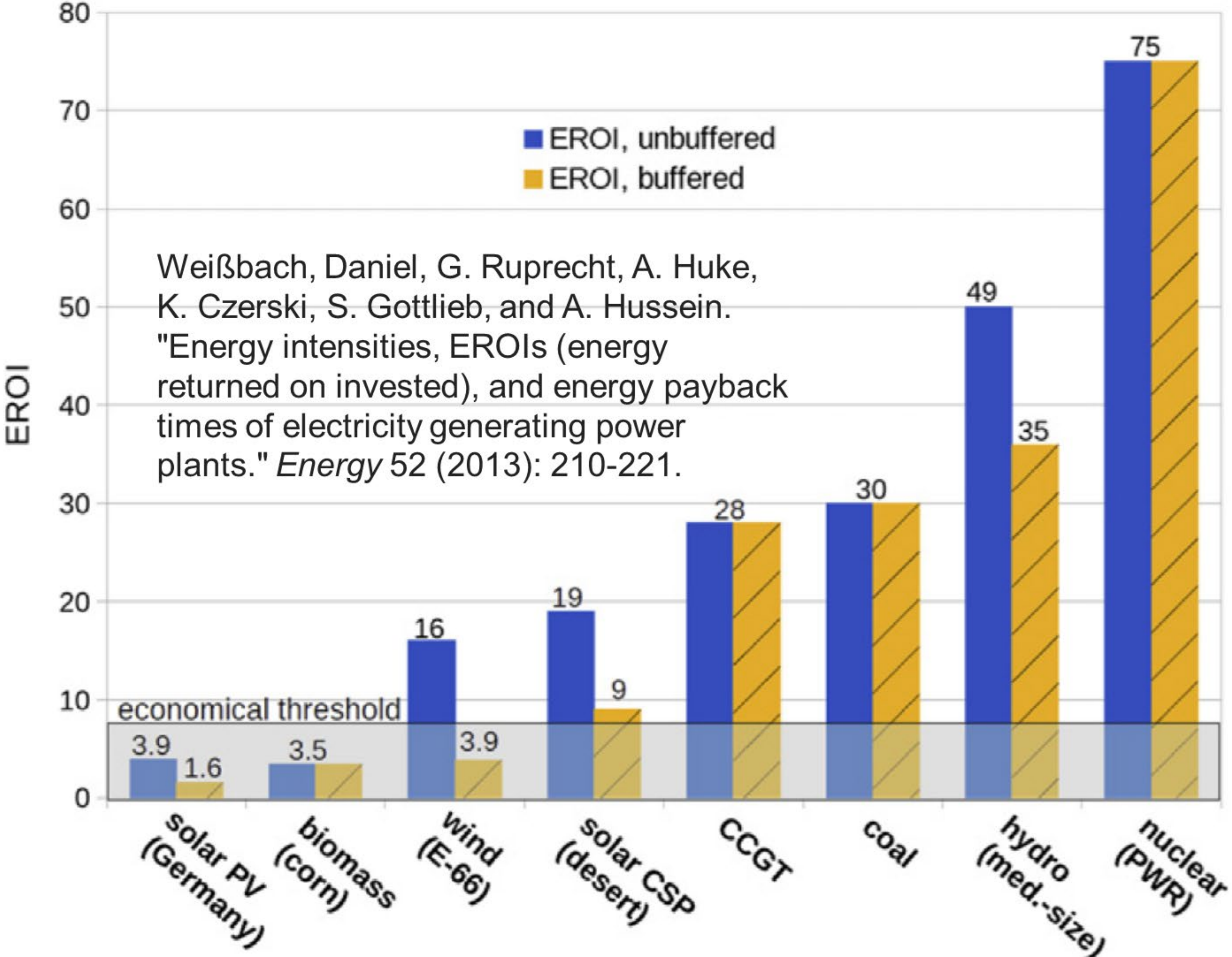

Weißbach, Daniel, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, and A. Hussein. "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants." *Energy* 52 (2013): 210-221.

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Can we move nuclear waste safely?

Croff AG, Hermann OW, Alexandder CW. Calculated, To-Dimensional Dose rates from a PWR Fuel Assembly. ORNL/TM-6754. Oak Ridge National Laboratory, Oak Ridge TN 1979.

<u>Approximate levels of risk</u>

10,000 rem ≈ Death

2,000 rem ≈ cataract event

400 rem ≈ LD50/30

100 rem ≈ gonad sterilization

20 rem ≈ cancer threshold

5 rem ≈ legal for radworker

0.5 rem < average US citizen

<u>How robust are the shipping containers?</u>

<u>https://www.nrc.gov/docs/ML1532/ML15322A230.pdf</u>

<u>https://www3.epa.gov/radtown/transporting-materials.html</u>

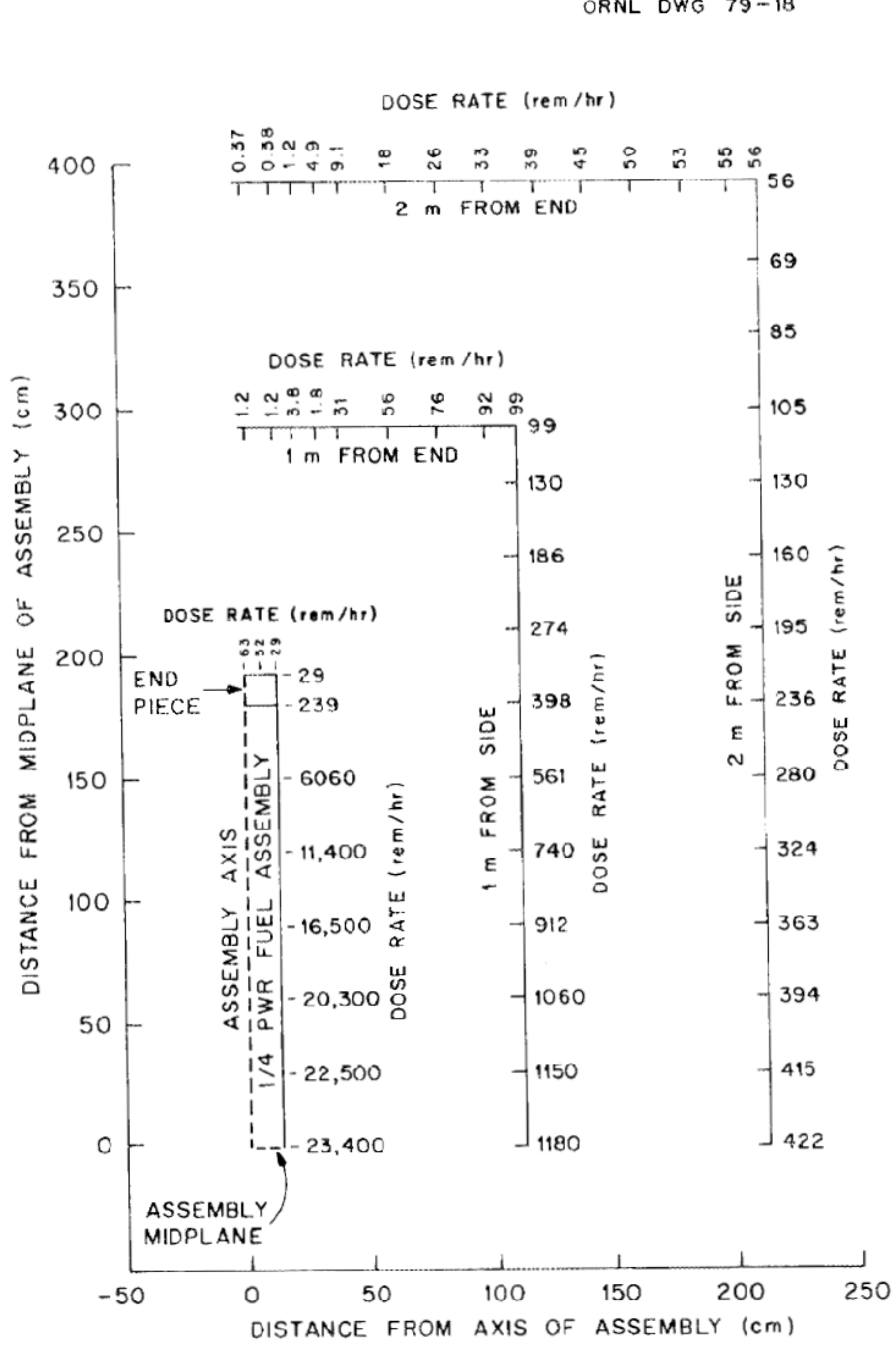

Fig. 8. Fission product dose rate from a 10-year-old PWR fuel assembly.

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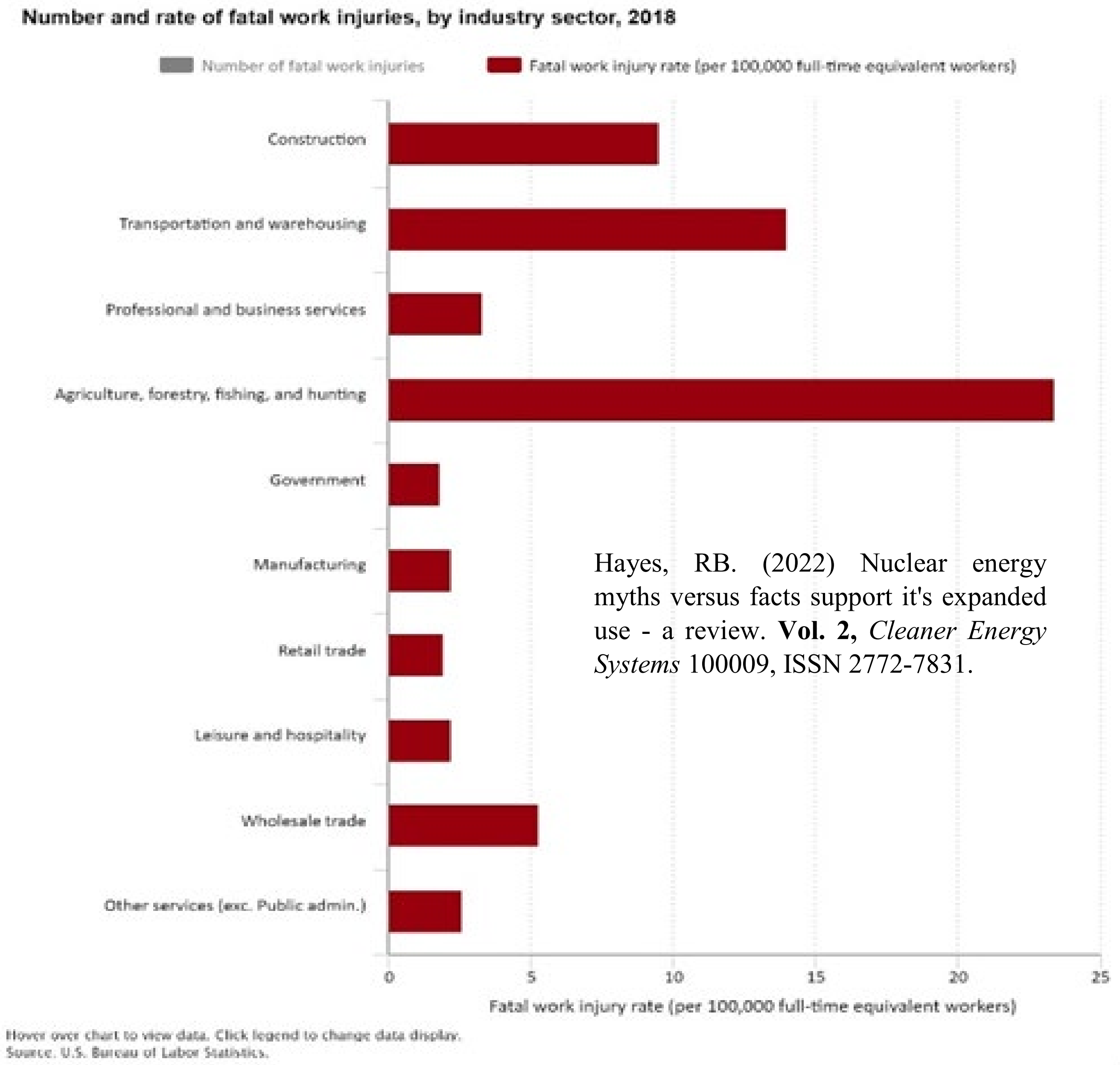
What are acceptable death rates?

An average of 4.4×10^{-5} fatalities per year for a 0.014 GW wind farm which looks negligibly small compared to the values on the right but not compared to nuclear. Using the value of 3×10^{-3} deaths per GW from wind, for the US nuclear capacity in 2018 of 8×10^{5} this would have been over 2500 deaths per year from nuclear (vs. 0).

GW, Aneziris, O. N., Papazoglou, I. A., & Psinias, A. (2016). Occupational risk for an onshore wind farm. *Safety Science*, **88**, 188-198. doi:10.1016/j.ssci.2016.02.021



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https://www.aljazeera.com/news/2021/11/16/infographic-the-world-nuclear-club
Accessed 1/22/2024