How Can Nuclear Energy Help Fight Climate Change?

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Aug 25, 2021

AIChE Virtual Section

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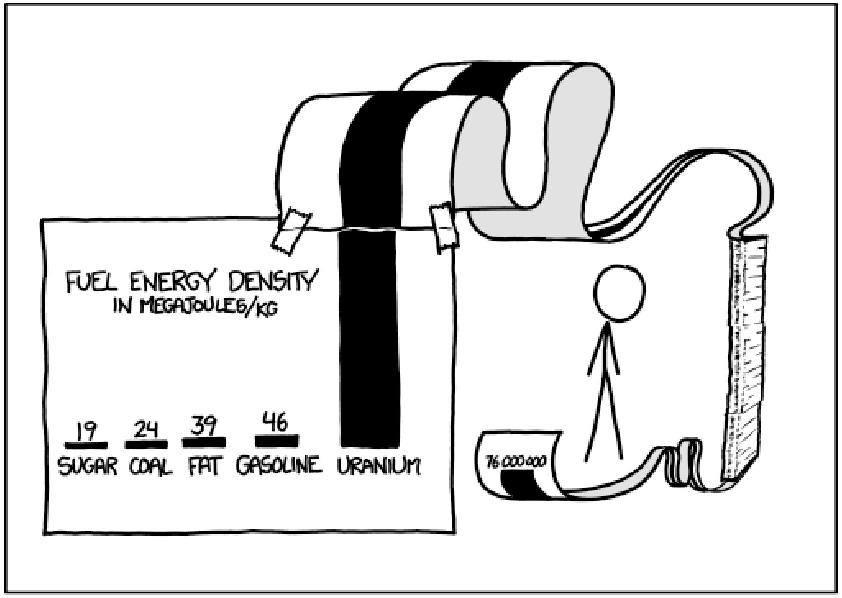
Outline

- Intro
- Nuclear Energy 101
  - Basic physics
  - Fuel cycles
  - Current reactor deployment
- New Reactor Deployment
  - LWRs
  - Non-LWRs
- Economics & Funding



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

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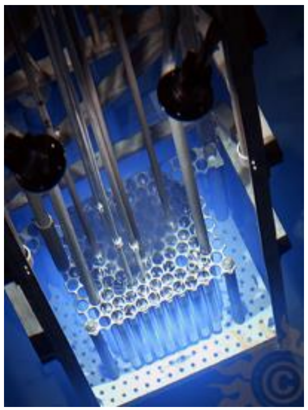
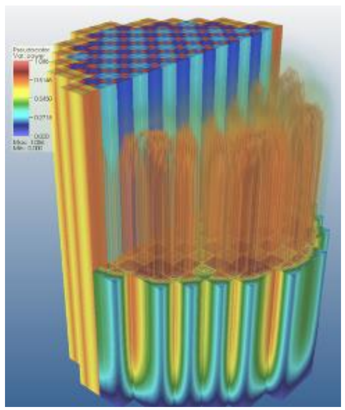
A Bit About Me





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CHANGING WHAT'S POSSIBLE

AGENCY REVIEW TEAMS
Meet the Biden-Harris agency review teams

good energy collective

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Nuclear Energy 101

We Need Cleaner Energy

- Nuclear's lifecycle emits very little air pollution

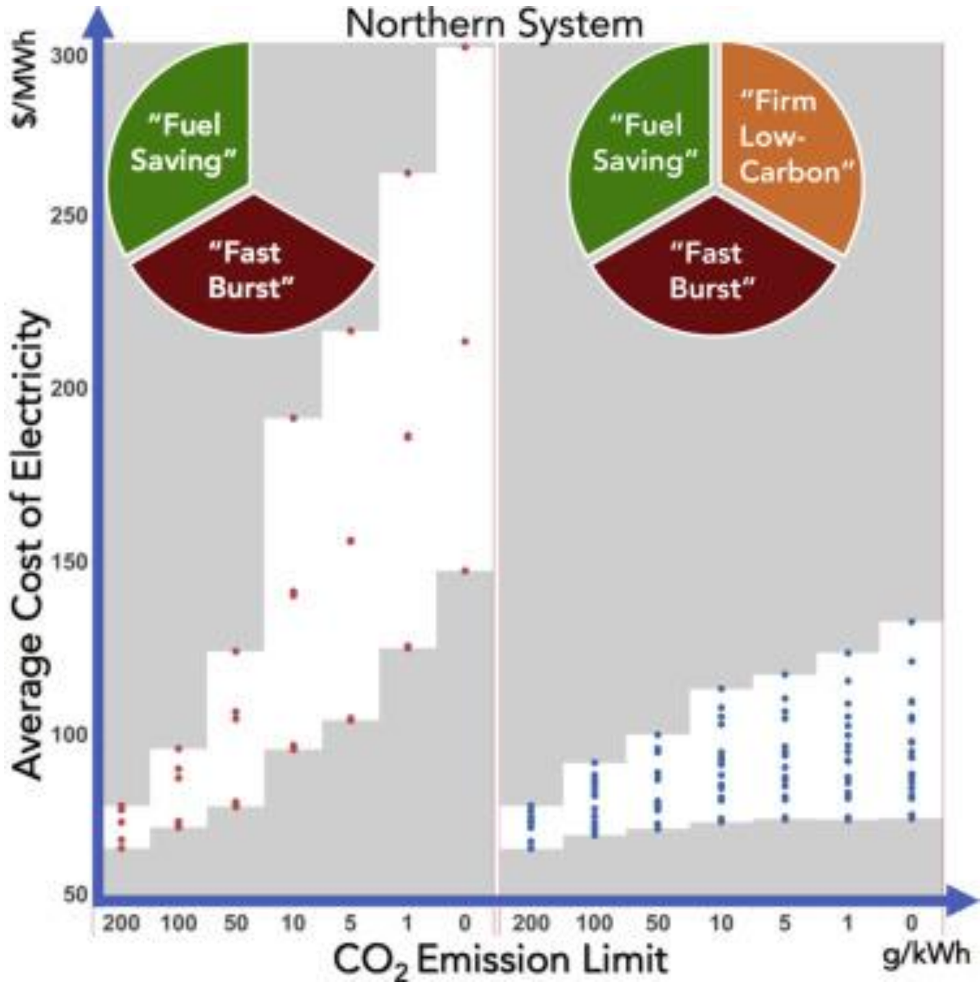
g CO_2 eq /KWh	Solar (PV / CSP)	Wind	Nuclear	Coal	Natural Gas
Min	5 / 7	2	1	675	290
Max	217 / 89	81	220	1689	930

- Nuclear energy is an important component
  - Can be deployed at large scale today
  - Is reliable and dispatchable
  - Is resource efficient
  - Can be economical

http://srren.ipcc-wg3.de/report/IPCC_SRREN_Annex_II.pdf

We Need Many Generation Types

- Studies have shown that firm resources reduce cost and resource needs for full decarbonization
- Nuclear energy, or something similar, is needed for the **last 20-40% of decarbonization**



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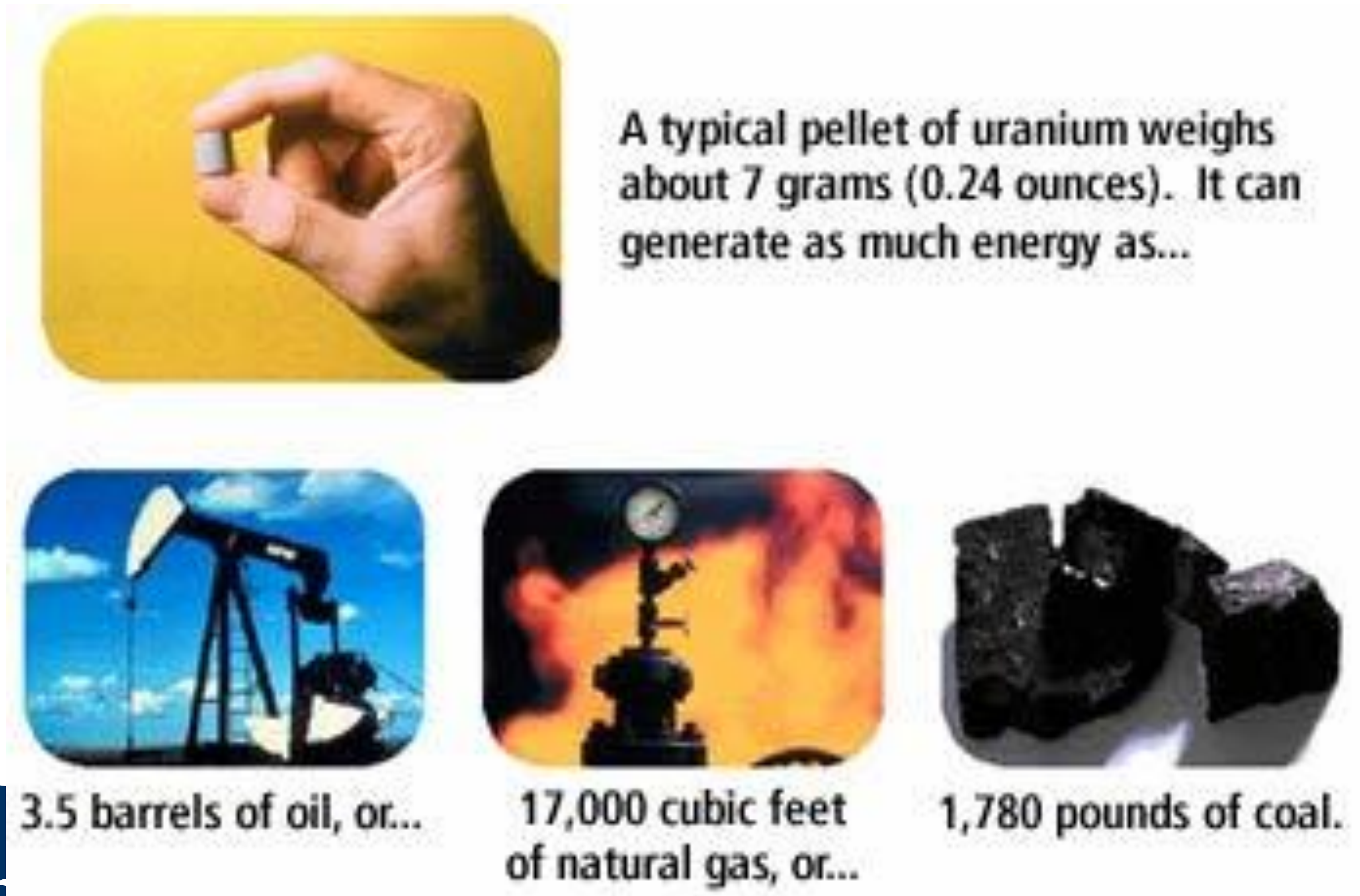
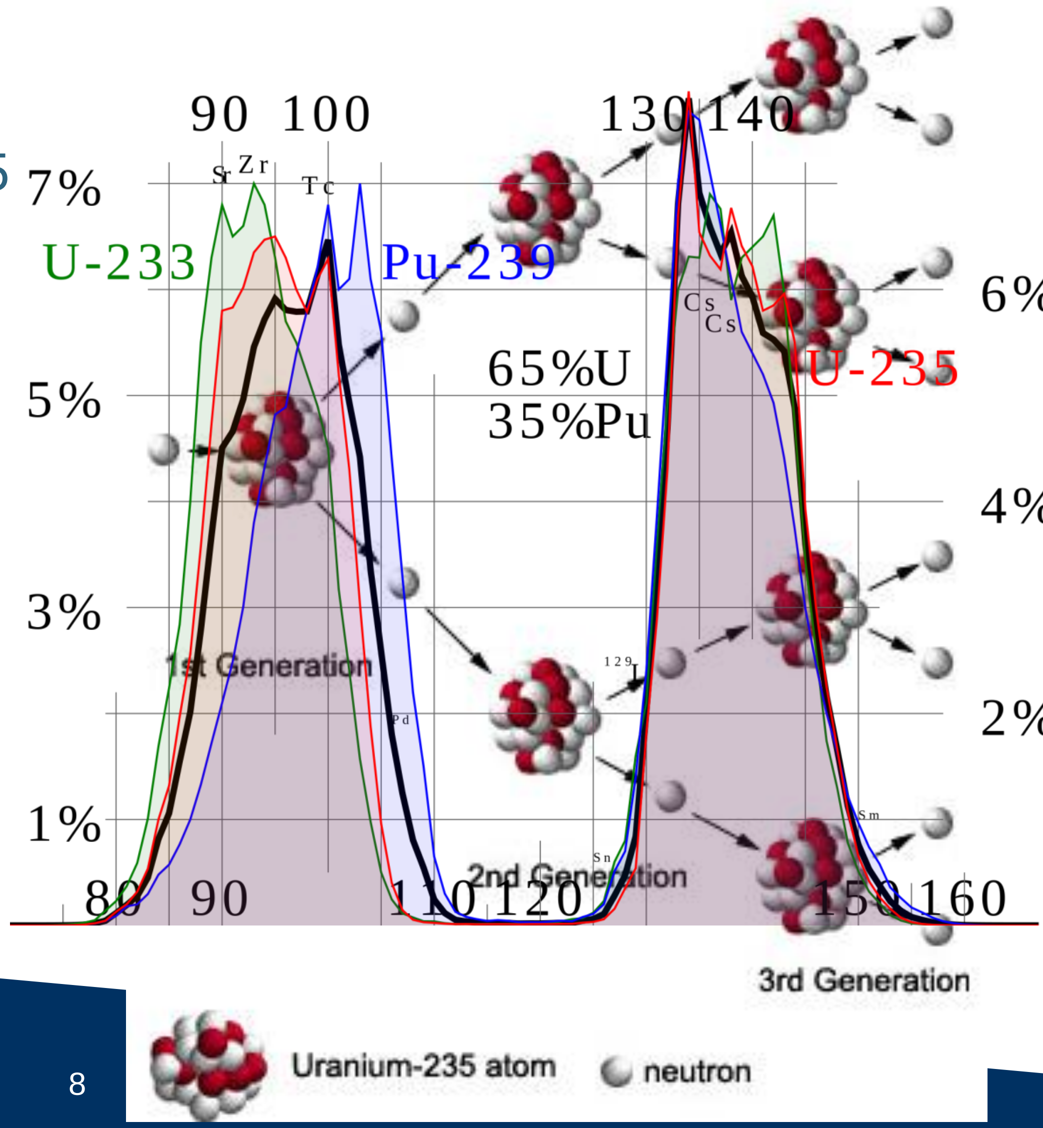
https://www.cell.com/joule/pdf/S2542-4351(18)30386-6.pdf

Why Care? Energy Density…



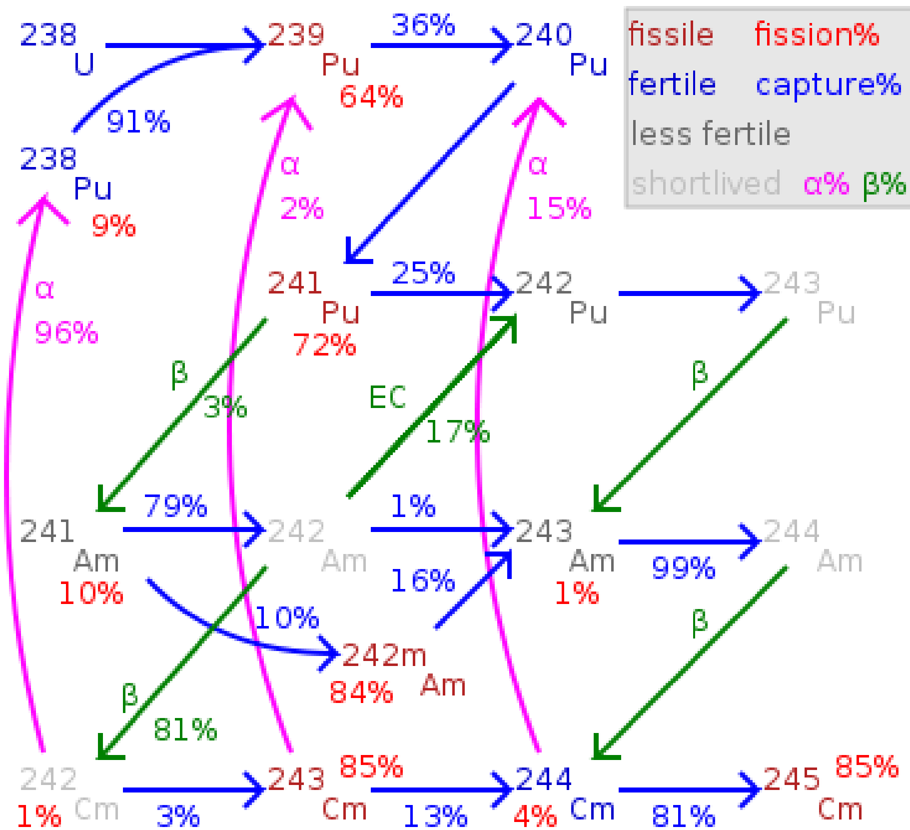
A Complicated Hot Rock

- One fission releases
  - 1 to 5 more neutrons (~2.5 on average)
  - ~200 MeV of energy
- Steady state = critical
- Today's fuel is 3 to 5% ^{235}U
- Natural is 0.7% ^{235}U
- ^{235}U becomes two new atoms



Breeding and Burning

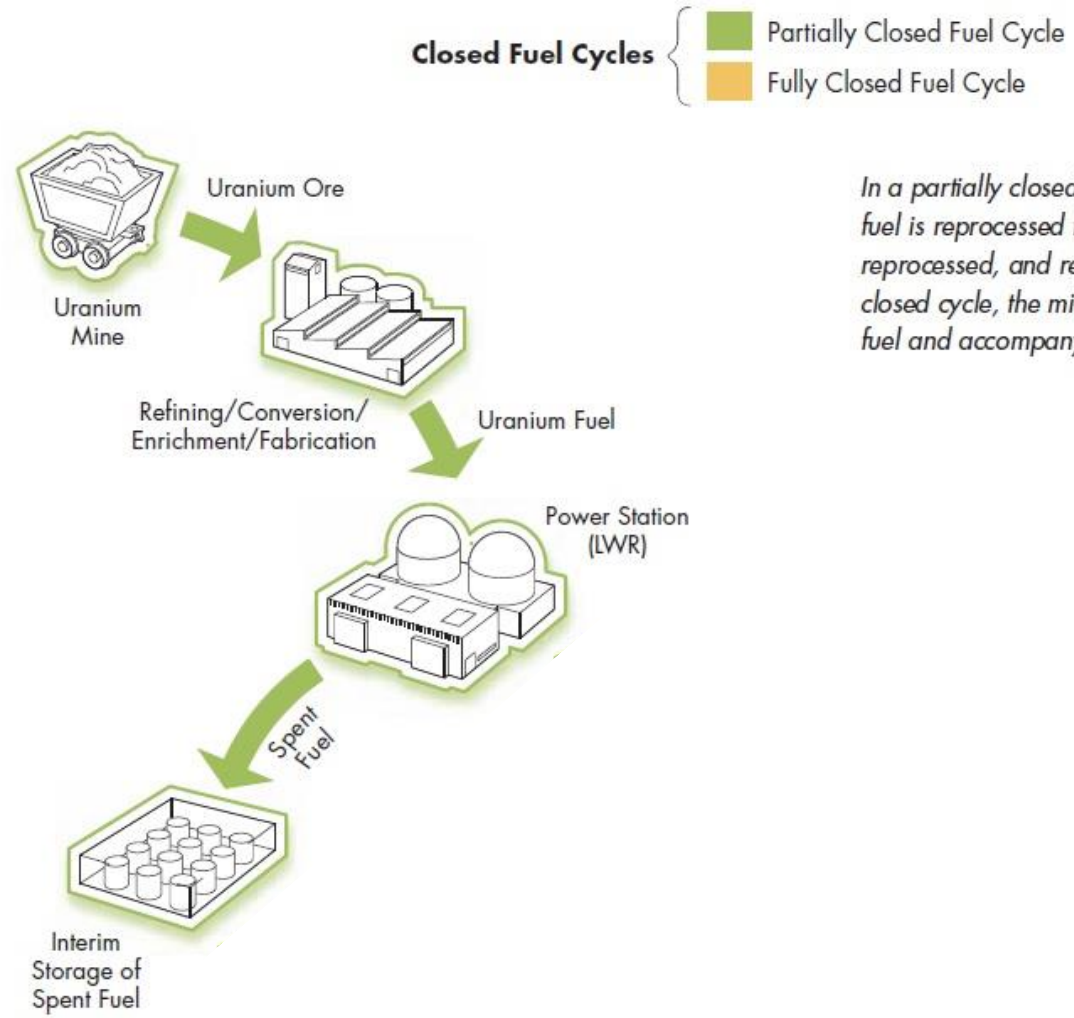
Breeding: create more fuel



Burning: consume waste

- Transuranics created in reactor core
- Transuranic elements have long half-lives
- Can be fissioned to produce energy
- Remaining fission products are radioactive for less time

https://en.wikipedia.org/wiki/Breeder_reactor



In a partially closed cycle, the uranium and plutonium from spent LWR fuel is reprocessed for use in a fast reactor (FR); this fuel is burned, reprocessed, and refabricated repeatedly in a closed loop. In a fully closed cycle, the minor actinides are also extracted from the spent LWR fuel and accompany the major actinides in the closed cycle.

https://webberenergyblog.wordpress.com/2012/02/24/nuclear-fuel-cycles-past-present-and-the-future-in-the-us/

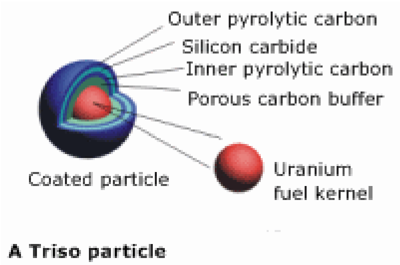
Physics Options

Neutrons causing fission:

- Fast
- Thermal

Fuel Form:

- Ceramic
- Metallic
- Particle
- Liquid



Coolant type:

- Light or heavy water
- Gas (usually He)
- Salt (usually F-based)
- Liquid metals
- Sodium
- Supercritical CO_2

Temperature:

- ~330 °C / ~650 °C / ~850 °C

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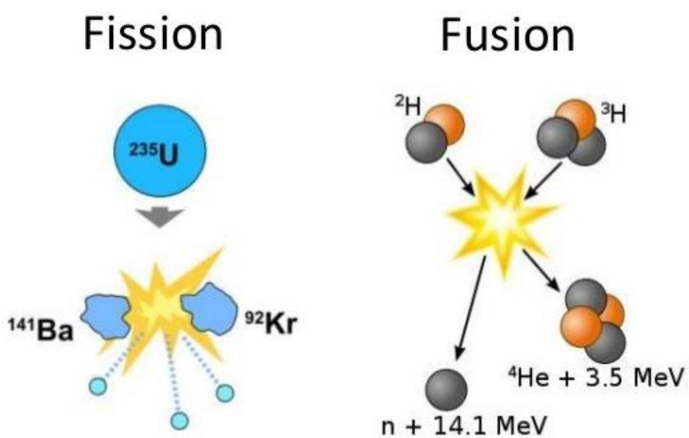
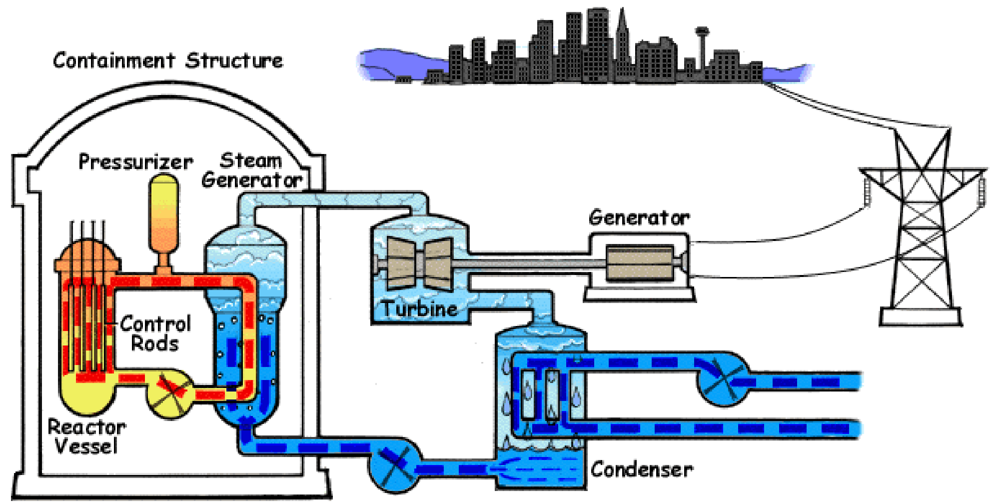
Design Trade Space

- Operational Safety
- Waste generation / consumption
- Fuel utilization / breeding
- Industrial process heat
- Operational flexibility
- Proliferation resistance
- Existence of materials
- Cost
- Market needs
- Size
- Licensing
- Supply chain existence
- Public opinion

Fission, Fusion, Reactors





Fission:

- Split a heavy atom into two lighter ones + neutrons
- Making electricity for > 60 years

Fusion:

- Fuse two light atoms into a heavier one + (often) neutron
- May soon pass “breakeven”

Existing nuclear reactors

- Most use water coolant, ~1 GW scale
- 442 reactors in >30 countries
- 10% of global electricity,
  20% of US electricity
- New “Gen III+” designs use more passive safety

https://chem.libretexts.org/Courses/can/intro/17%3A_Radioactivity_and_Nuclear_Chemistry/17.07%3A_The_Discovery_of_Fission_and_the_Atomic_Bomb, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

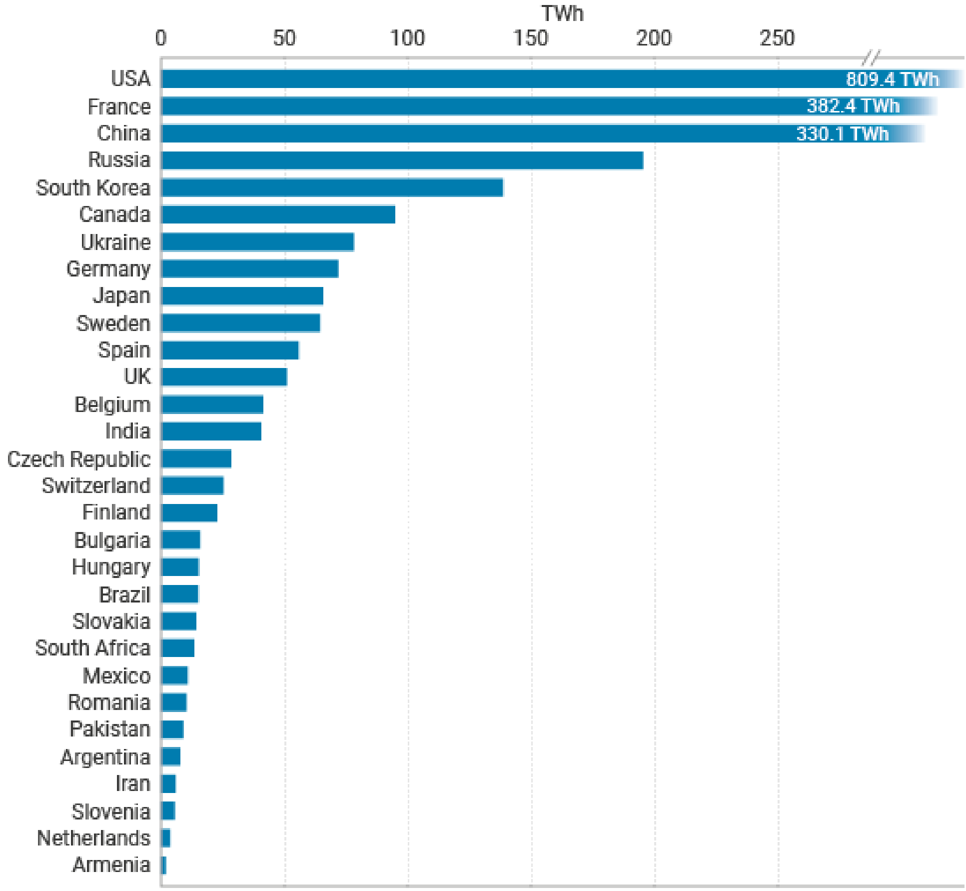
The Current Fleet

Generation III

- 32 countries + Taiwan are operating ~440 reactors
- Most of them are LWRs

Generation III+

- ~50 under construction in 16 countries
- ~100 ordered / planned
- >300 proposed



Source: IAEA PRIS Database

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https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx, https://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx

WHICH ENERGY SOURCE IS THE SAFEST?

Energy use is a necessity in the modern economy, but the practices of extracting and using energy also create a deadly trade-off.

NUCLEAR IS SAFEST

Even including Chernobyl and Fukushima incidents, nuclear is the safest power source per TWh.

A BRIGHT FUTURE

There are still some deaths attributable to renewables such as accidents and via lifecycle analysis, but they are among the safest forms of energy on earth.

WATER DAMAGE

Hydro is normally very safe, but it has one extreme outlier that skews the data.

In 1975, the Banqiao Dam in China collapsed during a typhoon, killing 171,000 people.

BLACK DEATH

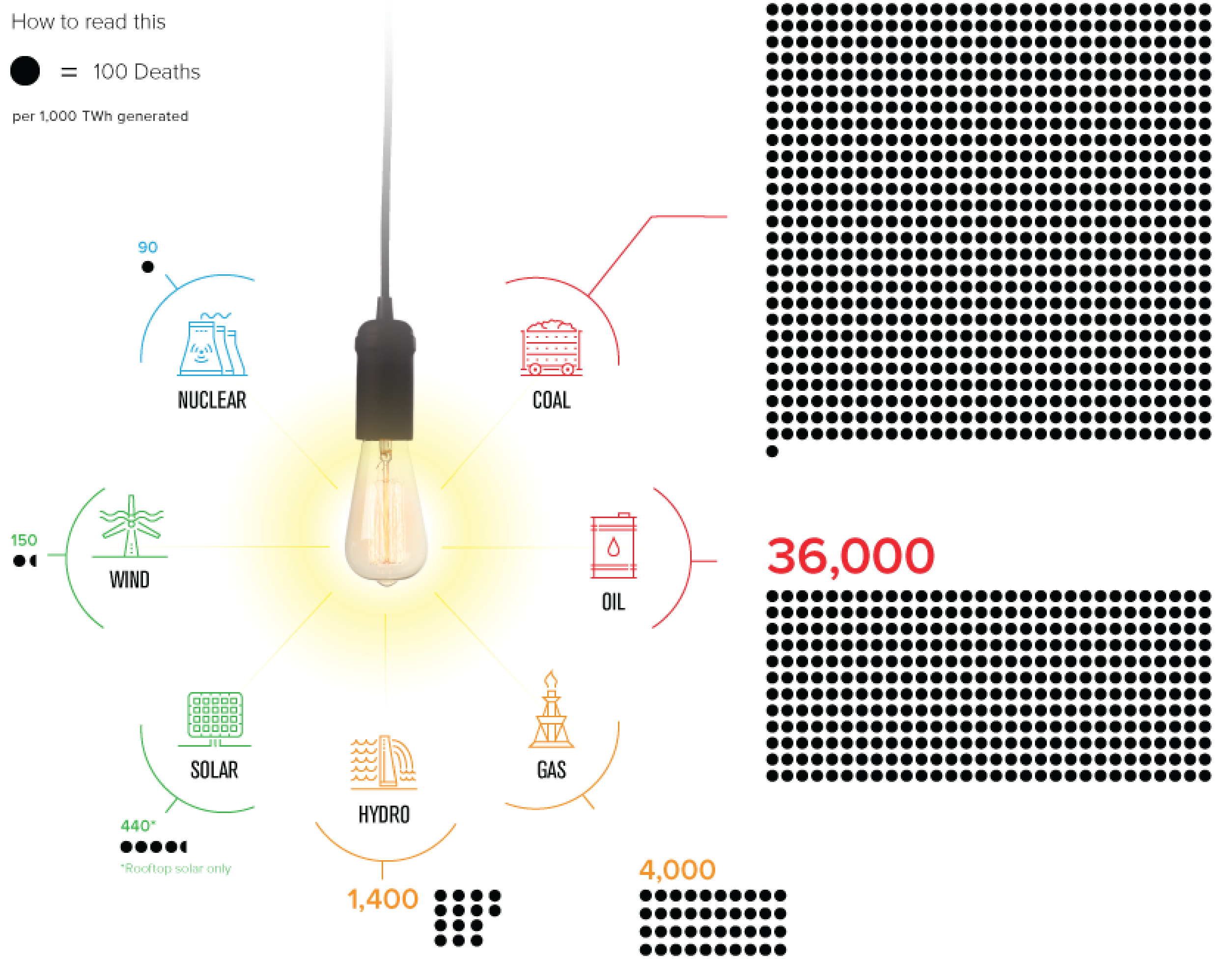
When the human and environmental costs of coal are added up, it's the biggest killer of any energy source by far.

Air pollution alone in China kills over

4,400

people per day.

Safety

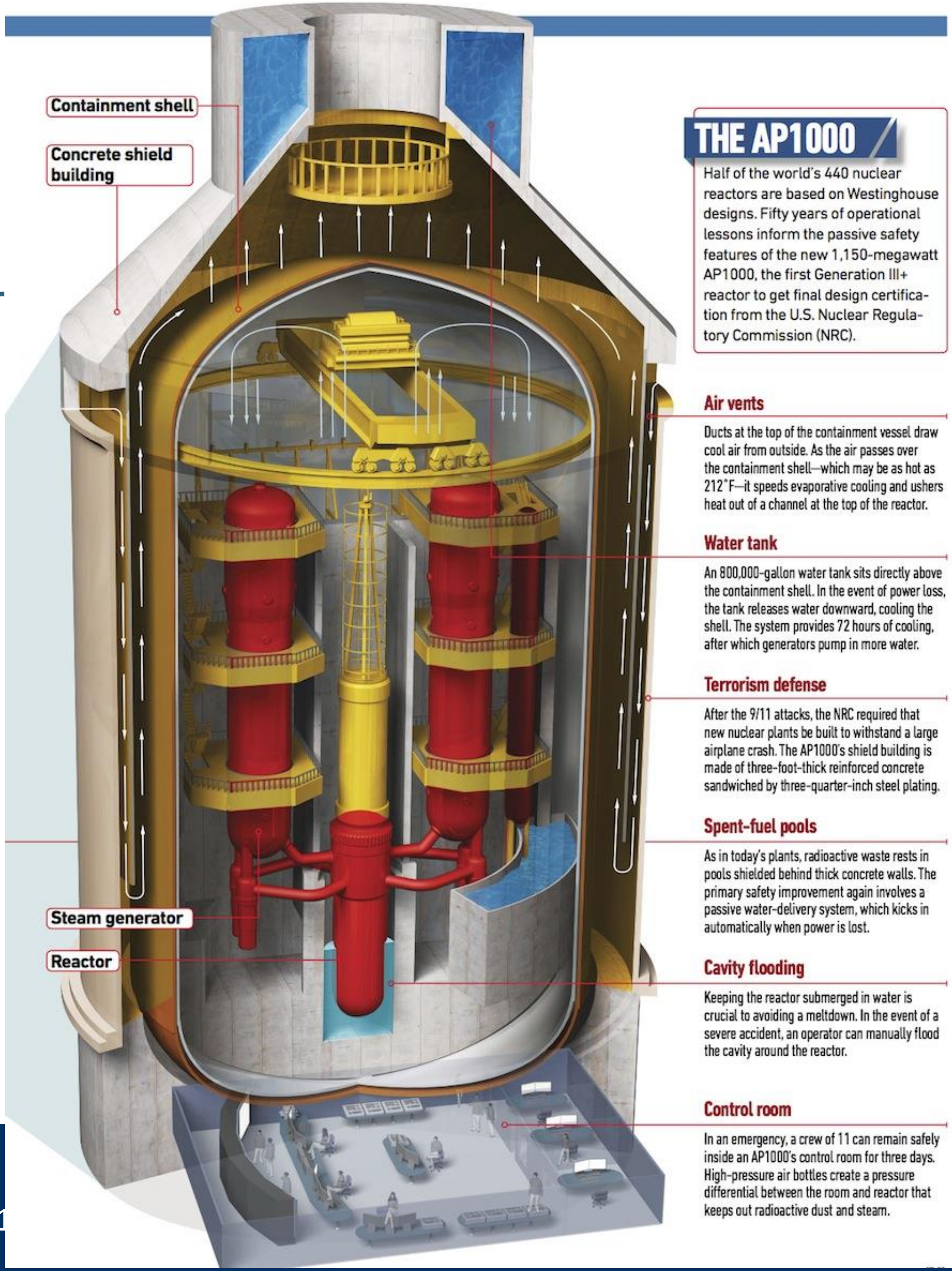


Source: Forbes

New Reactor Deployment

Current LWR Focus

- Qualifying existing reactors for further operation (gen II & III)
  - "saving the existing fleet"
  - CESs in various states
- Building Gen III+ LWRs
  - Enhanced safety features
  - Improved economics in some economies
- Building small modular



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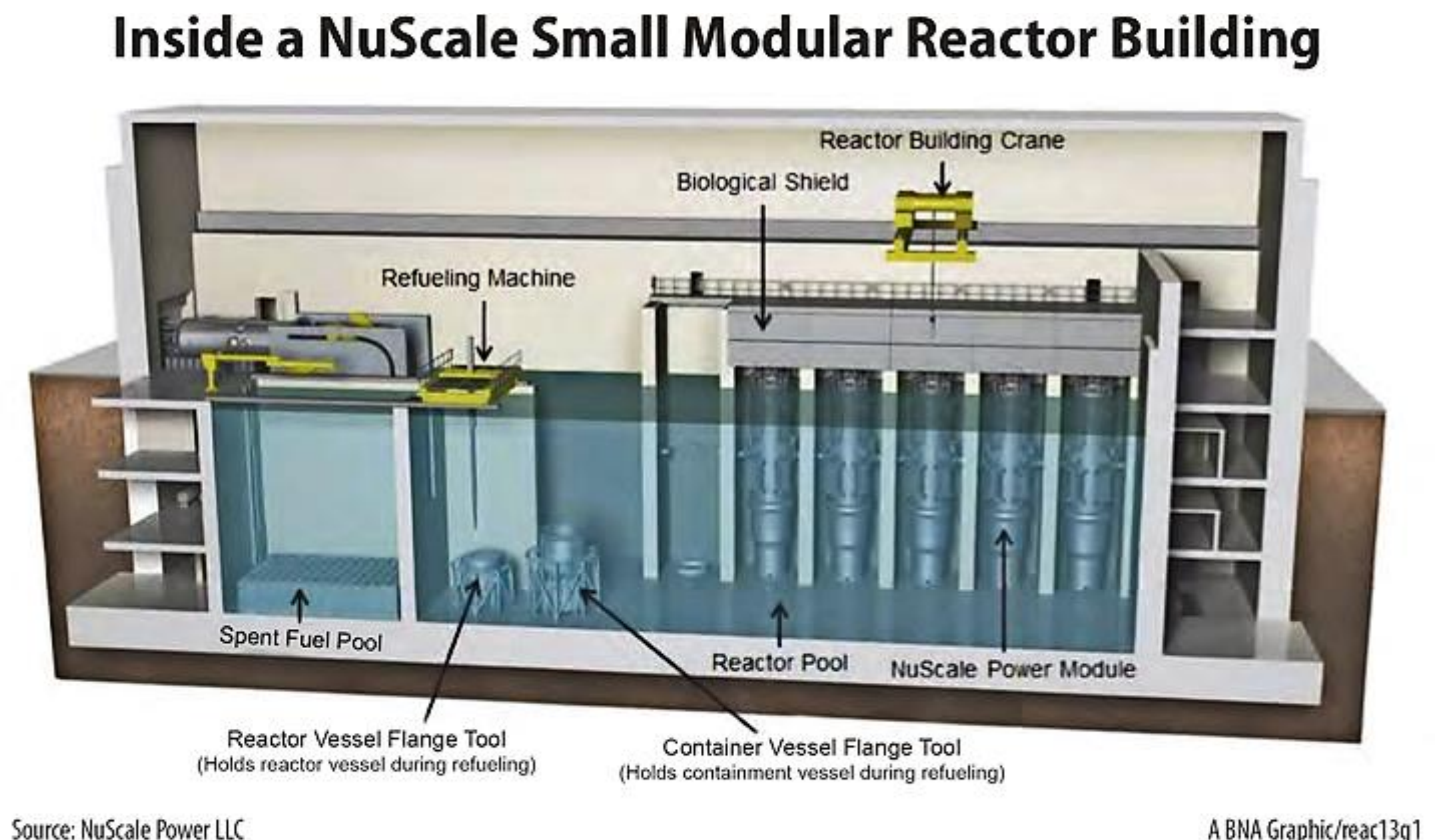
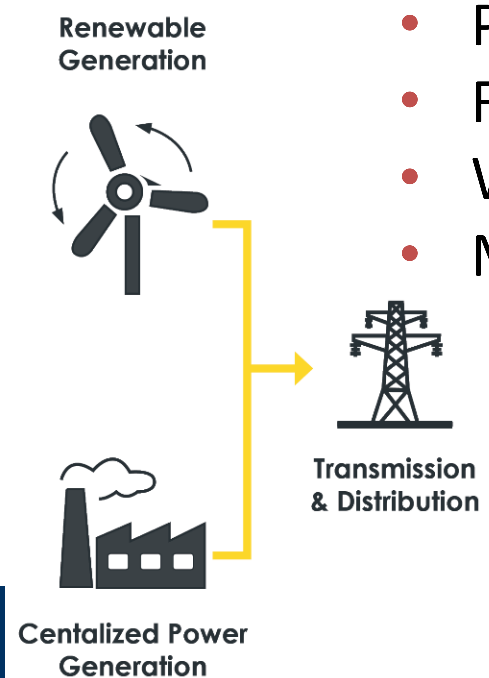
Case Study: Small Modular LWR

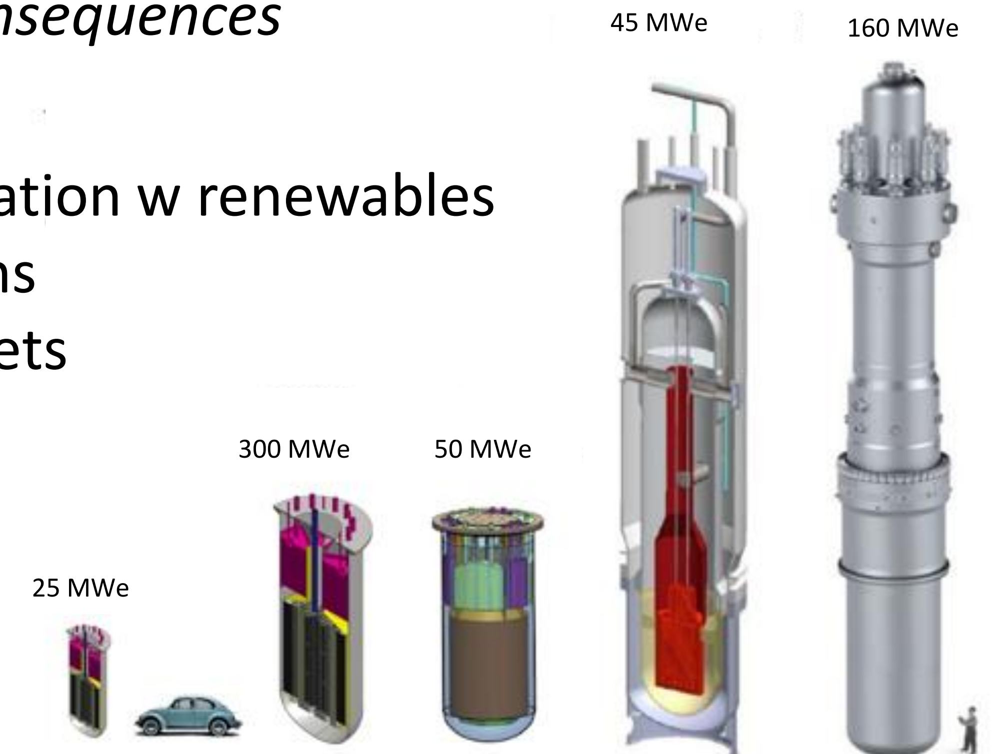


Advanced/Gen IV Reactors

- Small modular, and/or use *not* water to transfer heat
- Most use different fuel forms and enrichment levels
- Lower pressures, higher temps
- Potential for *no offsite consequences*



- Process heat
- Flexible integration w renewables
- Waste solutions
- Multiple markets



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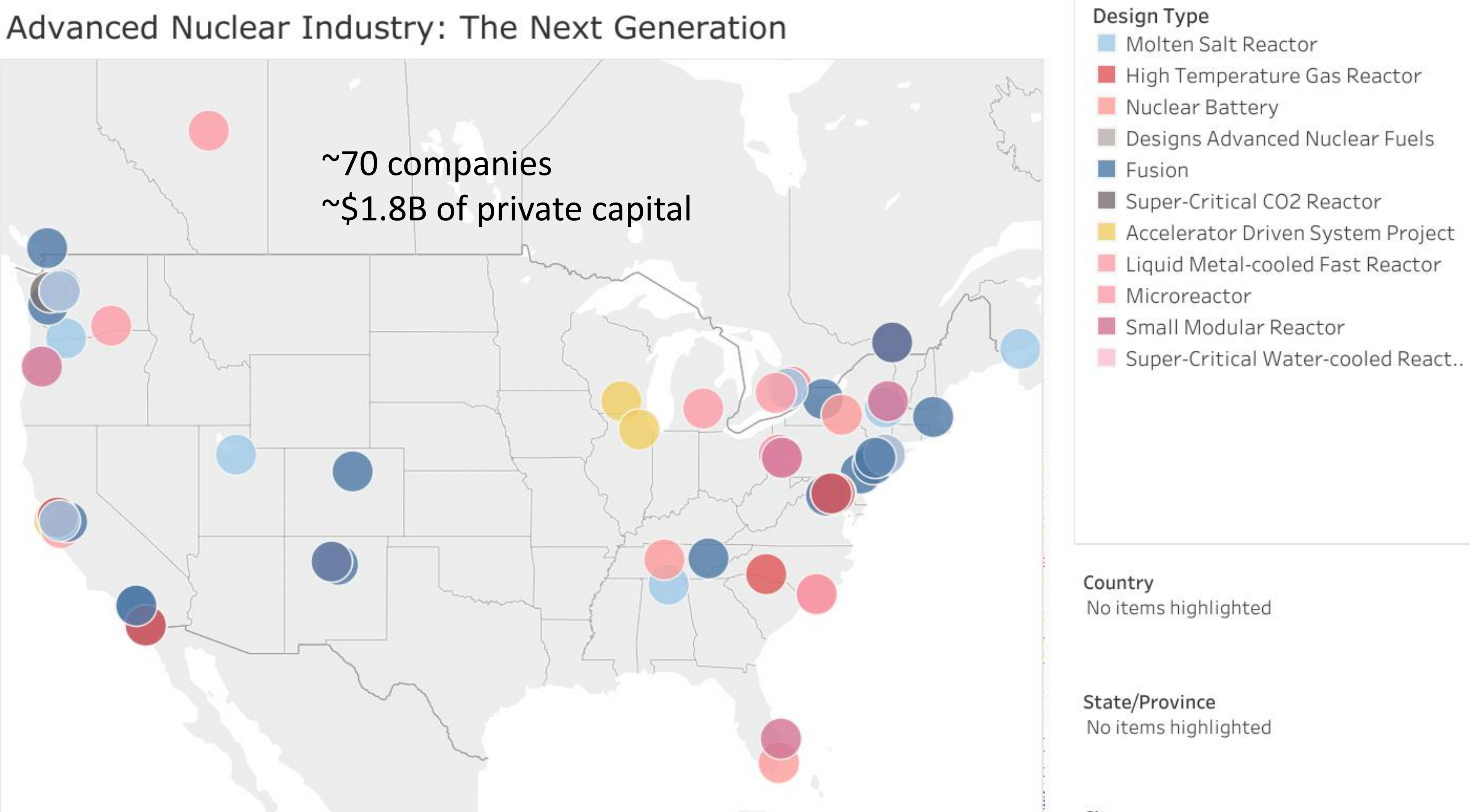
https://www.iaea.org/newscenter/news/iaea-launches-new-version-of-advanced-reactors-database, https://www.nextbigfuture.com/2013/12/molten-salt-reactor-about-50-times.html

Designing the Next Fleet

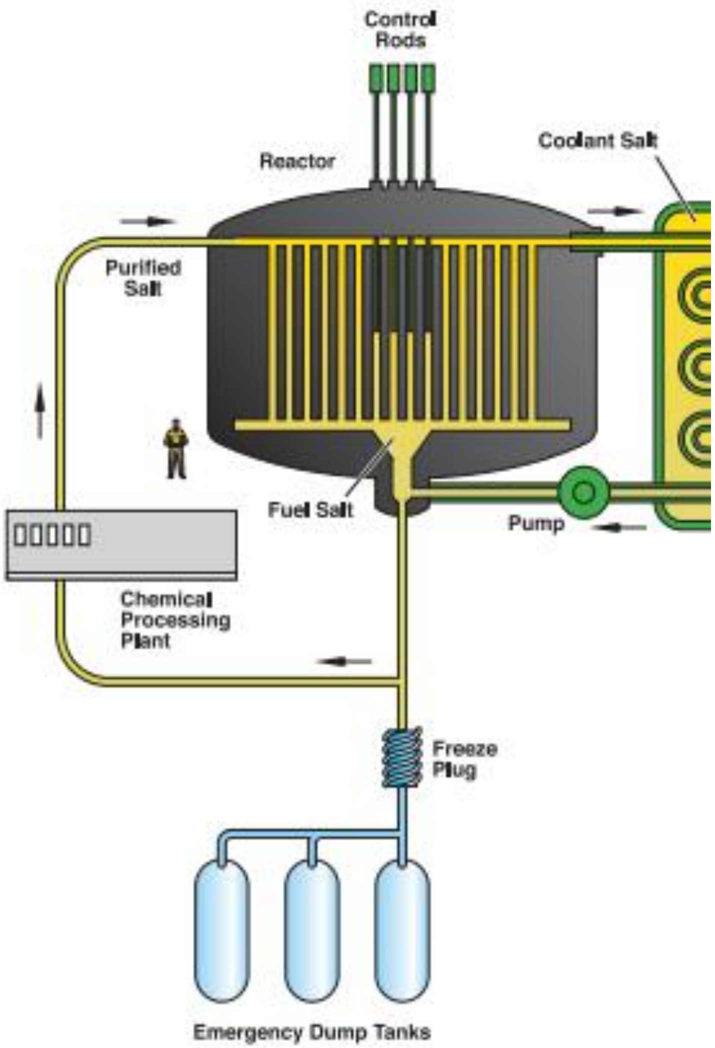


~70 companies
~$1.8B of private capital

Case Study: Molten Salt Reactor

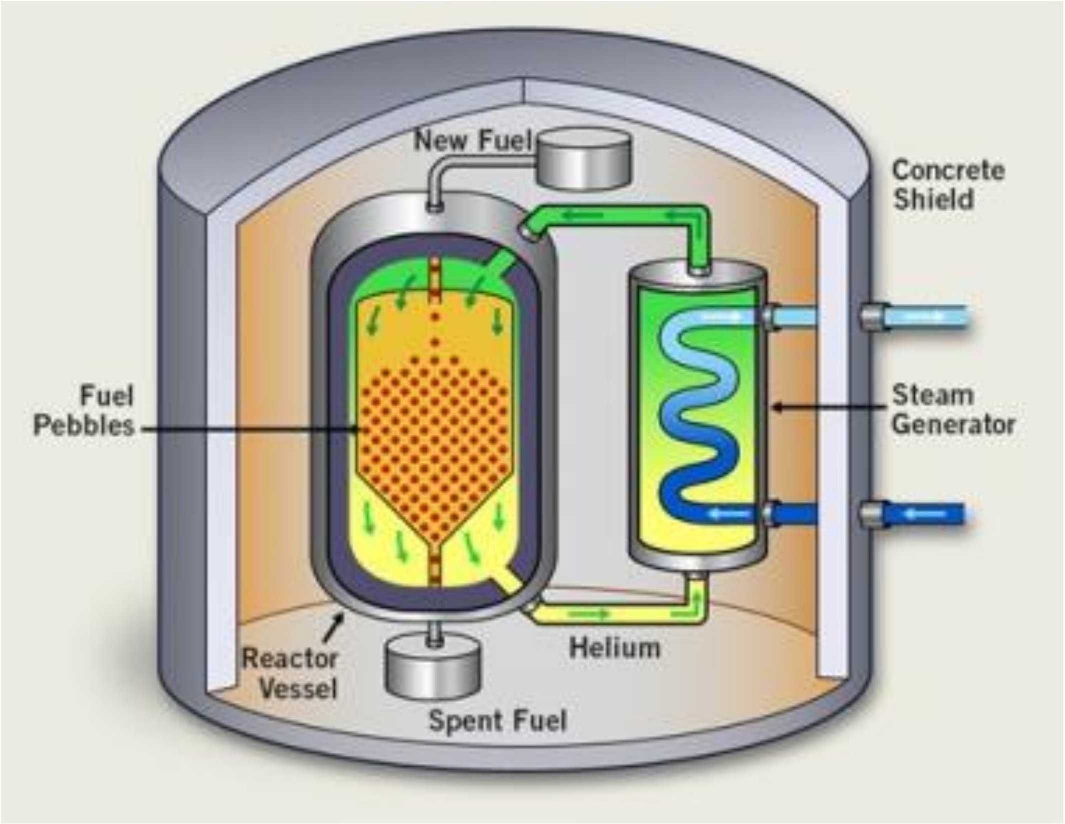
+ Advanced safety
+ Process heat (> 650 °C)
+ Various enrichments; can use Th
+ Breed / consume waste
+ Online refueling

- Materials challenges
- Process challenges
- Maintenance challenges



http://www.neimagazine.com/news/newsmolten-salt-reactors-enjoy-15-minutes-of-fame-4290903

Case Study: High Temp Gas Reactor

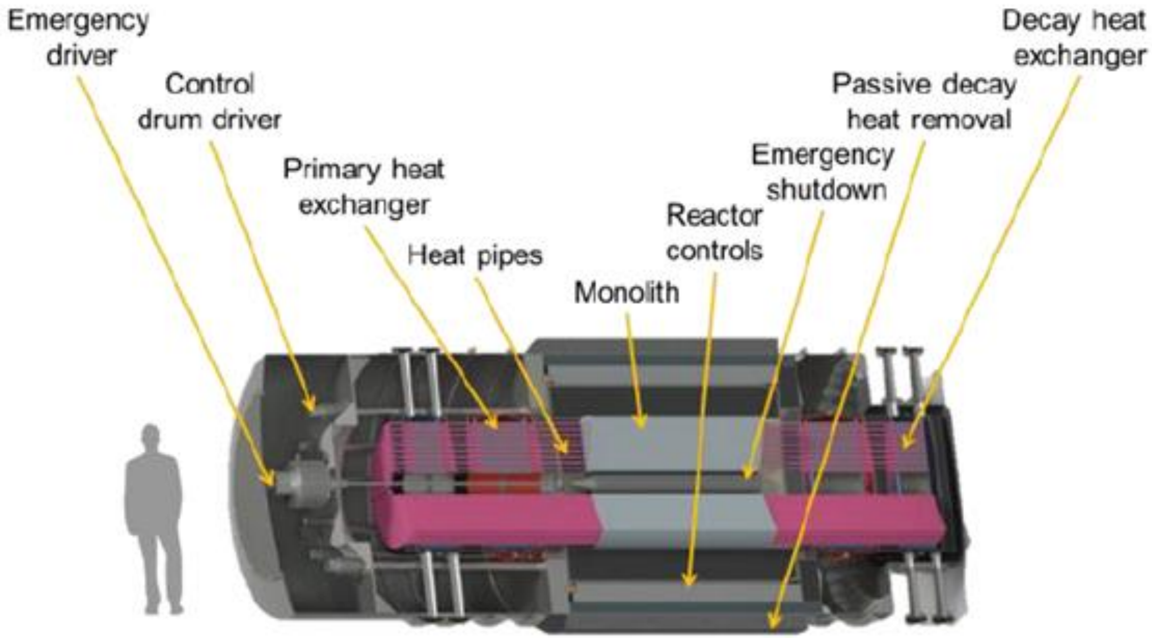


- + No core meltdown accidents
- + Process heat (>850 °C)
- + Proliferation is difficult

- – Difficult to recycle
- – Low power density
- – Materials challenges

https://neutronbytes.com/2016/04/09/progress-report-on-htgr-reactors-in-china-and-u-s/

Case Study: MicroReactors



- \+ Versatile market options
- \+ Factory fabricated
- \+ Self-regulated
- \+ Heat or power

- – Economics?
- – Materials?

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https://energypost.eu/next-generation-nuclear-25mw-smaller-safer-can-be-sited-anywhere/

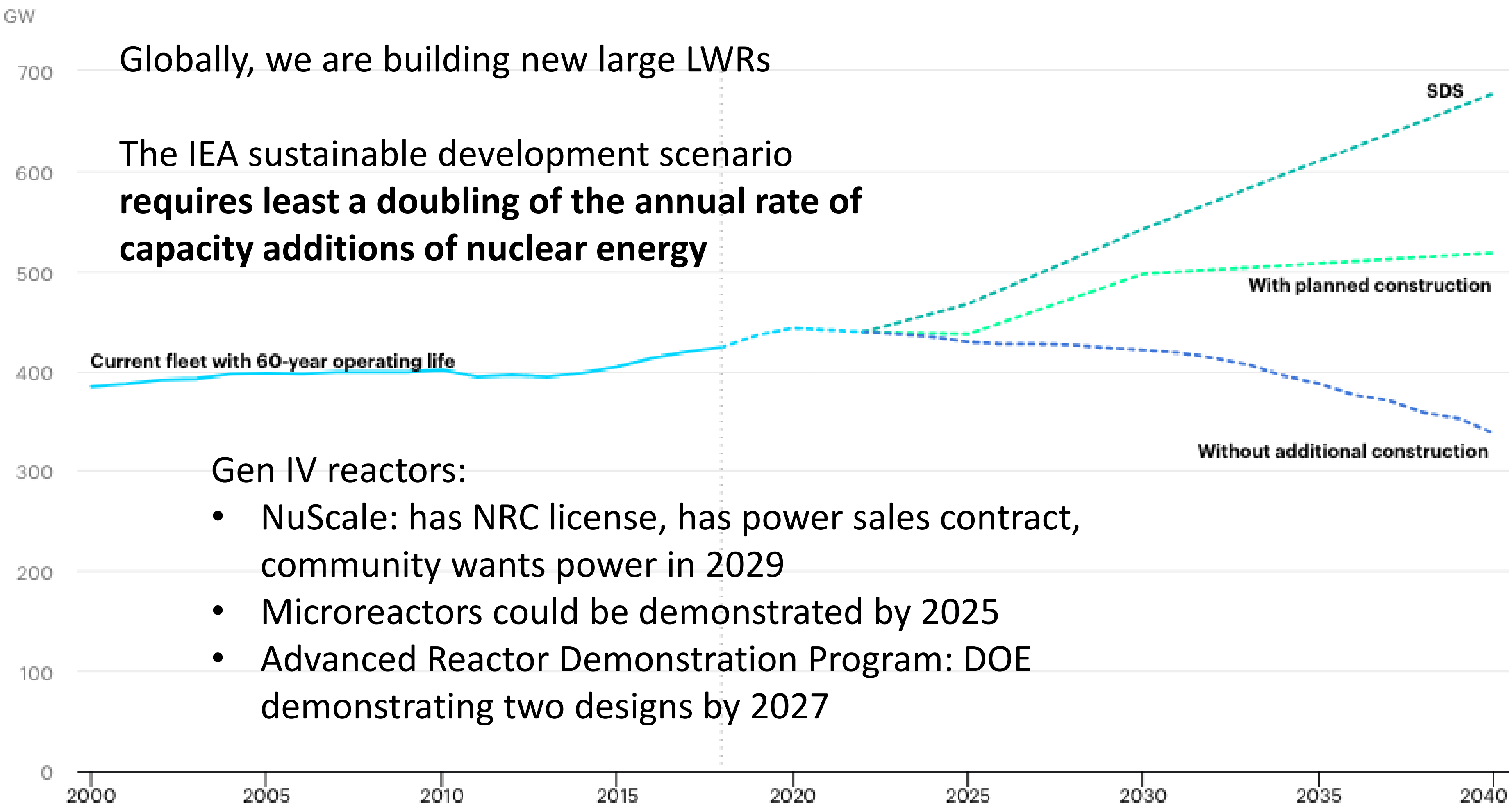
Where Are We / Possible Futures

Globally, we are building new large LWRs

The IEA sustainable development scenario **requires least a doubling of the annual rate of capacity additions of nuclear energy**

Gen IV reactors:

- NuScale: has NRC license, has power sales contract, community wants power in 2029
- Microreactors could be demonstrated by 2025
- Advanced Reactor Demonstration Program: DOE demonstrating two designs by 2027

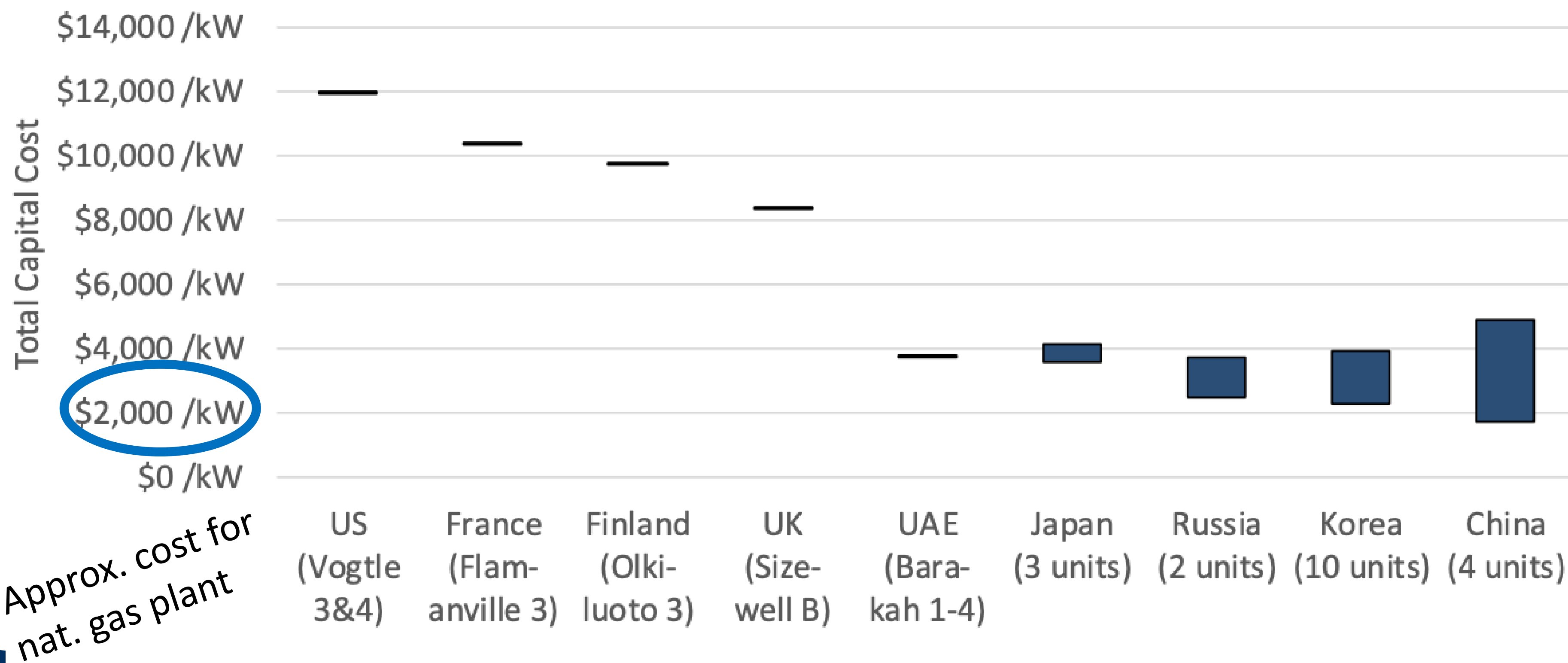


https://www.iea.org/reports/tracking-power-2019/nuclear-power#abstract

Economics & Funding

Gen III+ Reactors Can Be Cost Competitive

Figure 1. Total Capital Costs for Historical and Ongoing Nuclear Projects in Database



CleanTech Catalyst Ltd. *The ETI Nuclear Cost Drivers Project: Summary Report.* energy technologies institute. April 2018.

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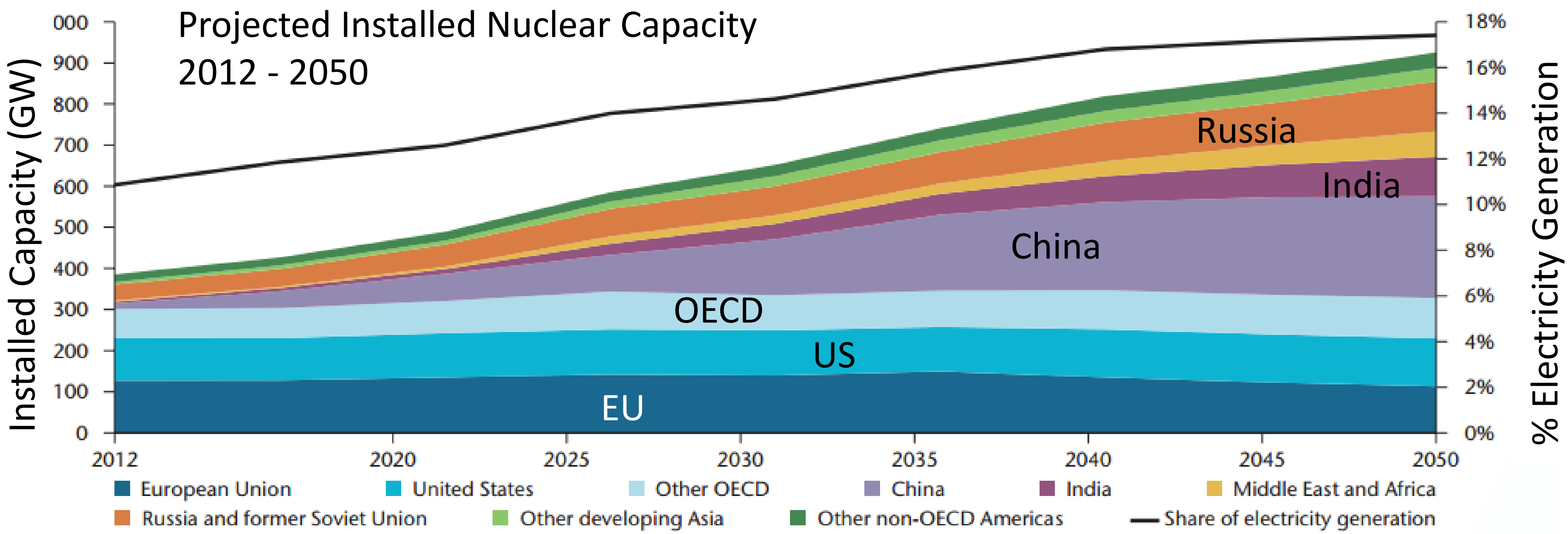
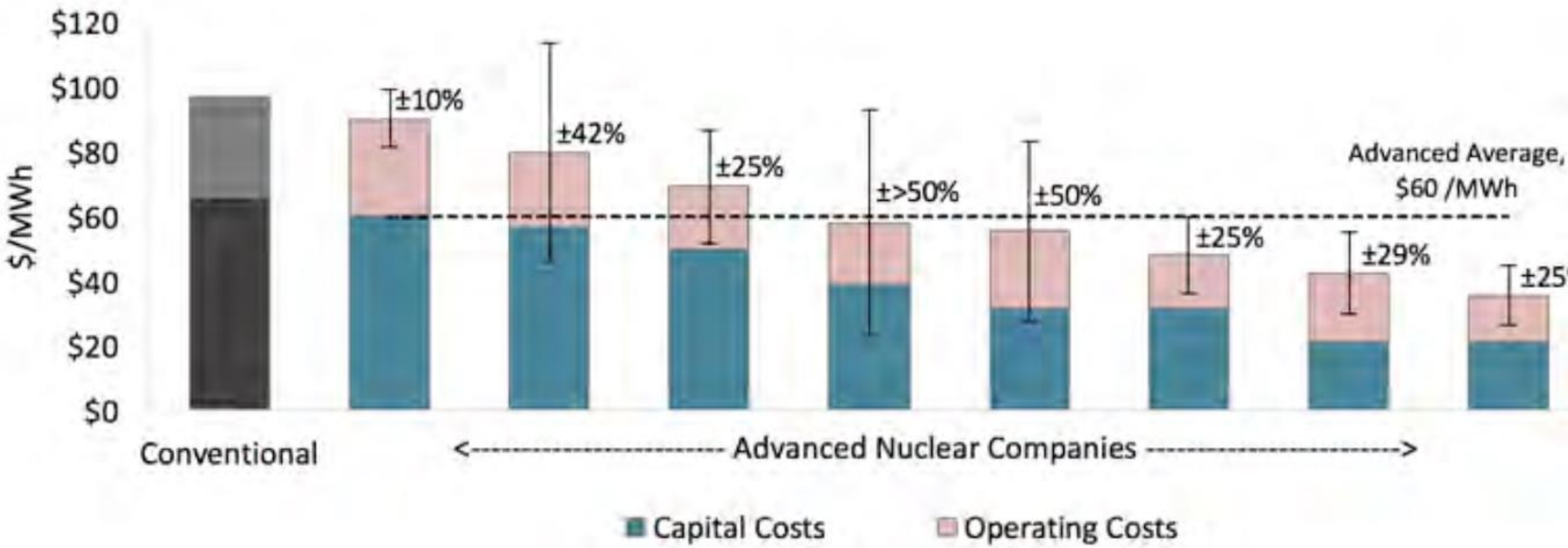
What's Being Built Where?



International Energy Agency, *Technology Roadmap: Nuclear Energy*, 2015

Advanced Rxtrs Could Be Cost Competitive

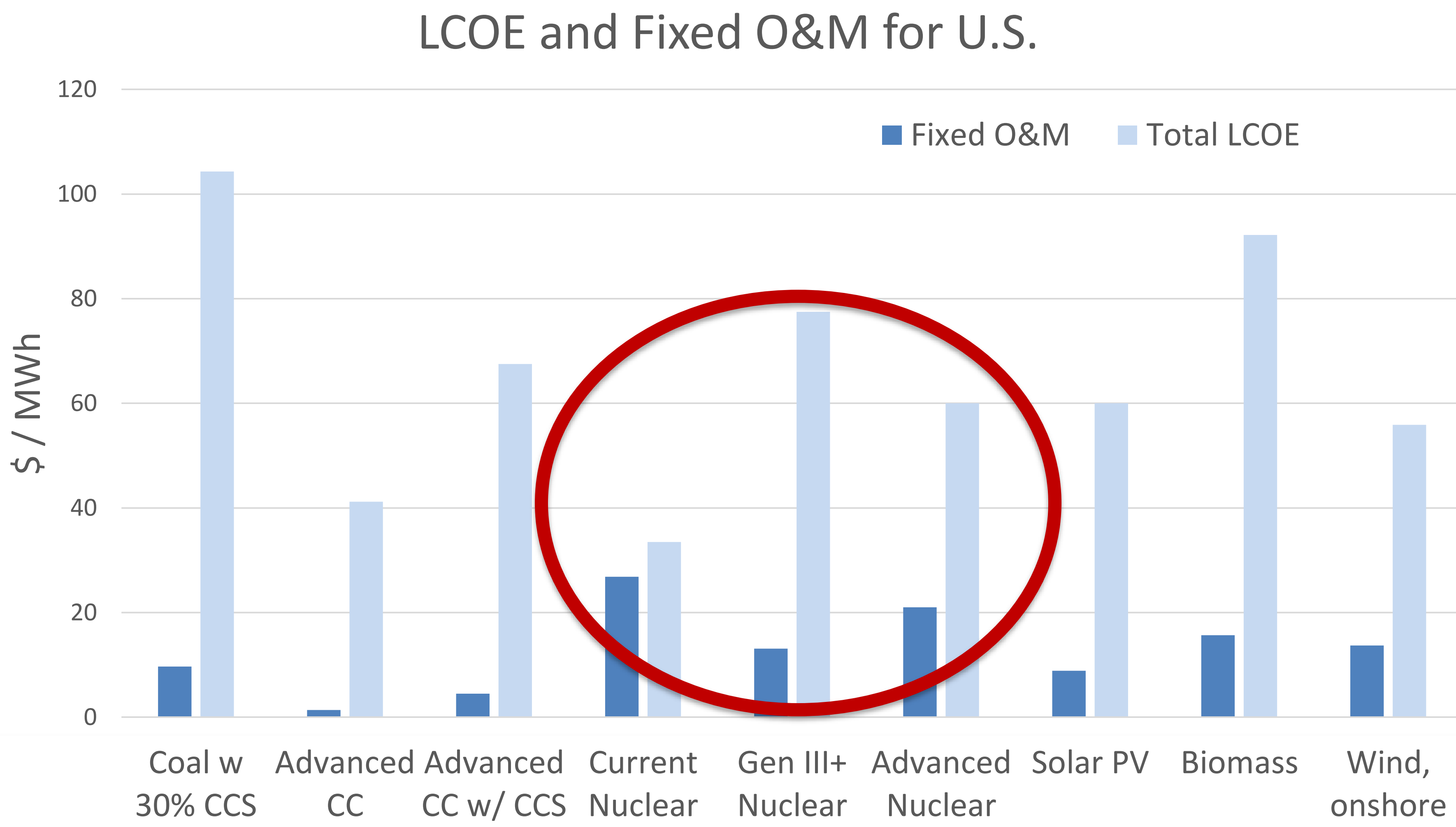
- Potential LCOE for Nth of a kind ARs assessed with a cost accounting framework developed by the Generation IV International Forum
- Includes plants at least 250 MW in size



LCOE in 2016 dollars. Error bars reflect companies’ self-reported confidence bounds

Energy Options Network. *What Will Advanced Nuclear Power Plants Cost?.* Energy Innovation Reform Project. July 2017.

How Do Electricity Prices Compare?



https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf, https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf

U.S. Government Initiatives

- Most of DOE-NE's budget is Nuclear Energy Research and Development (FY20 $1.5B)
  - Of that, ~⅓ is for Idaho National Laboratory infrastructure
  - The other large bins are Advanced Reactor Demonstration Program (ARDP), Research Reactor RD&D, and Fuel Cycle R&D
- ARDP was created by Congress and not requested by NE; thru FY27:
  - Demo awards: X-Energy and Natrium, ~$3.2B with $160M so far
  - Risk Reduction Awards: 5 teams for ~$600M
  - Advanced Reactor Concepts-20: 3 teams for ~$56M
- Versatile Test Reactor (VTR): NE initiative $4.2B for FY27 completion; stalled and unlikely to move forward
- SMRs: NuScale, $350M, and Carbon Free Power Project (CFPP), ~$1.4B
- A plan for high assay low enriched uranium (HALEU) and a U reserve are priorities

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Opportunities

https://www.thirdway.org/blog/nuclear-reimagined

Electricity

- Large LWRs globally
- Next gen: multiple sizes + rampability = many potential markets

Deep Decarbonization

- Process heat (up to ~1000 C)
- Electricity / waste heat to enable other technologies

Timeline

- Gen III+ available now
- Gen IV commercially by 2030

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Summary

- Decarbonization is easiest with dispatchable clean energy as part of the mix
- Nuclear energy has a lot of beneficial properties
- Which are balanced by challenges
- Advanced reactors offer a pathway to resolve or lessen the challenges
- They may also have large benefits beyond the electricity sector

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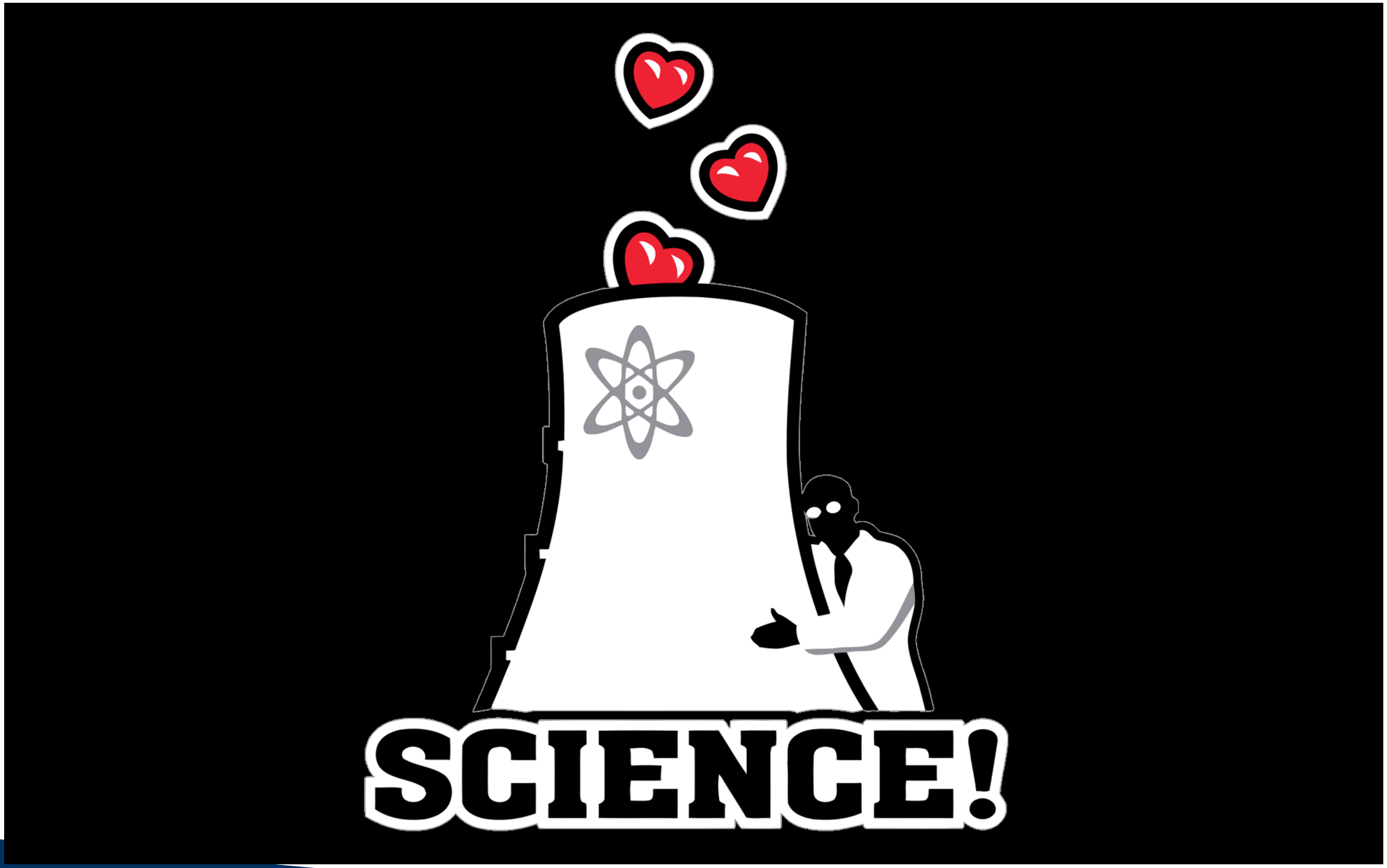
Thank You



Regulation

Nuclear Regulatory Commission

- An independent agency to ensure the safe use of radioactive materials for beneficial civilian purposes while protecting people and the environment (NRC)
- Only 10% funded by Congress
- Covers reactors, materials, and waste
- Headed by 5 Presidentially appointed Commissioners, 5-year terms, 1 Chairman (currently 2 spots vacant)
- Advisory Committee on Reactor Safeguards (ACRS) reviews and advises the Commission, primarily on safety
- Atomic Safety and Licensing Board (ASLB) conducts hearings for the Commission (trial-level adjudicatory body)

Regulations

- 10 CFR part 50: original way to license reactors
  - Get construction permit prior to construction
  - Get operating license after construction
- 10 CFR part 52:
  - Get combined construction and operating license
  - Use a certified design; doing inspections during construction
- Both pathways are highly specific to large LWRs
- 10 CFR part 53: planned new pathway for licensing advanced reactors actively under development