## Opening Address

Hon Ted O'Brien

# Navigating Nuclear

## UNSW Sydney - 13 May 2024

A one day opportunity to learn everything you need to know about nuclear energy and what it means for Australia's future from global experts.

## Closing Address

Dr Adi Paterson

## Speakers & Organising Committee

Jaz Diab - Women in Nuclear

Prof Koroush Shirvan - MIT

Prof Jacopo Buongiorno - MIT

Prof Rob Hayes - North Carolina State University

Dr Dave Collins - MIT/PhD UMelb

Prof Simon Michaux - Geological Survey of Finland/PhD UQ

Dr Sarah Lawley - PhD UAdelaide

Mark Nelson - Radiant Energy/UCambridge

Sai Prasad Balla - MIT

Steven Nowakowski - Rainforest Reserves Australia

Helen Cook - GNE Advisory

Dr Ross Koningstein - Google/PhD Stanford

Atte Harjanne - MP Finland Greens/PhD Candidate UAalto

Prof Mike Golay - MIT/PhD CornellU

Tony Irwin – ANU

Dr Mark Ho – Australian Nuclear Association

Dr John Harries – Australian Nuclear Association

## Organising Committee

Dr Dave Collins (Chair), Dr Mark Ho (President, Australian Nuclear Association), Jasmine Diab (President, Women in Nuclear), Dr John Harries (Secretary, Australian Nuclear Association).


## Acknowledgments

Sincere thanks to the following for their support and advice without whom the workshop would not have been possible: Dr Robert Barr, Connor Davies, Prof Julien Epps, Prof Stephen Foster, James Fleay, Tony Irwin, Prof Ed Obbard, Hasliza Omar, Robert Parker, Dr Adi Paterson, Chiara Scalise, Peter Sjoquist, Dr Tim Stone, Prof Peter Tyree, Darka de Vries and the speakers and organising committee.


## Chatham House Rules

The Q&As and the Discussion panel were not recorded under the agreed Chatham House Rules.

## Speakers & topics

| No | Topic | Speakers and affiliation |
|---|---|---|
| 1 | *Opening address* | *Hon Ted O'Brien – Australian Parliament* |
| 2 | *Introduction to Navigating Nuclear* | *Jasmin Diab – Global Nuclear Security Partners* |
| 3 | *How does nuclear energy work?* | *Prof Koroush Shirvan - MIT* |
| 4 | *Nuclear energy in the 21st century* | *Professor Jacopo Buongiorno - MIT* |
| 5 | *Radiological risk in perspective* | *Professor Robert Hayes - North Carolina State University* |
| 6 | *What would the environmental impacts of nuclear energy in Australia be?* | *Dr Dave Collins - MIT* |
| 7 | *Challenges and bottlenecks to the green transition* | *Professor Simon Michaux - Geological Survey of Finland* |
| 8 | *Australia's electricity system* | *Dr Sarah Lawley - PhD University of Adelaide* |
| 9 | *What is the value of nuclear energy?* | *Mark Nelson - Radiant Energy Group* |
| 10 | *What happens inside an operating nuclear power plant?* | *Sai Prasad Balla - MIT* |
| 11 | *Environmental impacts of renewable energy in Queensland* | *Steven Nowakowski and Jeanette Kemp - Rainforest Reserves Australia* |
| 12 | *Current nuclear energy developments around the world* | *Helen Cook - GNE Advisory* |
| 13 | *A discovery that nuclear was nonpartisan in the USA* | *Dr Ross Koningstein - Google* |
| 14 | *How nuclear became green in Finland* | *Atte Harjanne - Finland Parliament* |
| 15 | *Experience and lessons from creating nuclear safety cultures* | *Professor Michael Golay - MIT* |
| *Not recorded* | *Discussion panel* | *Chair: Tony Irwin - ANU* |
| 16 | *Closing address* | *Dr Adi Paterson – ANSTO (retired)* |

# Radiological Risk in Perspective

## *What every decision maker should know*

[redacted] UNSW Sydney, Australia, May 13, 2024

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
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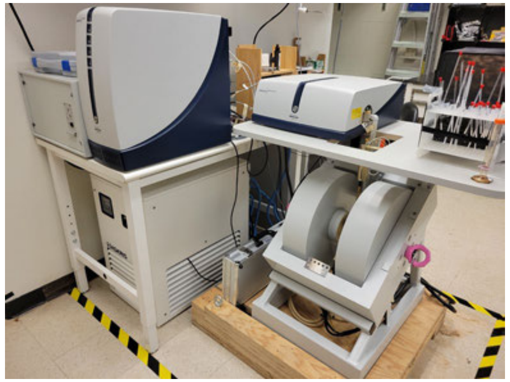

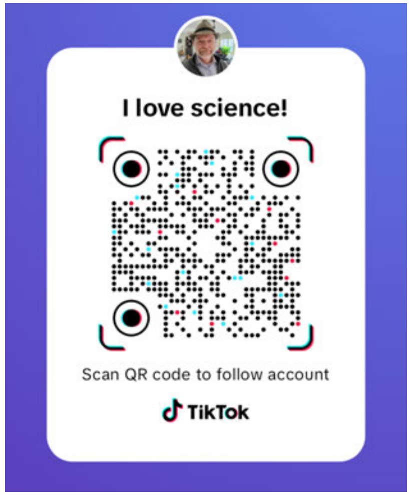


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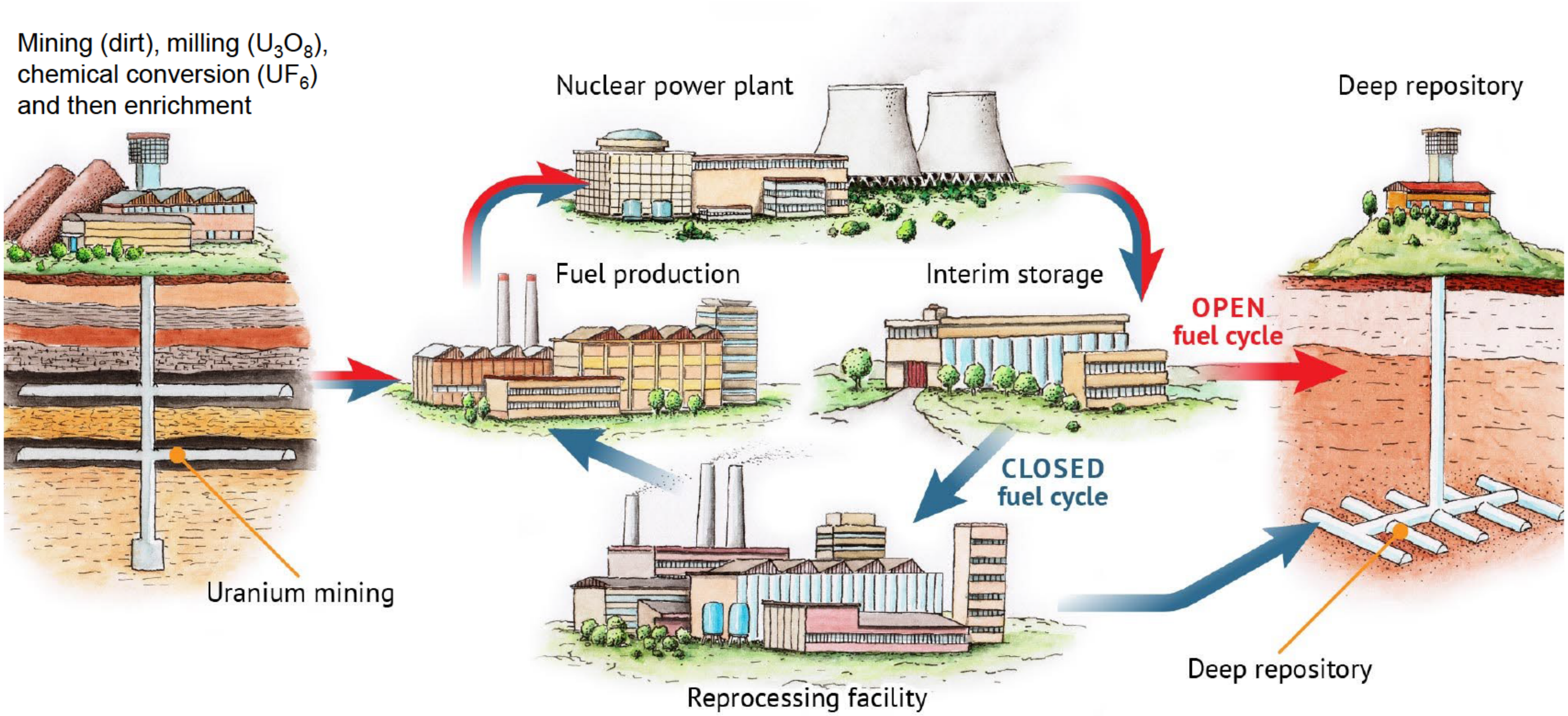
# What are we going to cover?

- 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

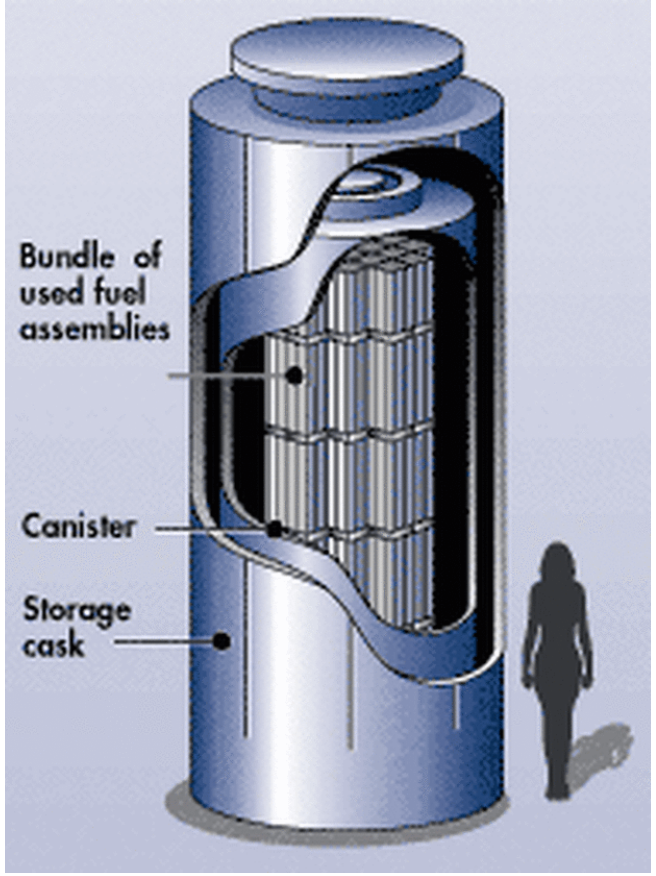
# The nuclear fuel cycle

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



# 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





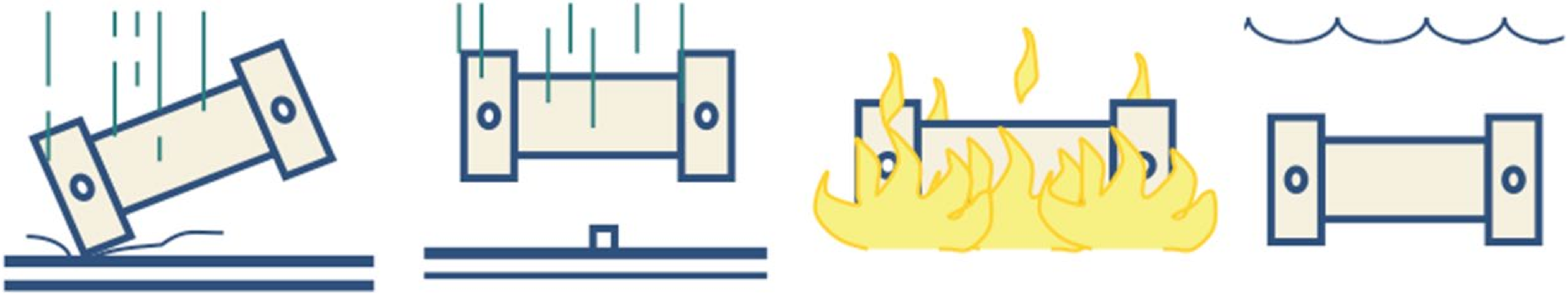
# Interim storage

# 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

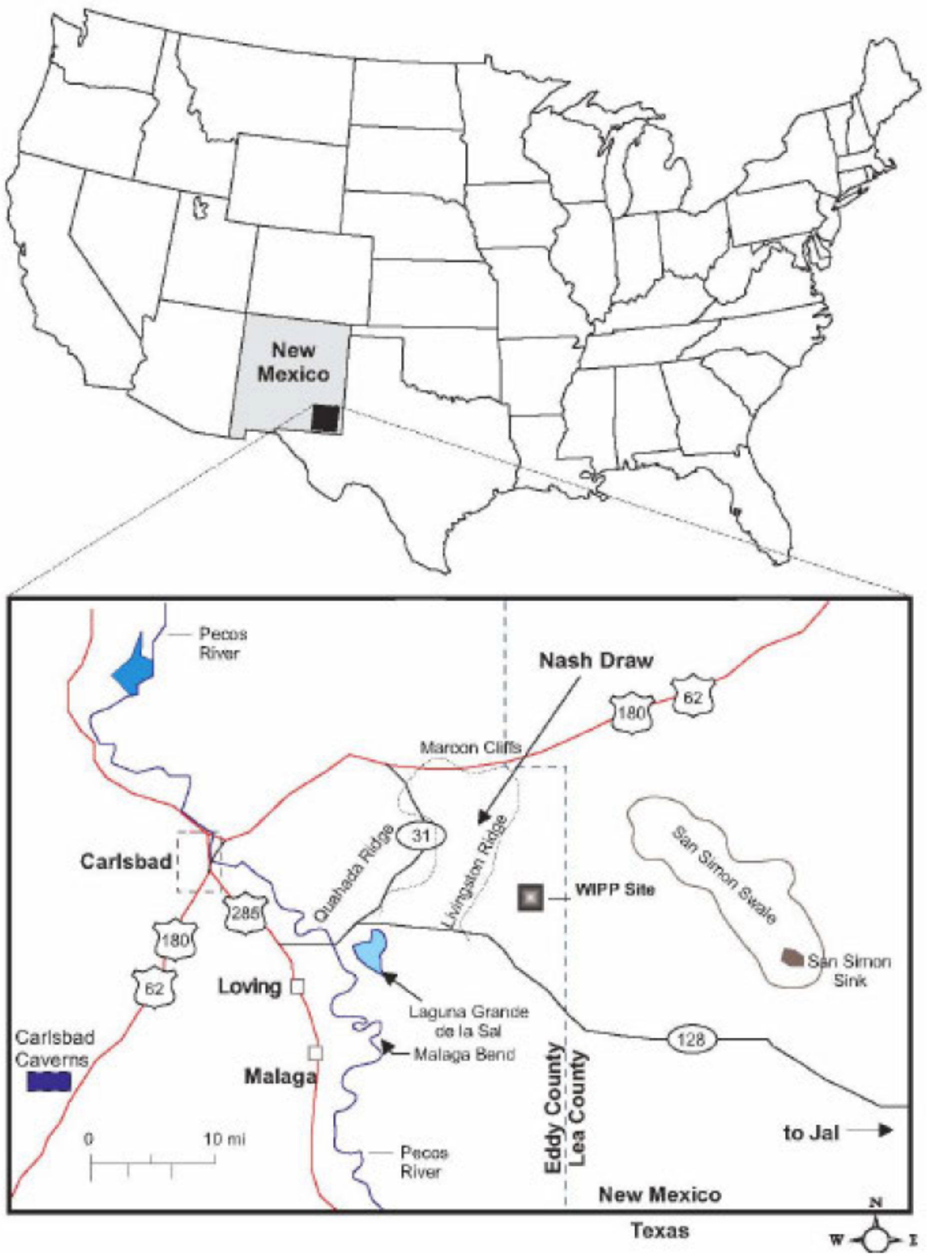
# Transportation Safety

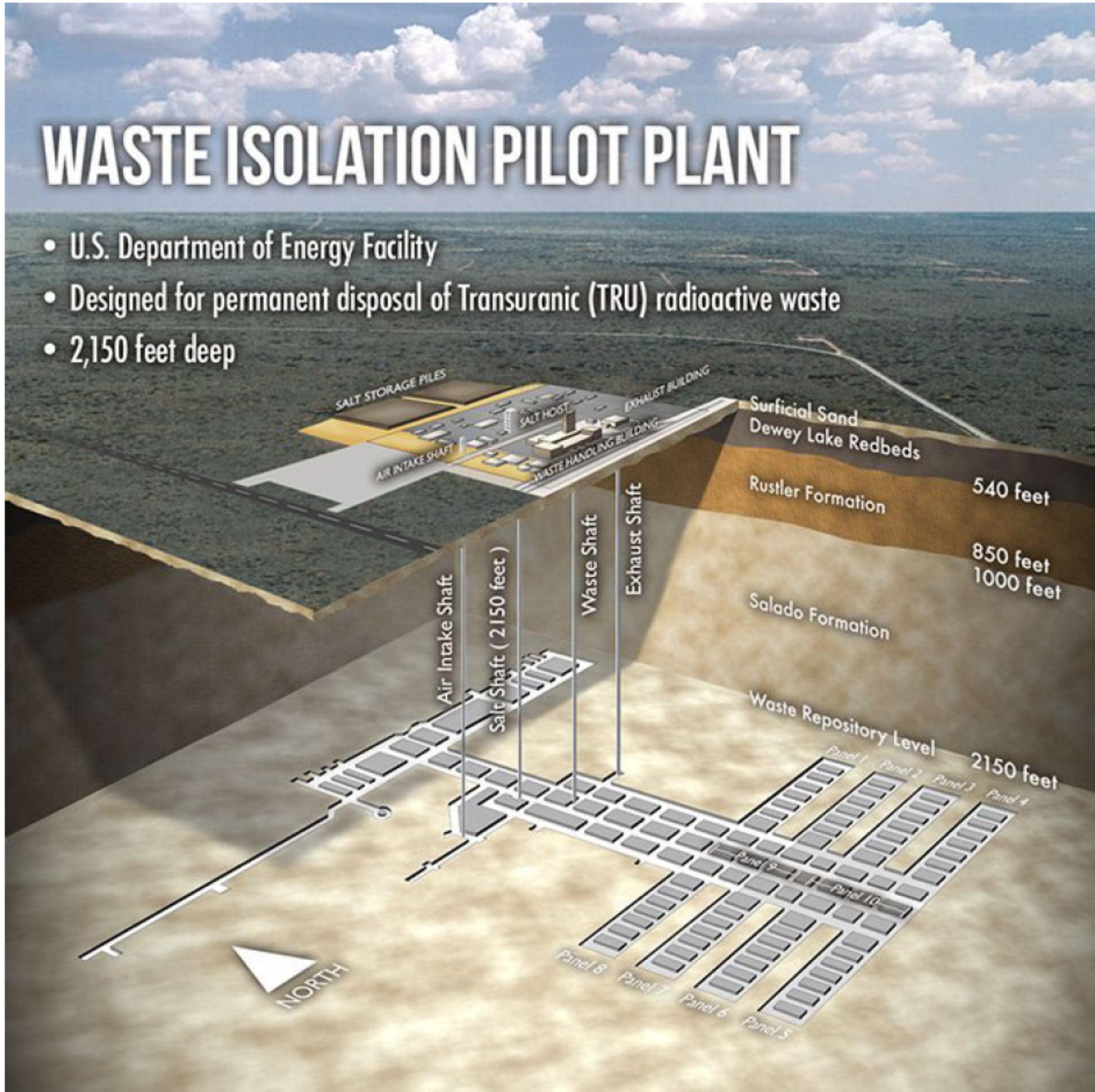


U.S.NRC
United States Nuclear Regulatory Commission
*Protecting People and the Environment*
As of July 2018

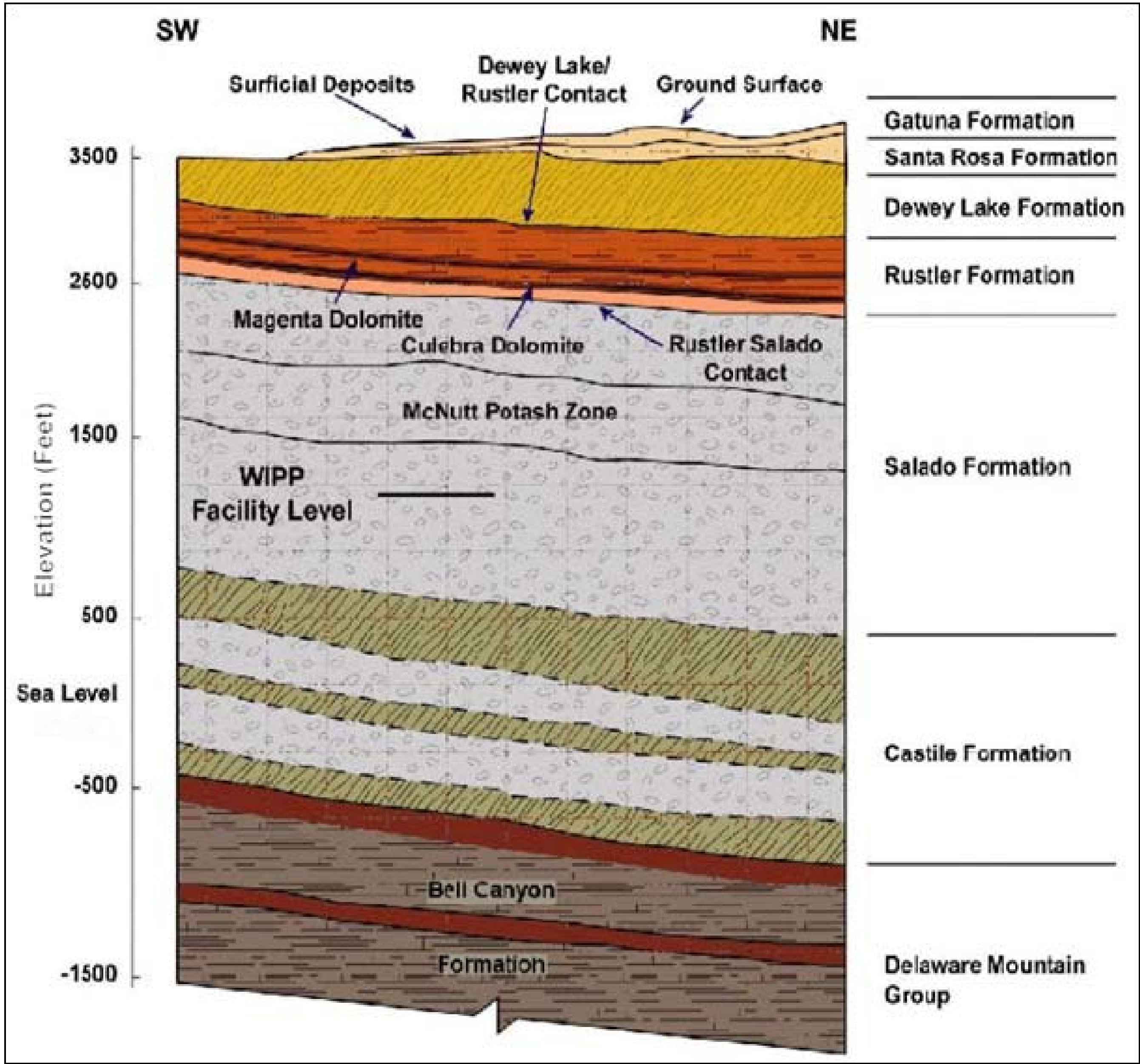
1. 30 ft drop onto unyielding surface
2. 40 inch drop onto steel bar
3. 1475º F for 30 min
4. 50 ft water for 8 hrs

# Permanent Disposal



# Waste Isolation Pilot Plant (WIPP)



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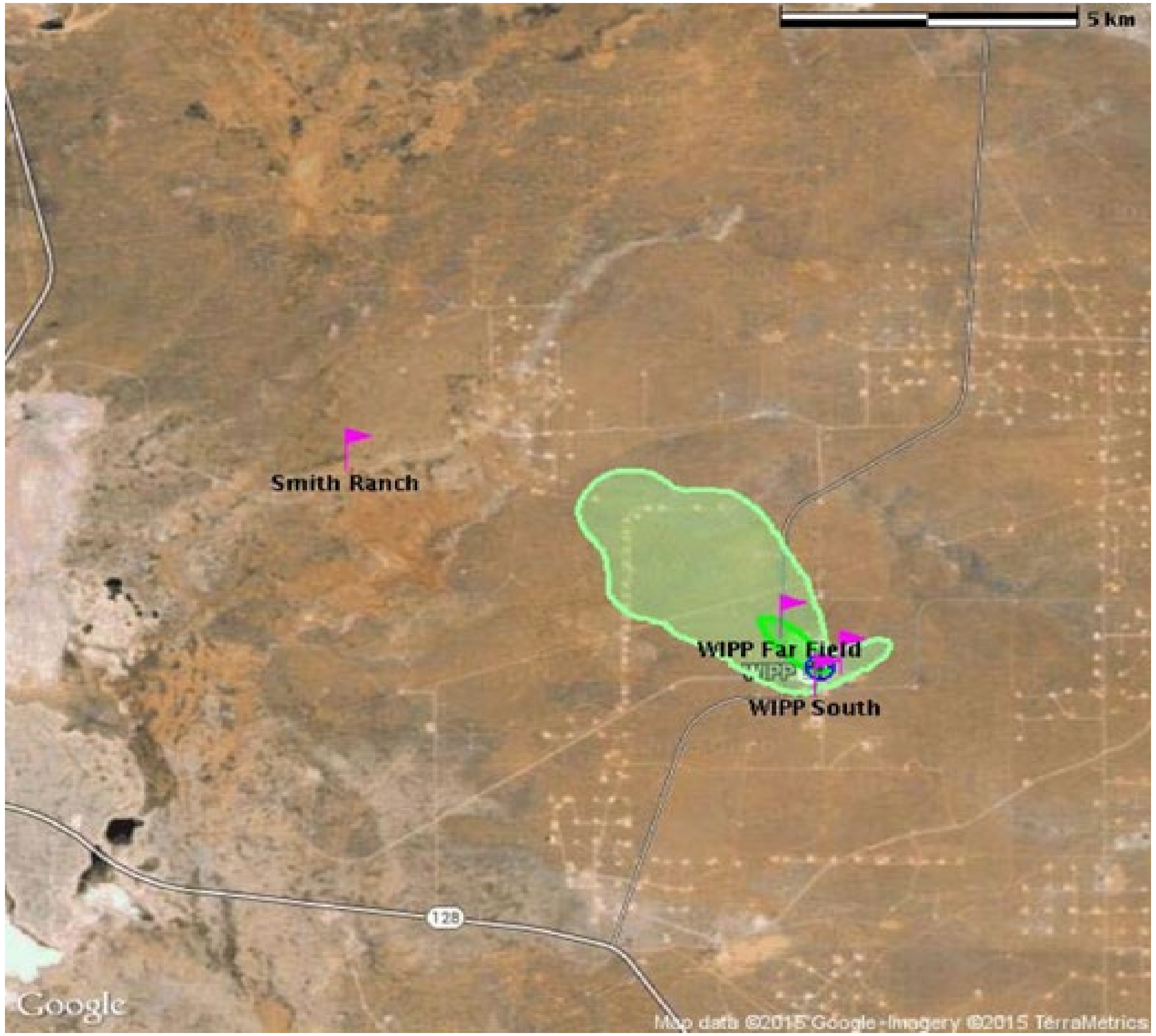
# The 2014 WIPP release event




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

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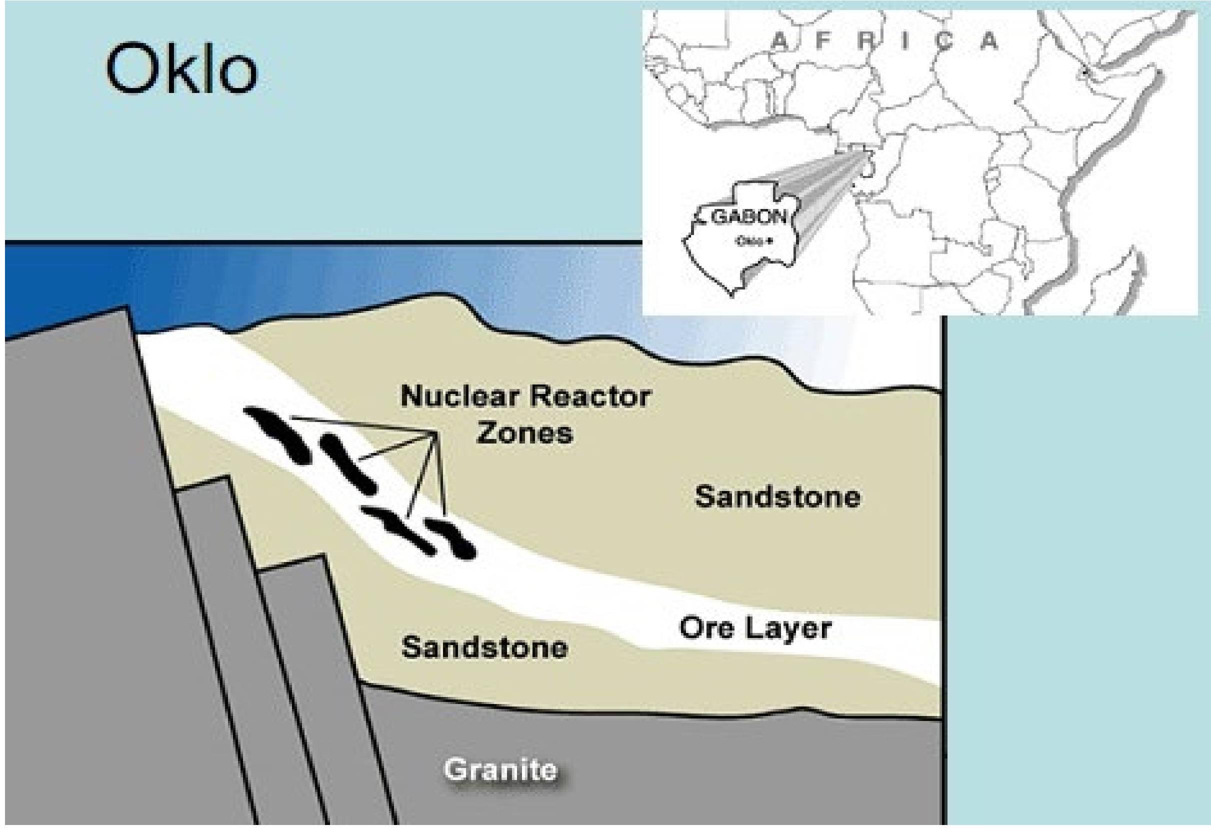
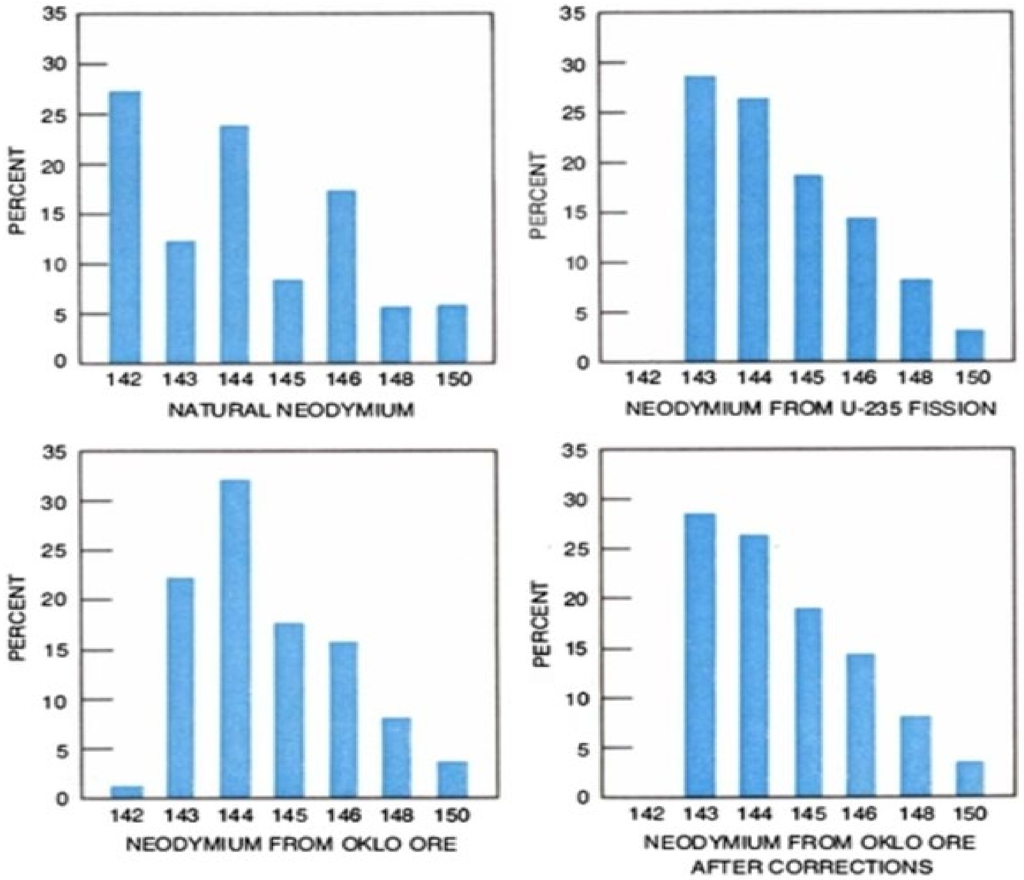
# Mother natures example of geological disposal for used nuclear fuel




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

# Radiation Risk in Context

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


# Radiation Risk in Context

- 1 mrem
  - 5 mrem

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

$^{40}K$

EPA

# Radiation Risk in Context

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


EPA

$^{40}K$


# 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

$^{40}K$


# Radiation Risk in Context

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

EPA


$^{40}K$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# Radiation Risk in Context

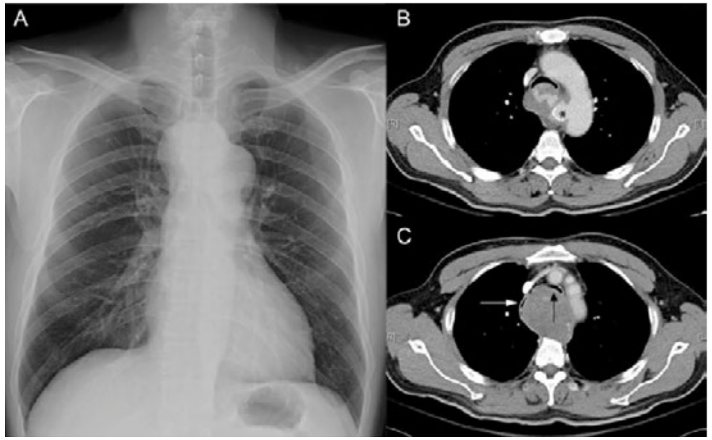


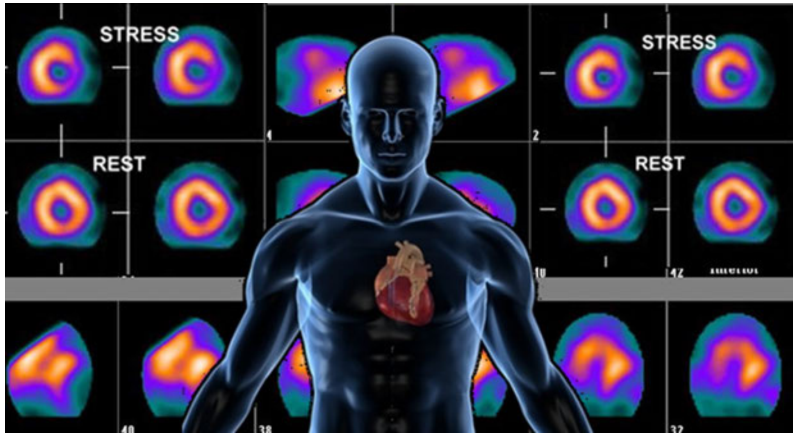

- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- **1,000 mrem,** minimum EPA evacuation guideline or nuclear medicine stress test or head, chest or hip CT scan



EPA

$^{40}K$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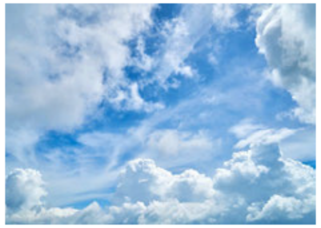
# Radiation Risk in Context

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



EPA





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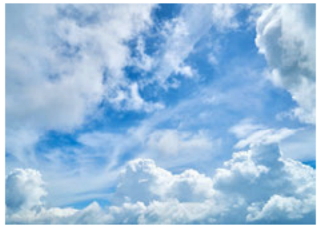
# Radiation Risk in Context

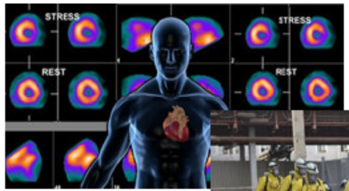
- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- **10,000 mrem** is potentially a 0.5% cancer probability
  - Typical cancer probability from all sources is 40%



EPA



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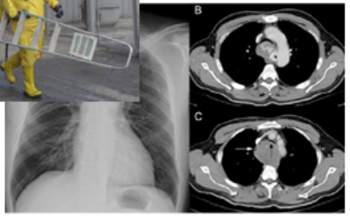
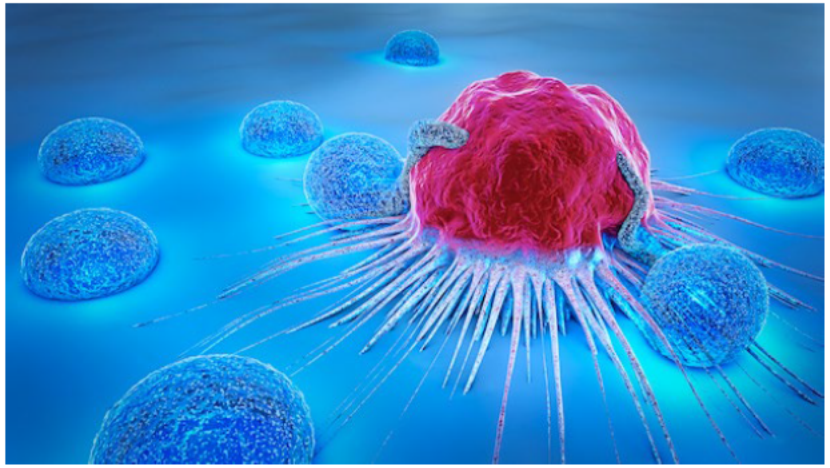
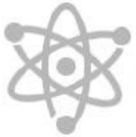
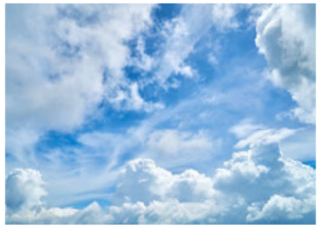




# Radiation Risk in Context

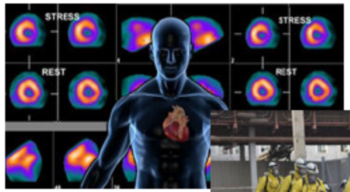
- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- **100,000 mrem** gives a 5% increase in cancer probability



EPA



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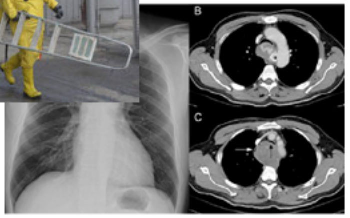
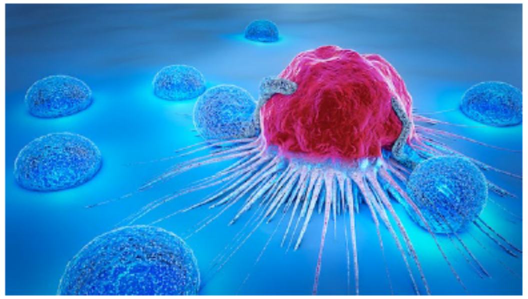
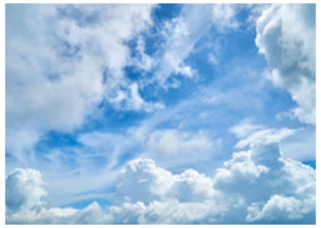




# Radiation Risk in Context

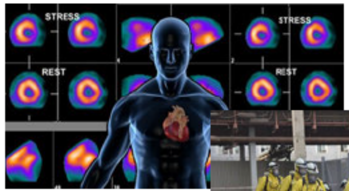
- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- 100,000 mrem
  - **500,000 mrem** is around the LD30/50 dose (lethality)



EPA



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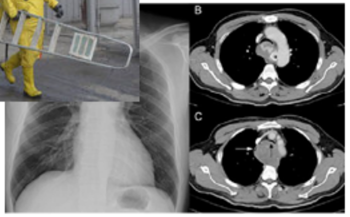


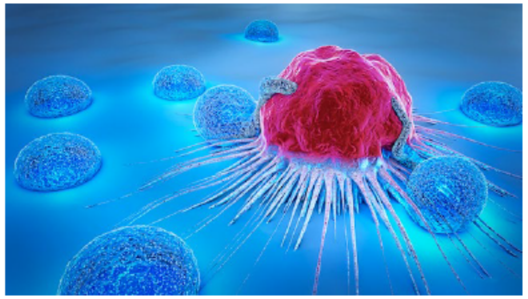

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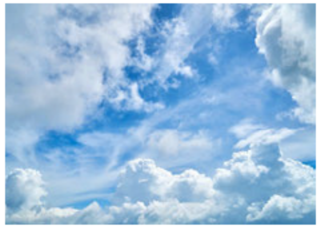
# Radiation Risk in Context

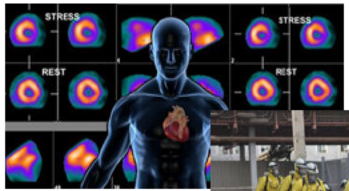
- 1 mrem
  - 5 mrem
- 10 mrem
  - 40 mrem
- 100 mrem
  - 320 mrem
- 1,000 mrem
  - 5,000 mrem
- 10,000 mrem
  - Observable medical effects
- 100,000 mrem
  - 500,000 mrem
- **1000,000 rem** likely death acute radiation syndrome



EPA



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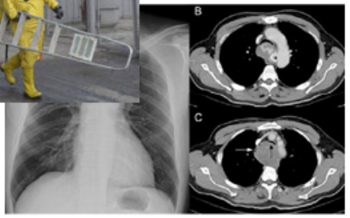
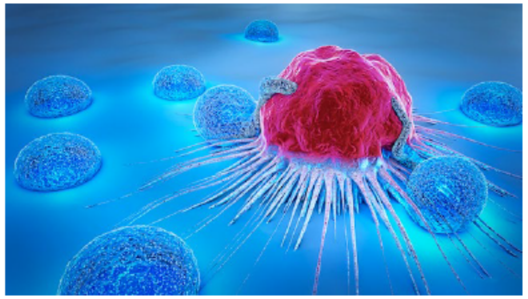
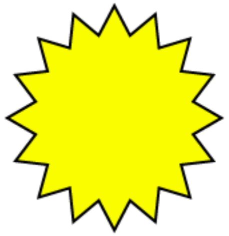


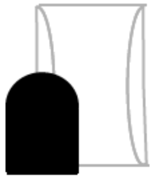

# Radiation Risk in Context

- 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

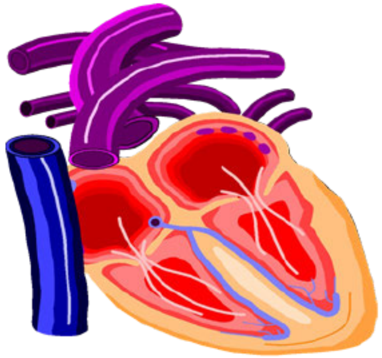
# Where do we get dose?



Solar Radiation



Nuclear Energy



Nuclear Medicine

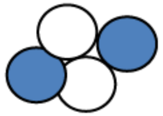
Terrestrial Radiation

CT scans & X-rays

Radioactive Waste

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

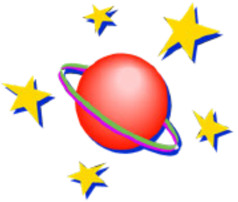
Radon



Consumer Products

Each Other

Food & Drink

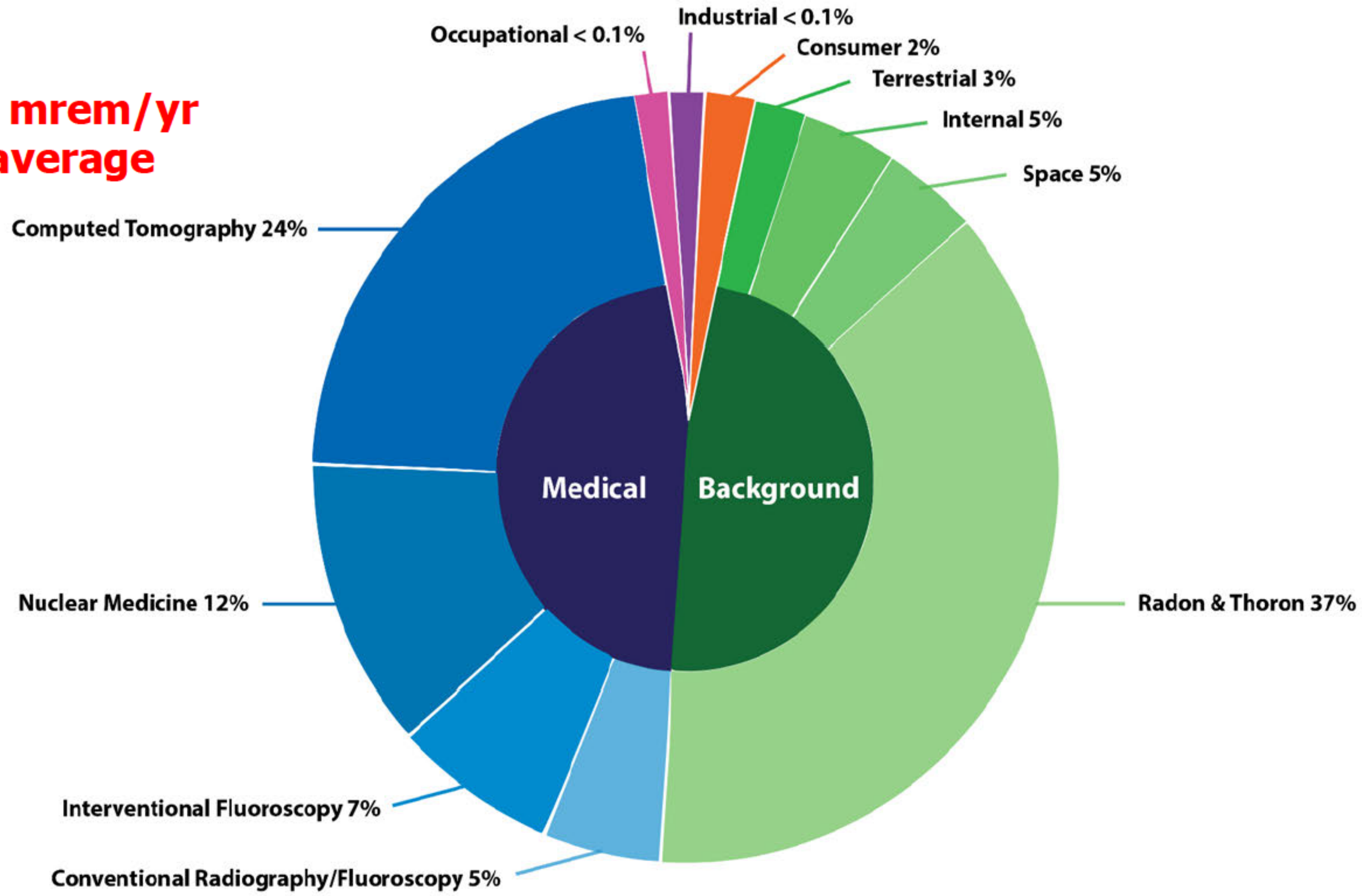


Cosmic Rays

NC STAT

625 mrem/yr
US average

## Sources of Radiation Exposure

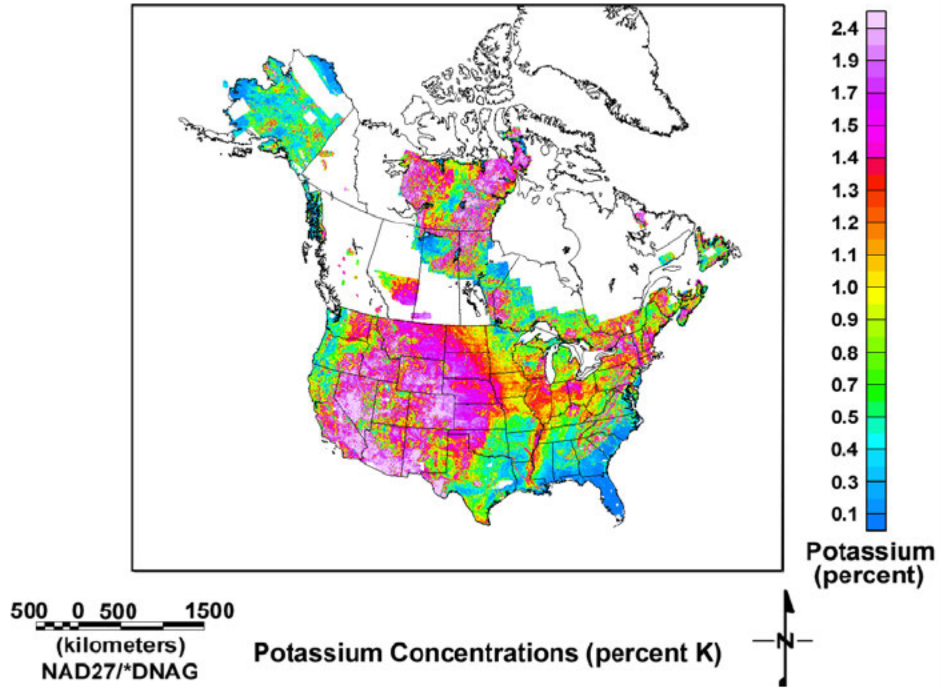


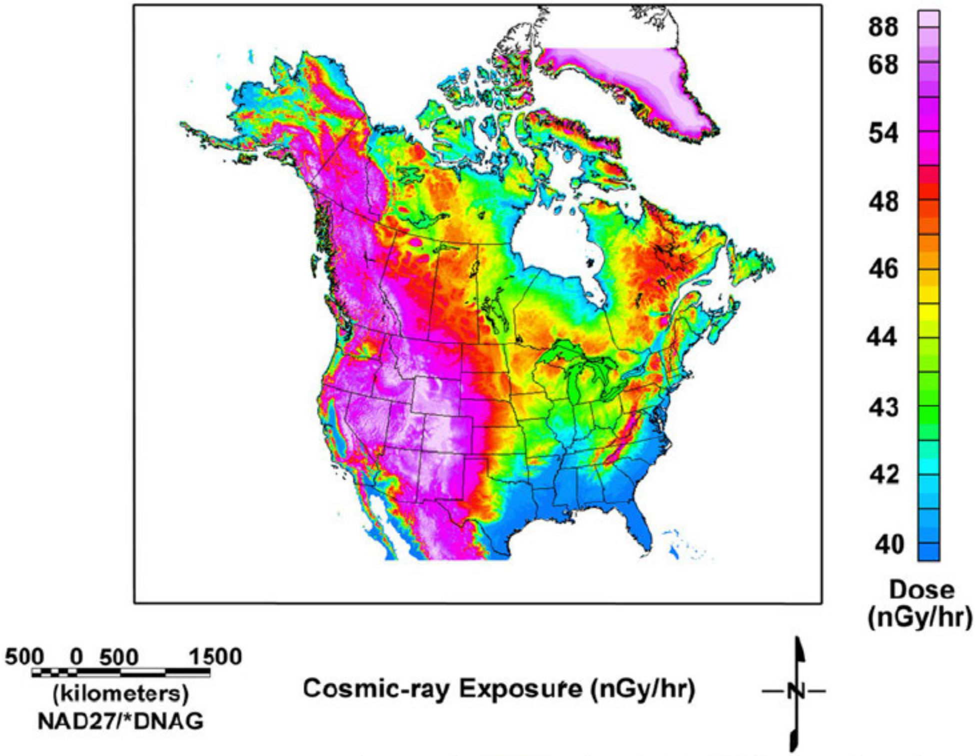

**Average Annual Radiation Dose**

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

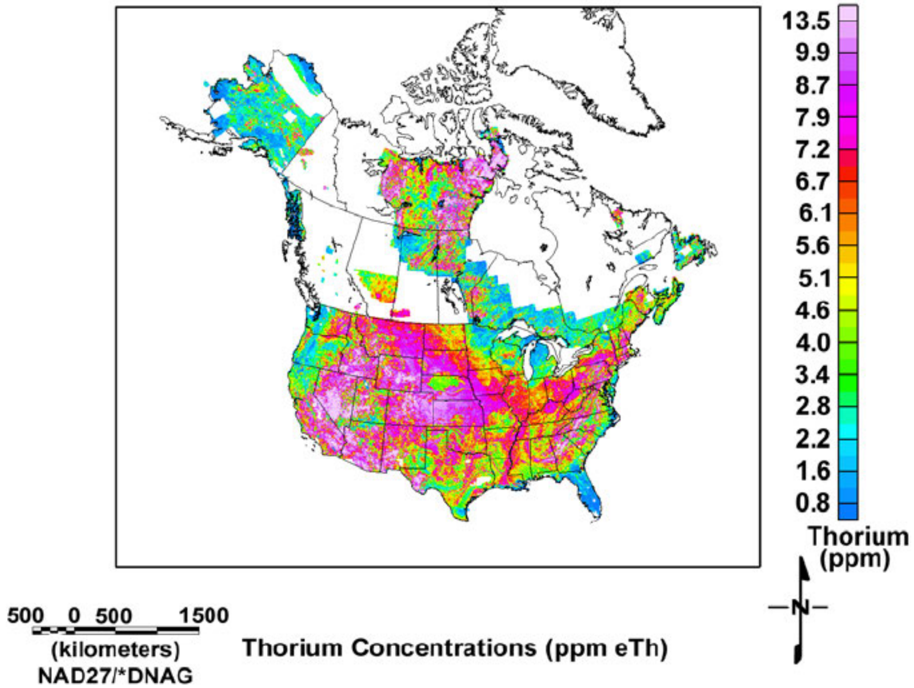
(Source: National Council on Radiation Protection & Measurements, Report No. 160)

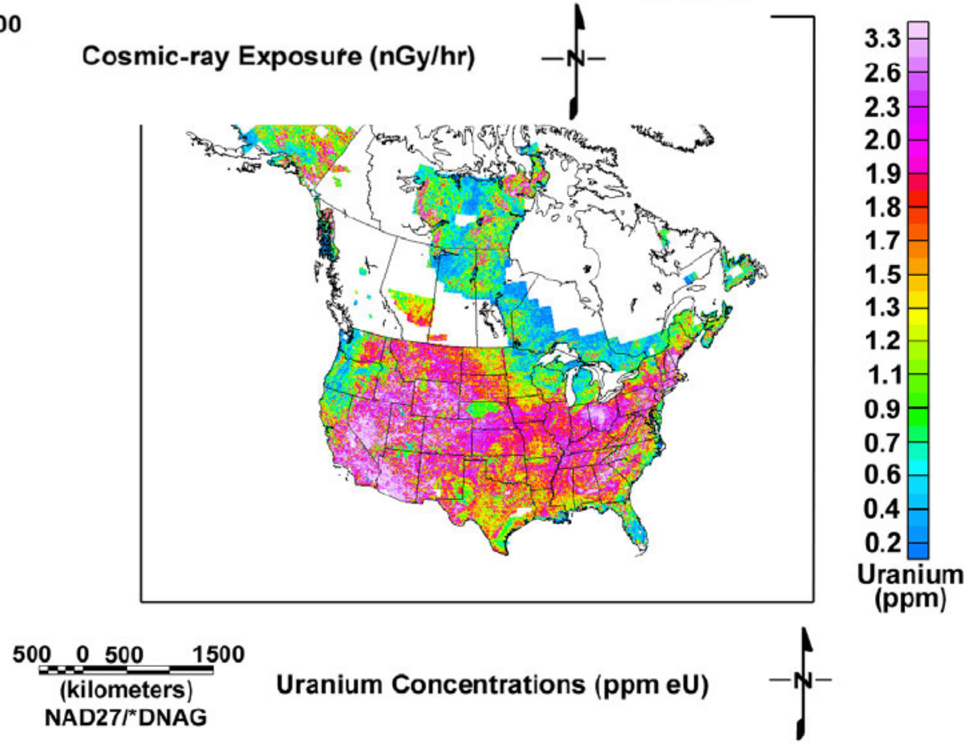
Department of
NUCLEAR




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



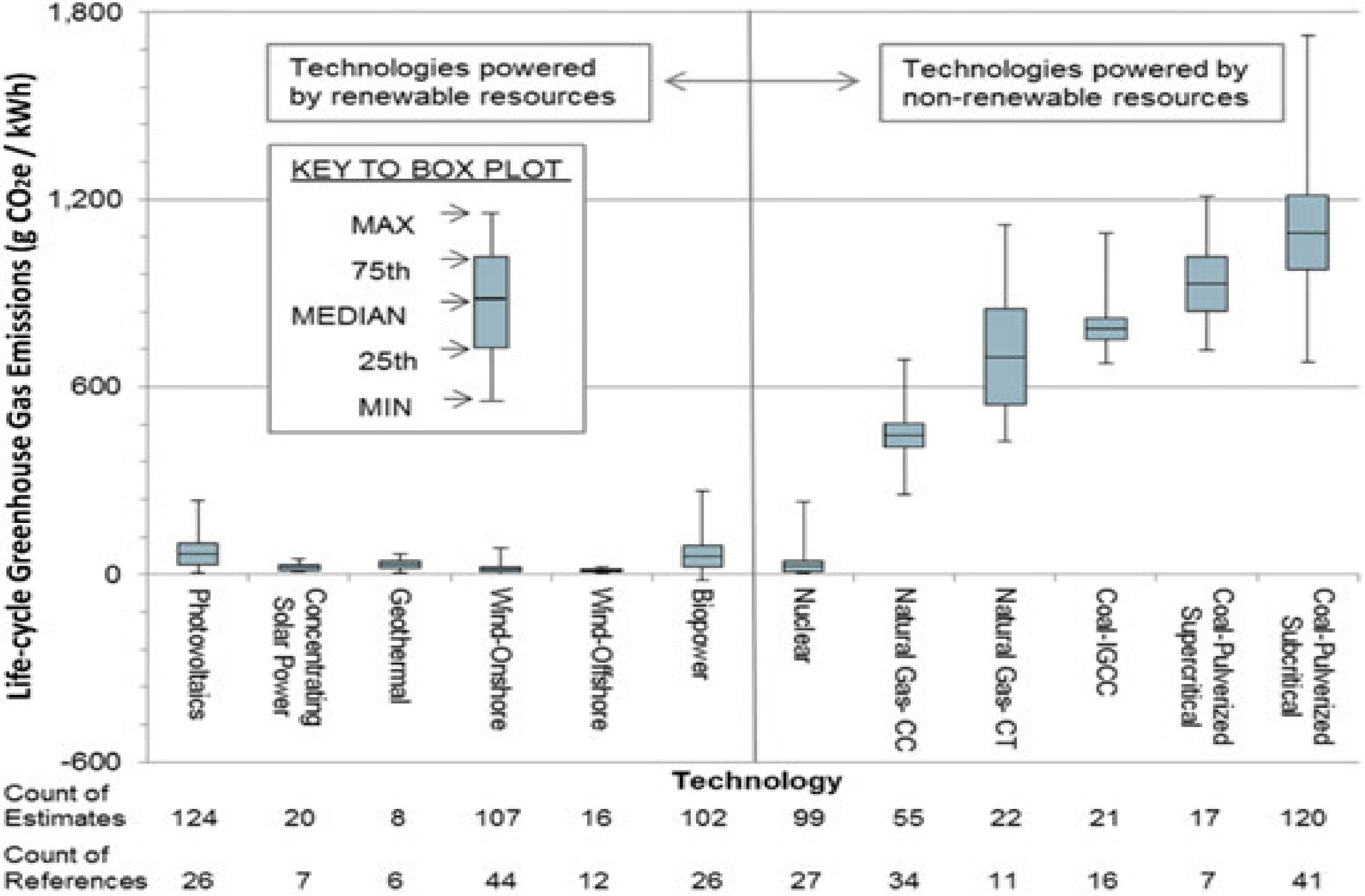



# Environmental impact

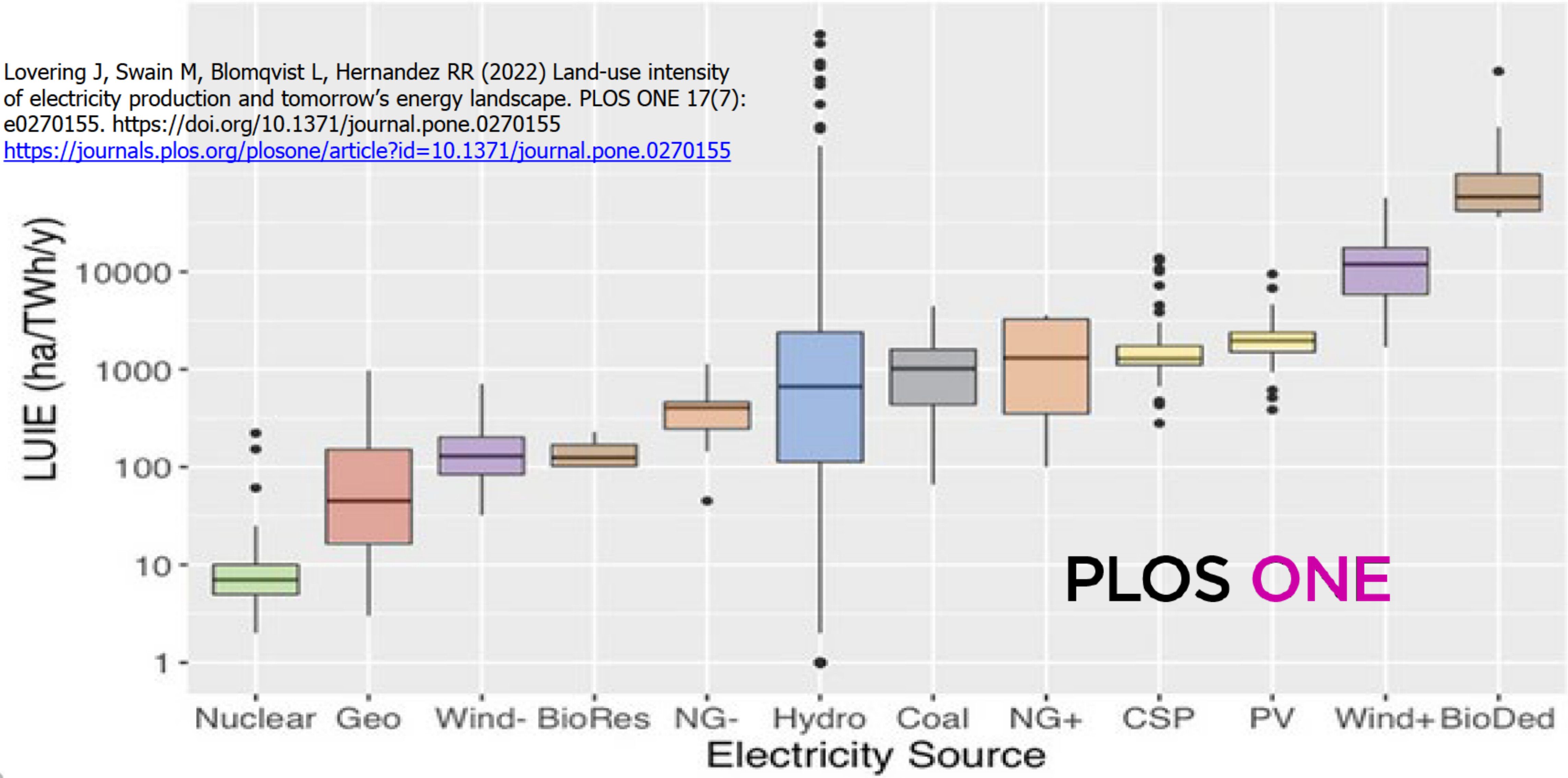
- Why renewables are so important
- Materials requirements
- Land and materials requirements
- Safety is important too

# 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



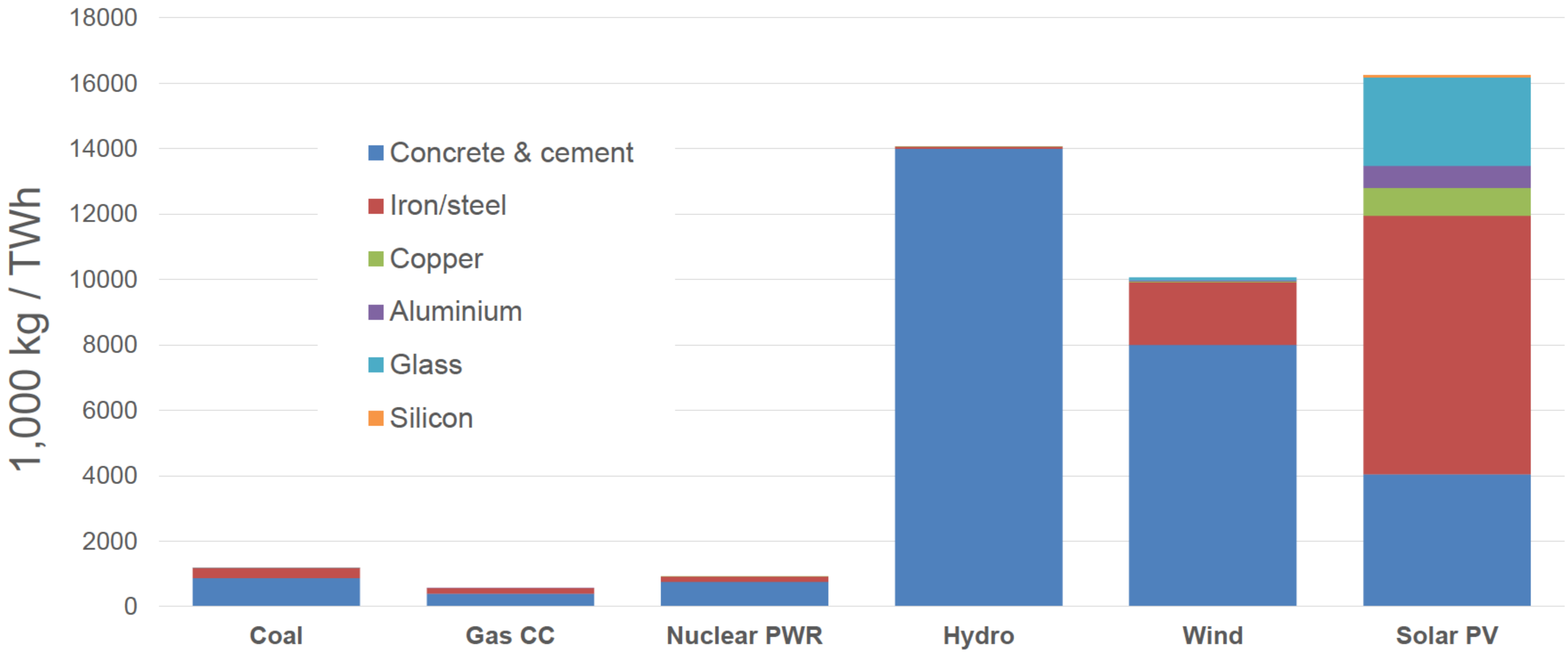
# Land requirements




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


# Aircraft (NPP) & similar events?


- **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

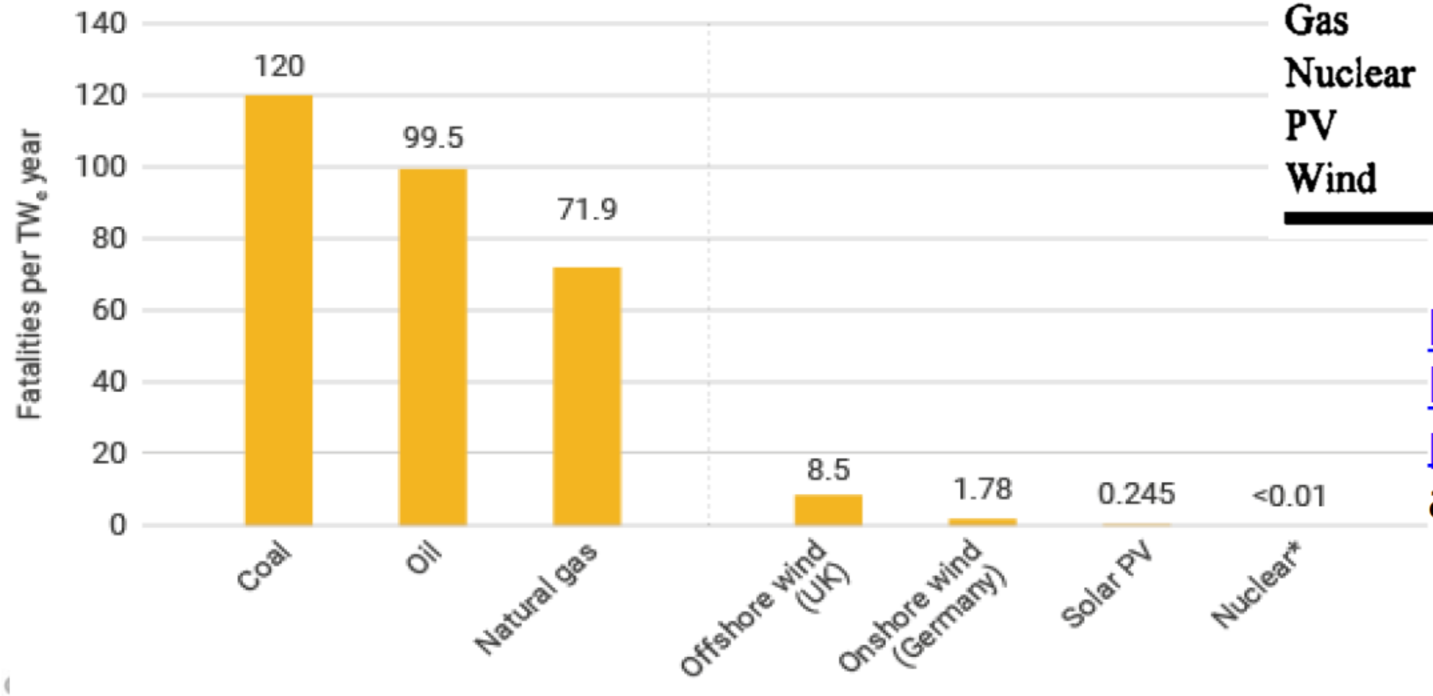
# Custom train design

# General safety

Krewitt, Wolfram, Fintan Hurley, Alfred Trukenmüller, and Rainer Friedrich. "Health risks of energy systems." *Risk Analysis* 18, no. 4 (1998): 377-383.

**Table III.** Occupational Health Impacts per TWh

| | Years of life lost | | Major accidents and diseases | | Minor accidents and diseases | |
|---|---|---|---|---|---|---|
| | Total | Net | Total | Net | Total | Net |
| Coal | 9.2 | 6.9 | 10.3 | 7.6 | 114 | 38 |
| Lignite | 1.5 | 0.2 | 1.1 | 0.1 | 29 | − 2.0 |
| Oil | 5.8 | 2.8 | 2.5 | 0.3 | 64 | − 3.2 |
| Gas | 0.6 | 0.1 | 0.4 | 0.04 | 10 | − 0.3 |
| Nuclear | 0.5 | 0.3 | 0.3 | 0.05 | 7.8 | 0.1 |
| PV | 35 | 0.7 | 30 | 0.8 | 752 | −54 |
| Wind | 2.1 | 0.3 | 1.8 | 0.4 | 50 | 7.8 |



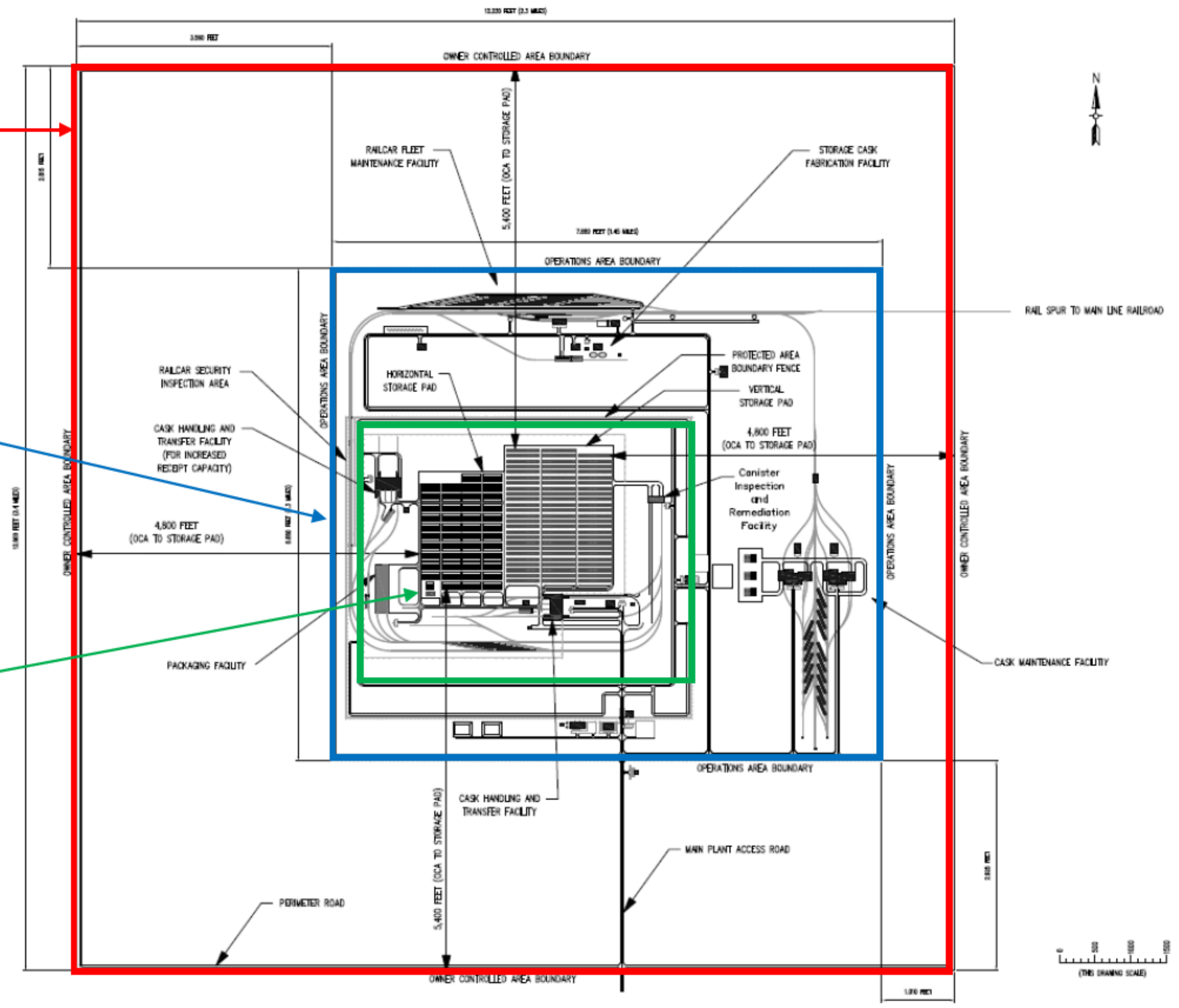

*Gen II PWR, Swiss.
Source: Paul Scherrer Institut. Data for nuclear accidents modified to reflect UNSCEAR findings/recommendations 2012 and NRC SOARCA study 2015

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

# 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



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# Questions?

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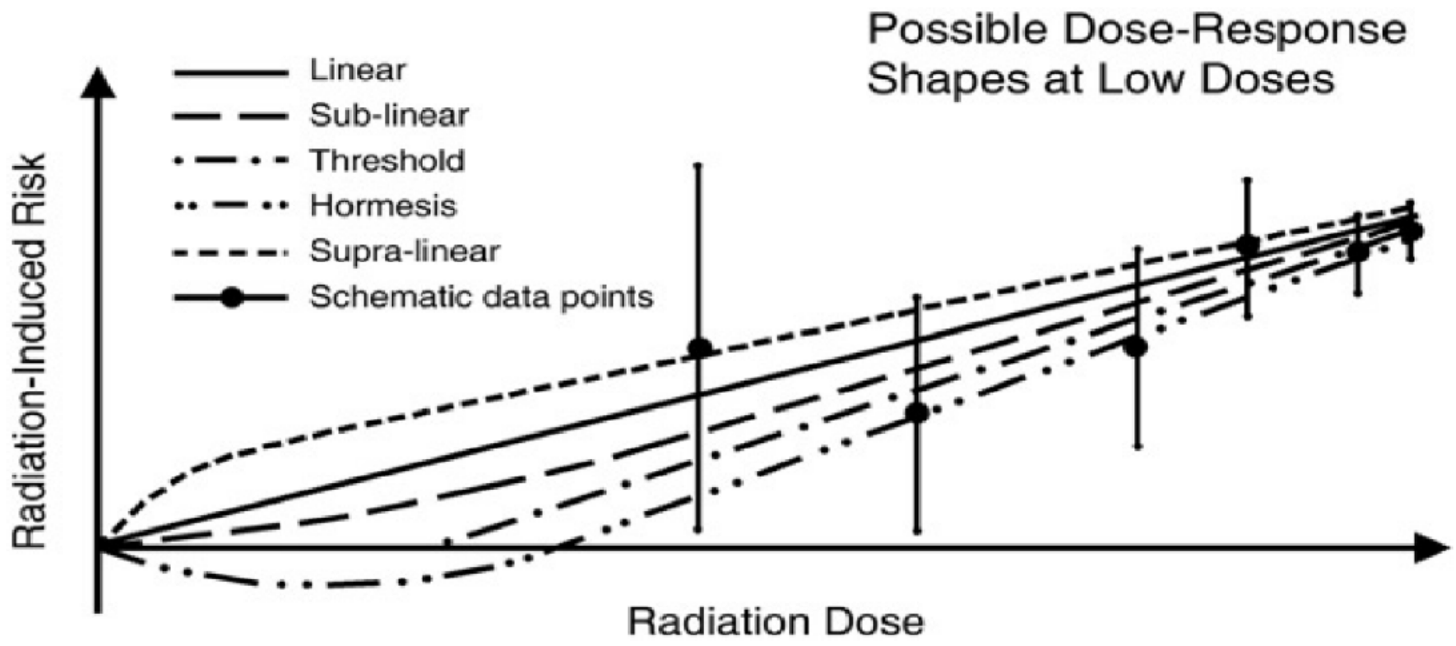
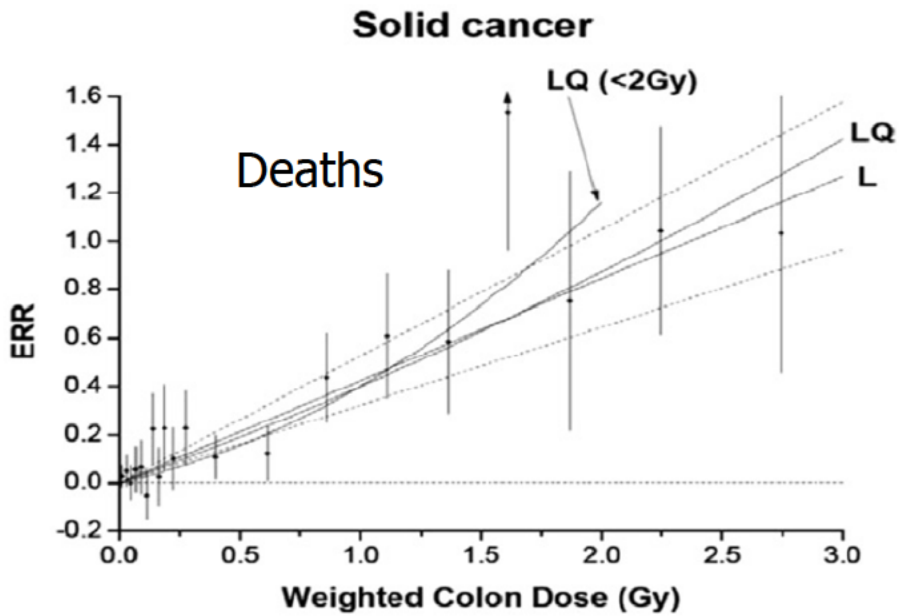
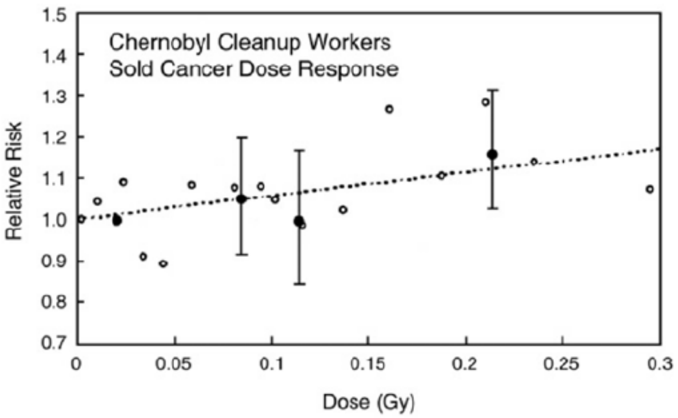
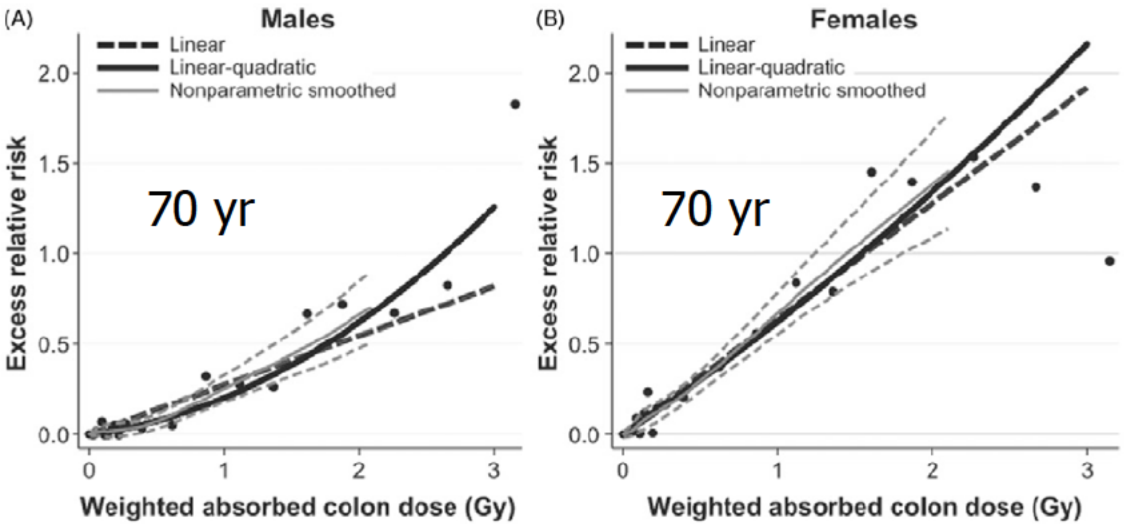
# Spare slides for anticipated questions

# Linear no-threshold theory





INTERNATIONAL JOURNAL OF RADIATION BIOLOGY,

2017 VOL. 93, NO. 10, 1079–1092
https://doi.org/10.1080/09553002.2017.1328750

# 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?

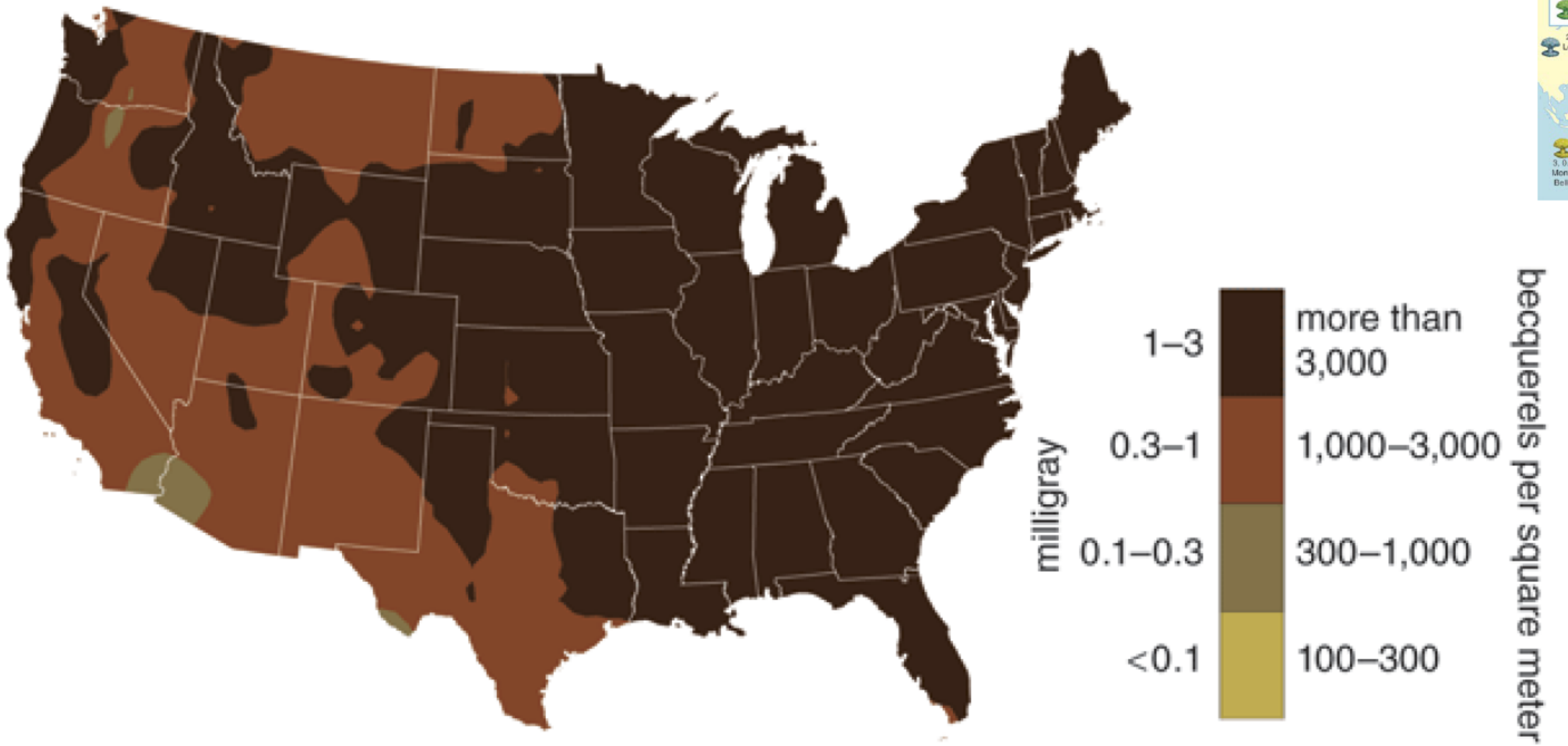
$$Risk = \sum_i Consequences_{\,i} \times Probability_{\,i} = \sum_i B_i \times$$

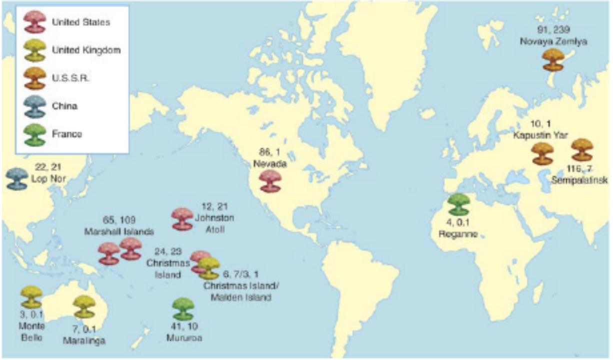
In a generic sense, this would be to say that if risks from *N* outcomes have energy risk metrics of $B_1$ through $B_N$, then if each of these risks can be reduced by amounts $C_1$ through $C_N$ per \$ (Note $C_i$ is a risk reduction per \$), then the optimal fraction of the monetary distribution $K_D$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

# Nuclear weapons background doses

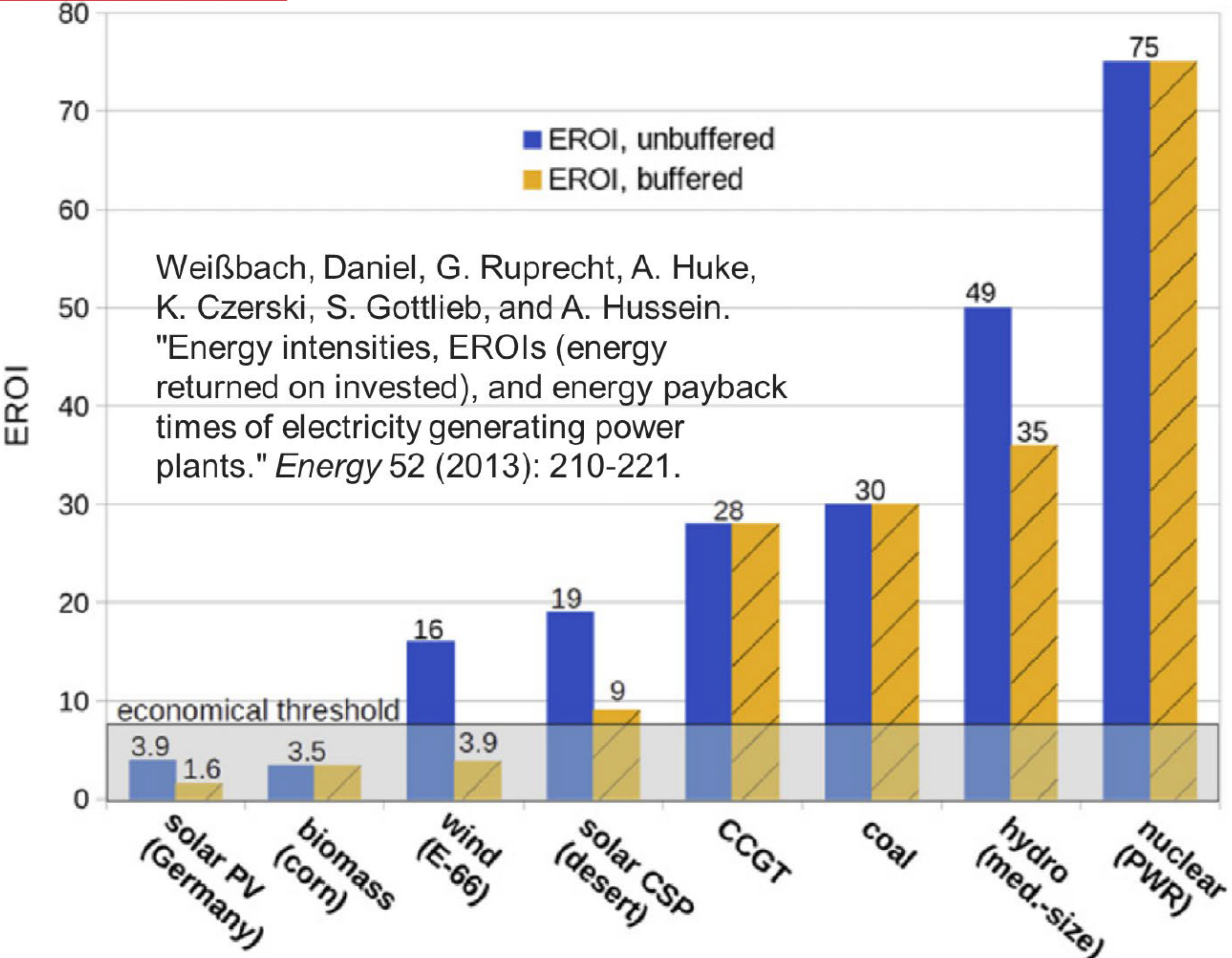
Dose to red bone marrow from global fallout for persons born on January 1, 1951,




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.


EROI, unbuffered
EROI, buffered
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.
EROI
80
70
60
50
40
30
20
10
0
economical threshold
3.9
1.6
3.5
16
3.9
19
9
28
30
49
35
75
solar PV (Germany)
biomass (corn)
wind (E-66)
solar CSP (desert)
CCGT
coal
hydro (med.-size)
nuclear (PWR)

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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

How robust are the shipping containers?
https://www.nrc.gov/docs/ML1532/ML15322A230.pdf
https://www3.epa.gov/radtown/transporting-materials.html

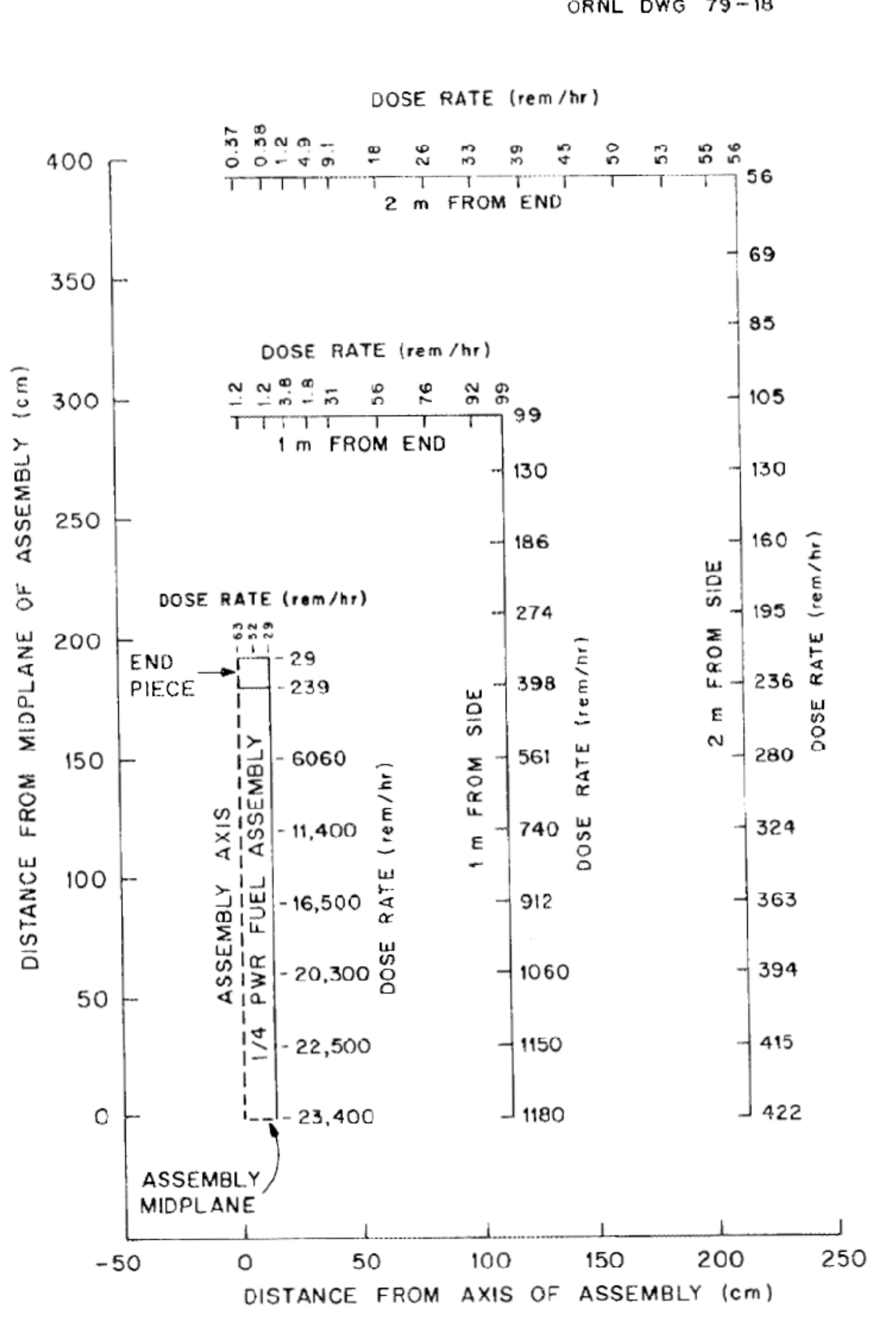


Fig. 8. Fission product dose rate from a 10-year-old PWR fuel assembly.

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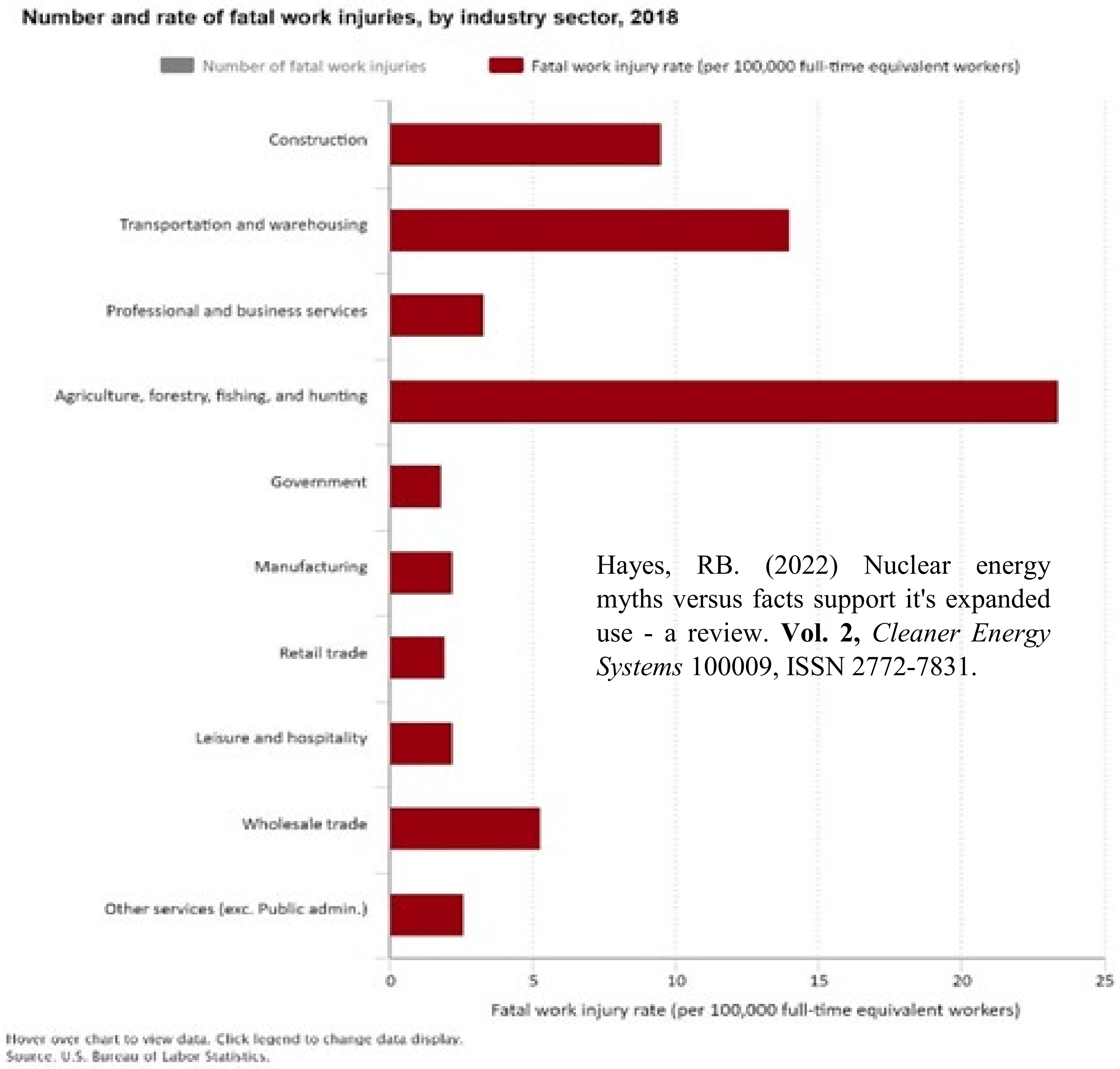
# What are acceptable death rates?

An average of $4.4\times10^{-5}$ 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 $3\times10^{-3}$ deaths per GW from wind, for the US nuclear capacity in 2018 of $8\times10^{5}$ 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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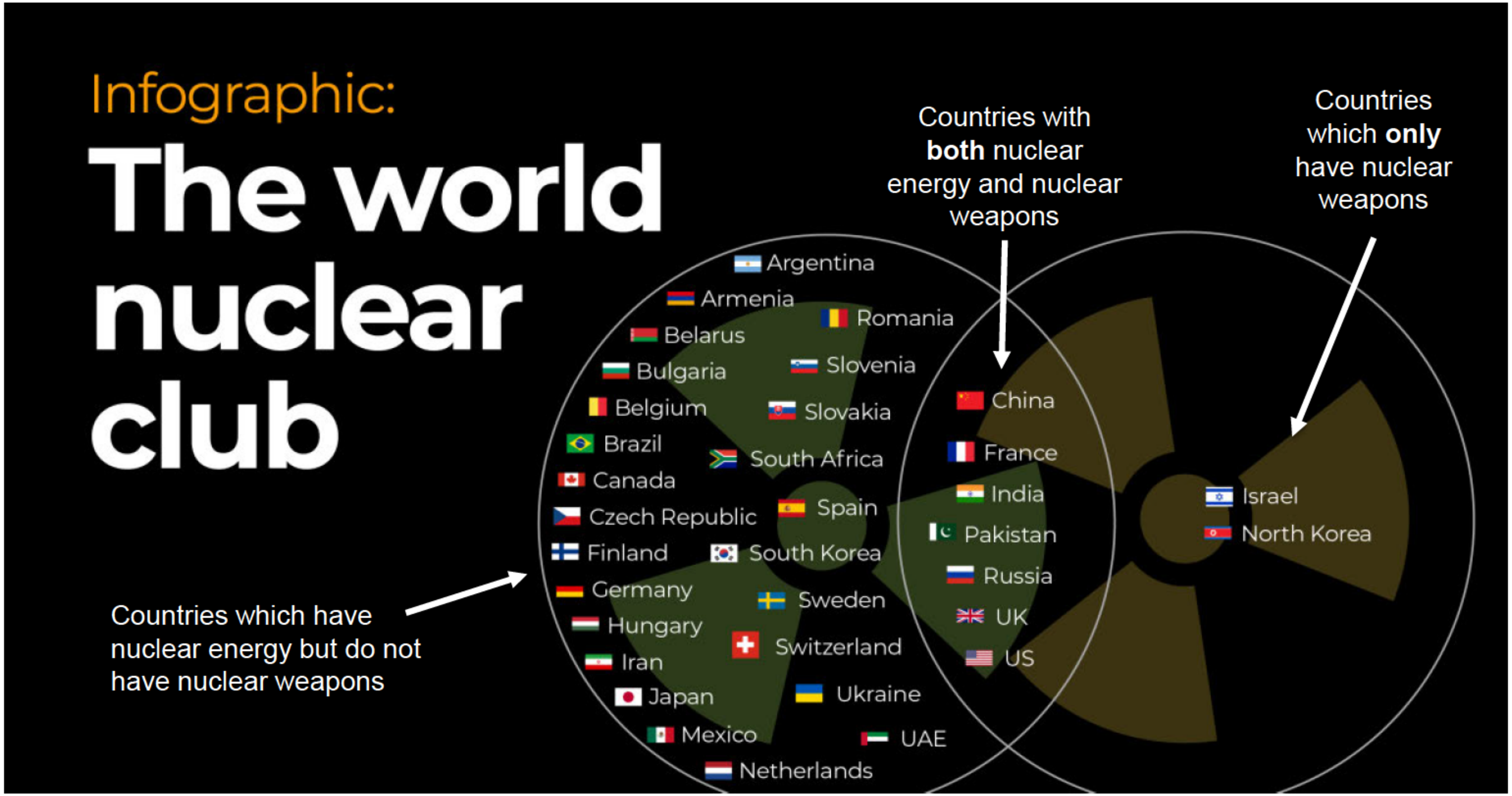




https://www.aljazeera.com/news/2021/11/16/infographic-the-world-nuclear-club
Accessed 1/22/2024