

IEEE NPSS School on Nuclear Power for Sustainable Development



THE OHIO STATE UNIVERSITY

Evolution of Nuclear Fission Technology: From Gen II to Gen III+ and Gen IV and SMR

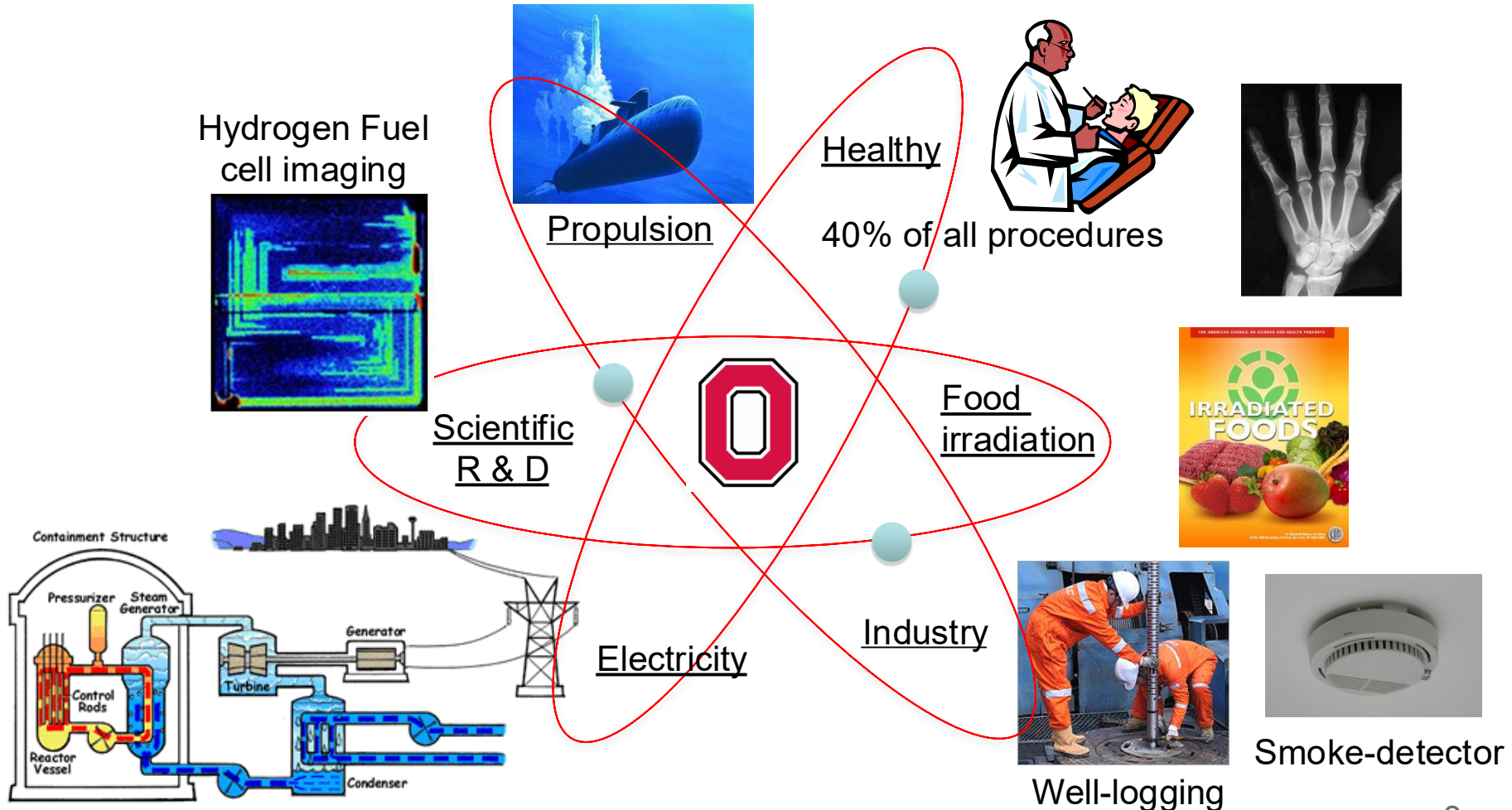
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- Fission & Neutron Economy
- Viewing the Present through the Lens of History
- Advanced Reactor Concepts



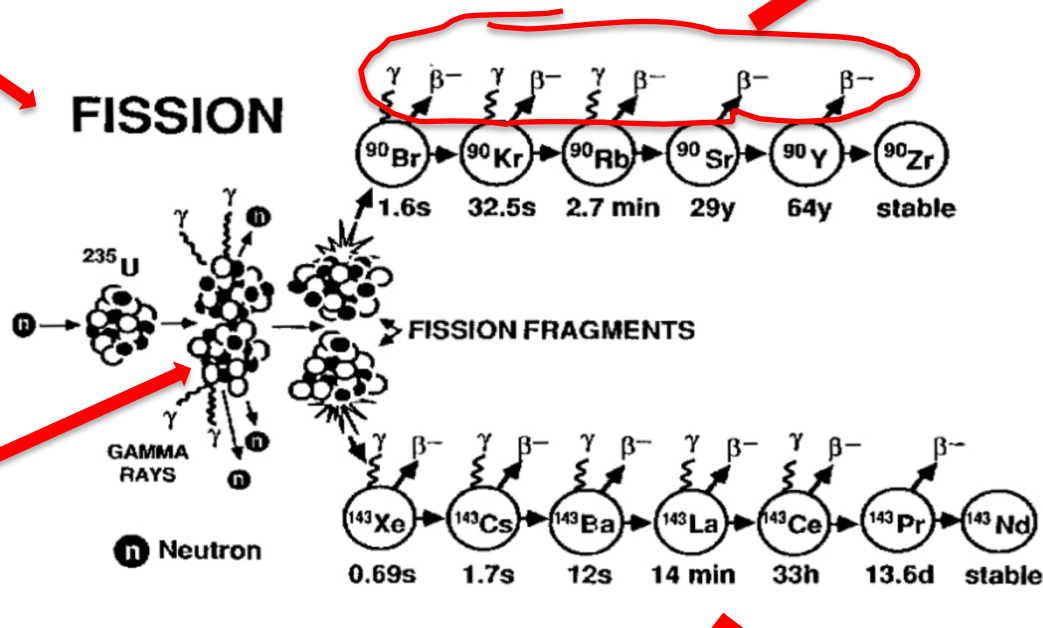
- Nuclear power is a low carbon emission, 7/24, dispatchable energy source that support **grid stability, energy security, and climate goals.**
- Accounts for total electricity generation 18% in USA and 10% in the world.





~ 200 MeV
energy released

These decay energy is 7% of all the
energy released – but the big problem!



~ 168 MeV
as fission
fragments

Fuel pellet, cladding, reactor
vessel, and confinement
building are 4 barriers
holding these fission
products



Energy Source	Fission Energy (MeV)	Heat Produced	
		MeV	% of Total
Fission Fragments	168	168	84
Neutrons	5	5	2.5
Prompt Gamma Rays	7	7	3.5
Delayed Radiations			
Beta particles & antineutrinos	20	8	4
Gamma Rays	7	7	3.5
Radiative Capture Gammas		5	2.5
Total	207	200	100

The electronvolt (eV) is built for particles because joules are too large there.

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$0.00000000000000000001602 \text{ J}$$

1 g TNT

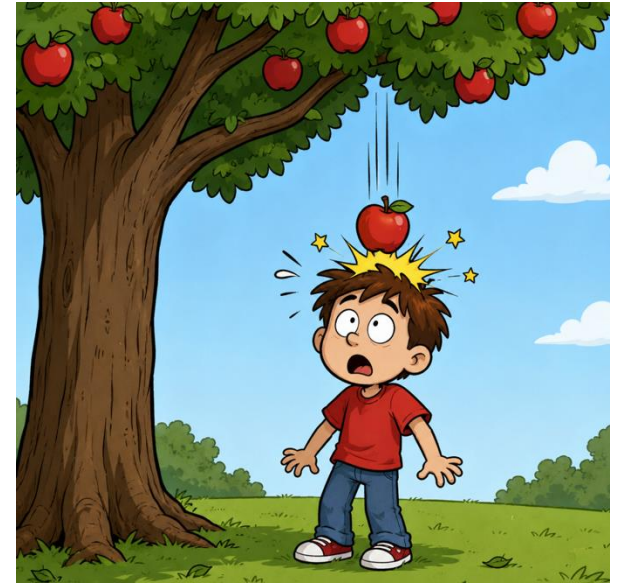
4,184 J

1 J



0.239 mg TNT

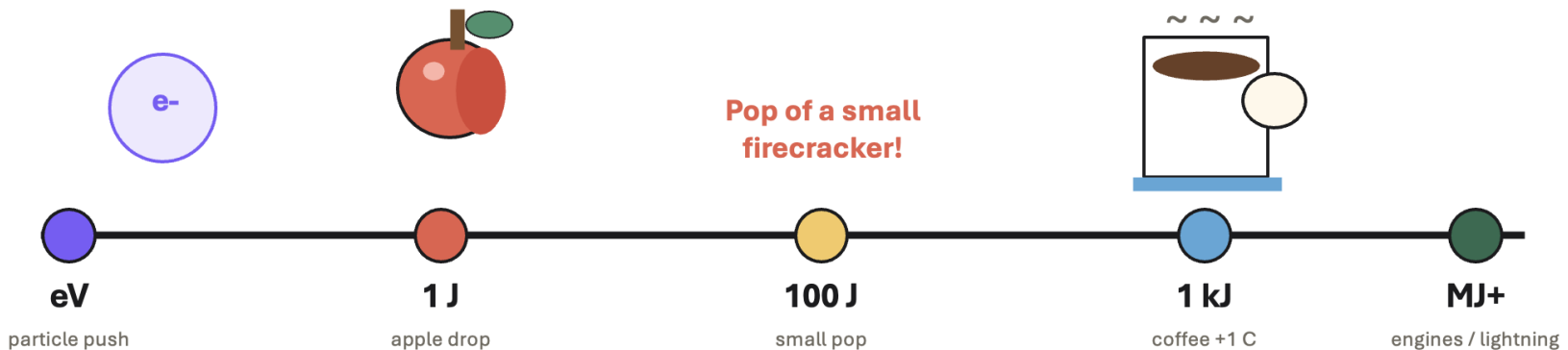
How much energy is 1 Joule?



$$E = mgh$$

$$0.10 \text{ kg} \times 9.8 \text{ m/s}^2 \times 1 \text{ m} \\ \approx 0.98 \text{ J} \approx 1 \text{ J}$$

**Pop of a small
firecracker!**





Electron volt (eV) and Joule - Energy units:

eV is an extremely small unit

1 fission releases about 200 MeV but only 3.2×10^{-11} J

How is that possible that a typical nuclear power plant produce 1000 MW (10000 MJ/s)?

The 200 MeV released from a single fission event is a very small amount of energy, but it can drive this gigantic turbine?



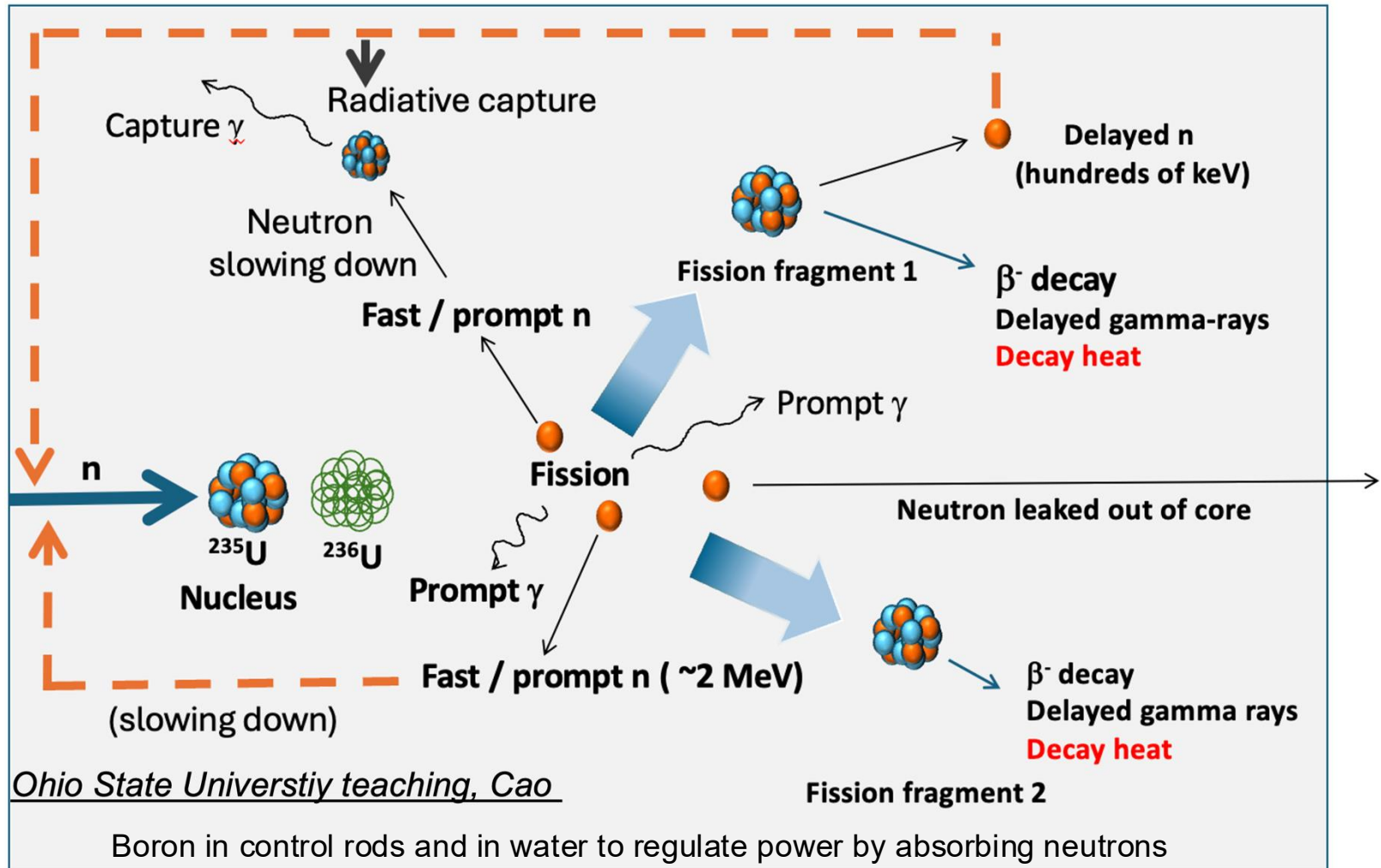
For a plant to produce 500 MW,

$$\frac{5.00 \times 10^8 \text{ J}}{3.20 \times 10^{-11} \text{ J/fission}} = 1.5625 \times 10^{19} \approx 1.56 \times 10^{19} \text{ fission events per second}$$

- **Sand:** about as many as all the grains of sand on Earth's beaches and deserts



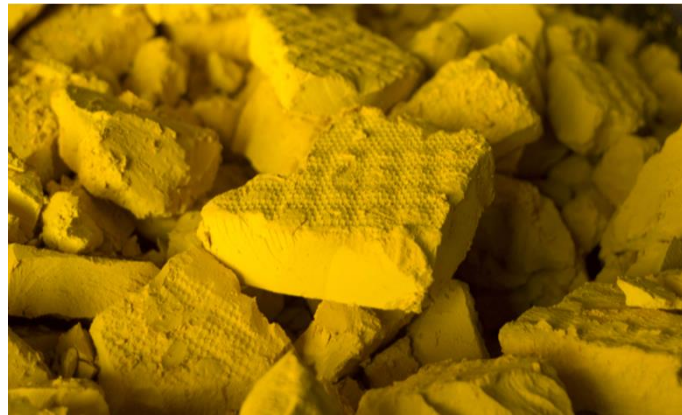
Reactor design is the art of optimizing a neutron economy





1. **Fuel:** Uranium

- Oxide
- Metal
- TRISO*
- Carbide
- Nitride
- Liquid salt



Yellowcake uranium is used in the preparation of uranium fuel that is used in nuclear reactors. (Photo: DOE)

2. **Moderator:**

- Light water
- Heavy water
- Graphite



3. **Coolant:**

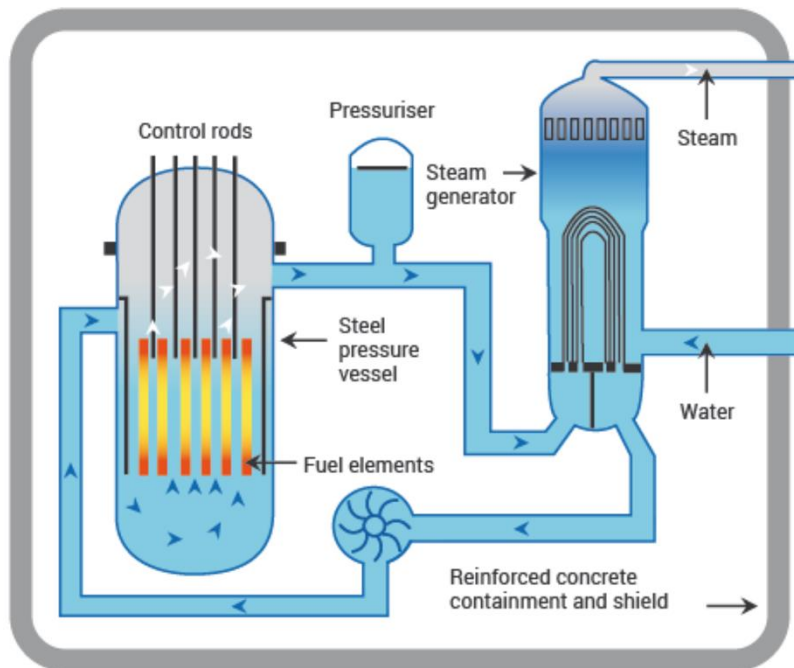
- Water
- Liquid Sodium
- Helium Gas
- Liquid Lead
- Lead-Bismuth Eutectic
- Molten Salt





Light Water Reactors

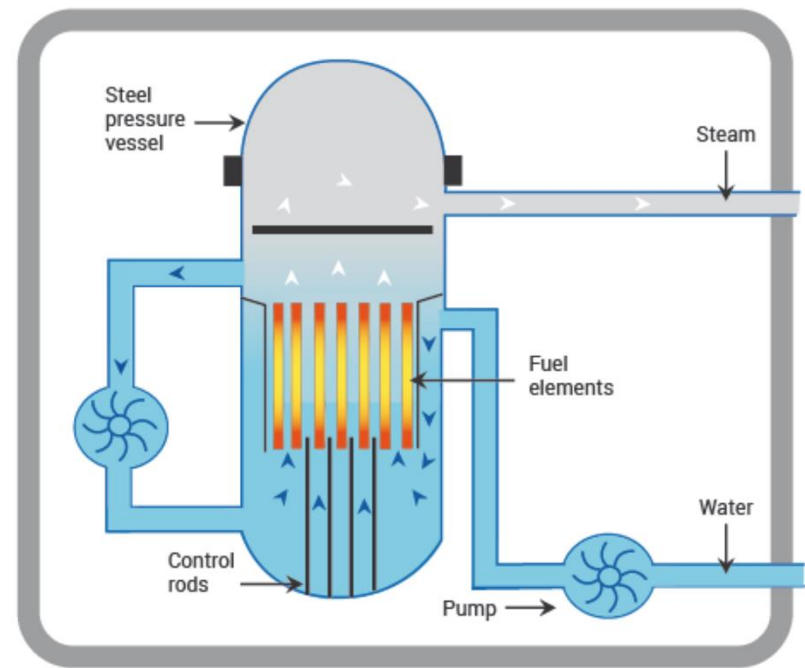
A pressurized water reactor (PWR)



307/440 (73%)

A PWR fuel assembly (typically 14×14 to 17×17) holds ~176–264 rods. A large reactor has ~150–250 assemblies containing 80–100 tons of uranium.

A boiling water reactor (BWR)



94/440 (21%)

~ 764 fuel assemblies, each containing 62 fuel rods, a total ~ 47,368 fuel rods, and 70-100 tons of uranium.



The **neutron** was discovered by **James Chadwick** in **1932**.

He published a short letter in *Nature* in February 1932 (“Possible Existence of a Neutron”)

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Letter | Published: 27 February 1932

Possible Existence of a Neutron

[J. Chadwick](#)

[Nature](#) **129**, 312 (1932) | [Cite this article](#)

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IT has been shown by Bothe and others that beryllium when bombarded by α -particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0.3 (cm.)^{-1} . Recently Mme. Curie-Joliot and M. Joliot found, when measuring



The French patents in May 1939

RÉPUBLIQUE FRANÇAISE
MINISTÈRE
DE L'INDUSTRIE ET DU COMMERCE
SERVICE
de la PROPRIÉTÉ INDUSTRIELLE

BREVET D'INVENTION
Gr. 5. — Cl. 2. N° 976.541

Dispositif de production d'énergie.

CAISSE NATIONALE DE LA RECHERCHE SCIENTIFIQUE résidant en France (Seine).

Demandé le 1^{er} mai 1939, à 16^h 55^m, à Paris.
Délivré le 1^{er} novembre 1950. — Publié le 19 mars 1951.

(Brevet d'invention dont la délivrance a été ajournée en exécution de l'article 11, § 7, de la loi du 5 juillet 1844 modifiée par la loi du 7 avril 1902:)

On sait que l'absorption d'un neutron par un noyau d'uranium peut provoquer la rupture de ce dernier avec dégagement d'énergie et émission de nouveaux neutrons en nombre en moyenne supérieur à l'unité. Parmi les neutrons ainsi émis, un certain nombre peuvent à leur tour provoquer — sur des noyaux d'uranium — de nouvelles ruptures, et les ruptures de noyaux d'uranium pourront ainsi aller en croissant suivant une progression géométrique, avec dégagement de quantités extrêmement considérables d'énergie.

On s'est rendu compte, conformément à la présente invention, que si l'on parvenait à provoquer une telle réaction au sein d'une masse limitée d'uranium (ou de composé d'uranium ou d'un mélange contenant de l'uranium), on pourrait extraire de cette masse et utiliser à des fins industrielles l'énergie ainsi développée par les chaînes de ruptures successives.

Mais on se heurte immédiatement à une difficulté primordiale : ces chaînes pouvant se ramifier d'une manière illimitée, la réaction peut devenir explosive, ce qui rendrait considérablement les possibilités d'utilisation de la masse d'uranium en question comme source maniable d'énergie industrielle.

On a donc cherché à maîtriser le dégagement d'énergie en l'empêchant de devenir explosif, et l'on a eu l'idée à cet effet :

1° Tout d'abord de réduire la vitesse de tout ou partie des neutrons libérés, de telle sorte qu'ils deviennent des neutrons lents, approximativement en équilibre thermique avec le milieu.

répartitions des constituants du dispositif, seraient ainsi le développement des chaînes;

2° Ensuite, d'introduire dans le dispositif un ou plusieurs éléments — à l'état de corps simples ou de combinaisons chimiques — susceptibles d'absorber les neutrons ralentis en proportion d'autant plus forte par rapport à l'absorption par l'uranium que la température est plus élevée.

Par le premier de ces moyens ou l'emploi conjugué de ces deux moyens, les chaînes peuvent se développer jusqu'à ce qu'une énergie suffisamment importante soit libérée, et être alors automatiquement interrompues ou limitées, évitant ainsi le développement explosif de la réaction.

On arrive ainsi à libérer de la masse d'uranium considérée, en vue de son utilisation industrielle, et au fur et à mesure des besoins, l'énergie qu'elle est susceptible de fournir par transmutations.

Pour réduire la vitesse de tout ou partie des neutrons émis, on introduit au sein de la masse d'uranium — et suivant une répartition qui n'est pas nécessairement uniforme — des éléments très légers tels que l'hydrogène, le deutérium par exemple, libres ou combinés, ou des éléments légers tels que le lithium, le carbone, l'oxygène par exemple, libres ou combinés.

Un avantage spécial des ralentisseurs très légers est de diminuer la proportion des neutrons qui sont absorbés par résonance dans l'uranium et qui peuvent être ainsi perdus pour le processus en chaînes.

Ces éléments pourront être introduits sous forme liquide, gazeuse ou solide (sauf pour exemple).

Patent I (May 1st 1939) :
“device for energy production”

“We know that the absorption of a neutron by a nucleus of uranium can provoke the break of the latter with **release of energy and emission of new neutrons** in average number **upper to one**. Among these neutrons, some can provoke new breaks of nucleus of uranium , thus making these breaks increasing according to a geometric progression We have realized, in accordance with the present invention, that if one manage to cause such a reaction within a **limited mass of uranium**, one could extract from this mass the energy then developed by **the chains of successive breaks**”

August 2, 1939: Albert Einstein signed the letter to President Roosevelt in USA that recent discoveries involving **uranium nuclear chain reactions** might make extremely powerful bombs possible and, importantly, that **Nazi Germany might pursue such a weapon..**



1. Birth (1938–1945)

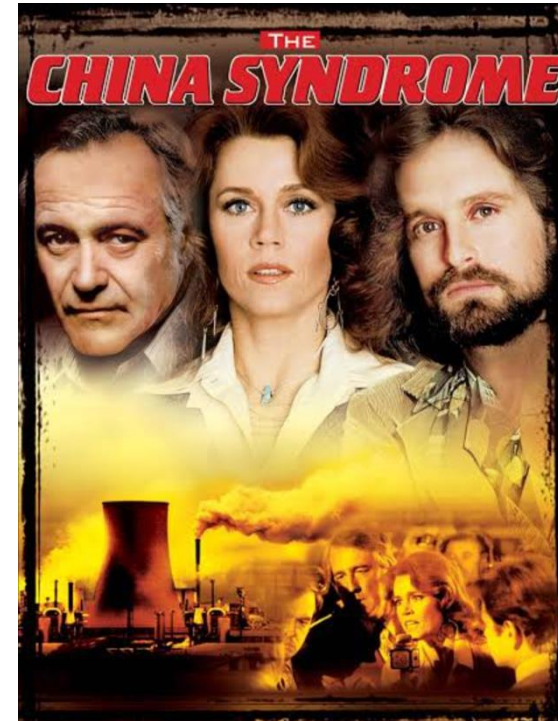
- Discovery of nuclear fission (1938)
- Manhattan Project (1942)
- First reactor (December 2, 1942)

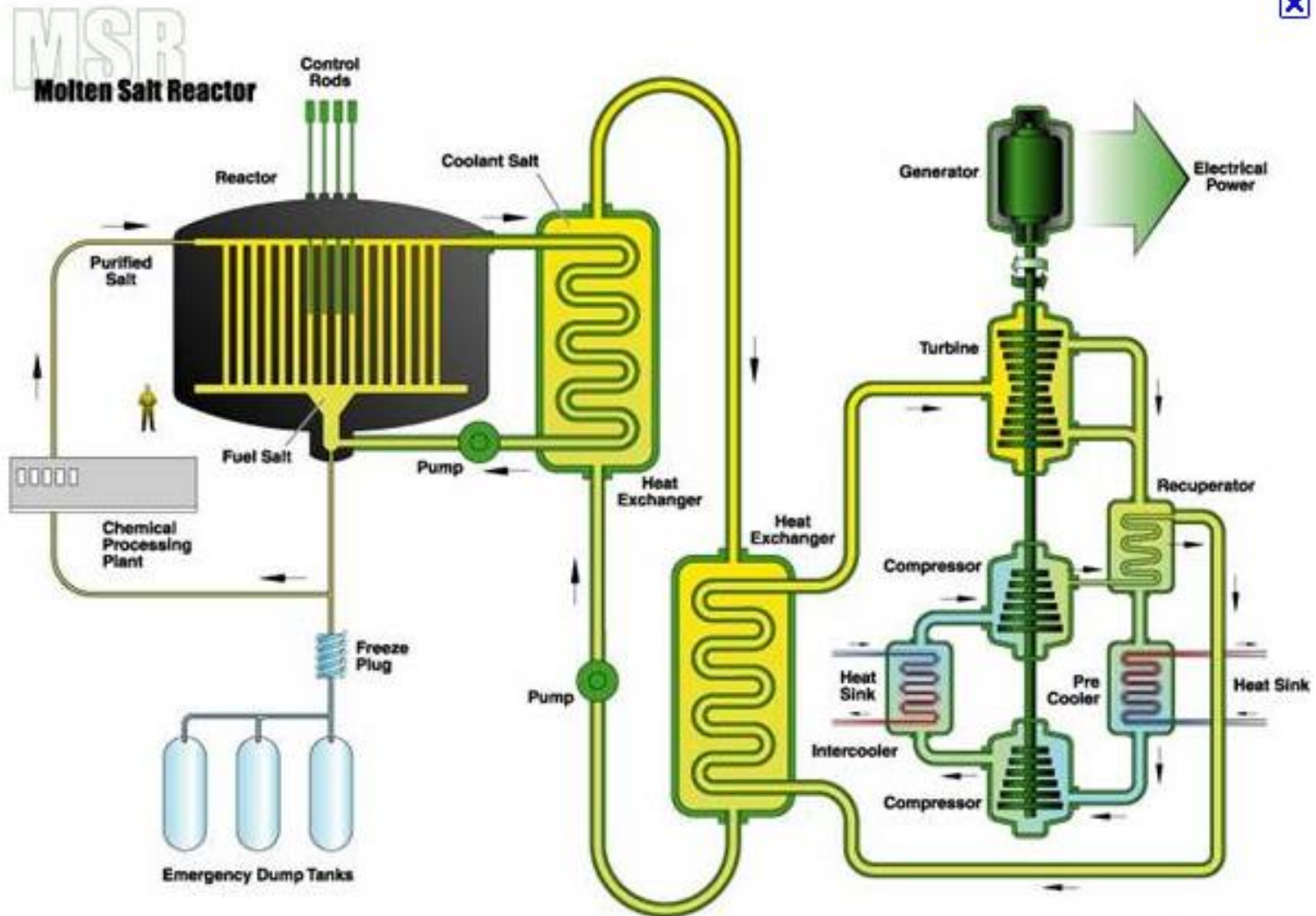
2. Golden Age (1945–1973)

- Rapid reactor innovation
- Research reactors (OSU research reactor 1961)
- Naval propulsion
- Commercial nuclear power (1954, Obninsk, 1957, Shippingport)
- Atoms for Peace
- Worldwide optimism
- ORNL becomes the world's premier reactor research center

3. The End of the First Nuclear Era (1973–1994)

- Safety becomes dominant; regulatory expansion
- Public opposition, advanced reactor programs cancelled
- Three Mile Island (March 28, 1979) - The Movie: China Syndrome was released in the United States on March 16, 1979
- Chernobyl (1986)
- Industry stagnation





02-GAS0607-02

- Because of coolant activation, the potential for sodium/water interactions between high-pressure steam and a low-pressure sodium loop, an intermediate coolant loop is used.
- This leads to two fundamental design choices: Pool vs. Loop

"Pool" Design

Control rods
Flow baffle
Coolant level
Fissile Core
Reflector/ Shield
Reactor pool pump
Biological shielding
Liquid metal coolant
Heat exchanger
Steam generator

Reactor pool
(primary coolant)

Intermediate loop

Power-generation loop

Intermediate loop

Reactor loop
(primary coolant)

"Loop" Design

Control rods
Fissile Core
Reflector/ Shield
Biological shielding
Liquid metal coolant
Heat exchanger
Steam generator

- Low pressure
- Recycle plutonium repeatedly
- Burn minor actinides (Np, Am, Cm)
- Reduce long-lived nuclear waste



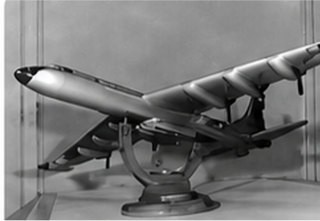
Viewing the present through the lens of history

ORNL Aircraft Nuclear Reactor Progress (1949–1961)

1

1949

Nuclear Aircraft
Concept Formulated



ORNL begins exploring the concept of a nuclear-powered aircraft.

2

1951

R.C. Briant Proposed
Liquid-Fluoride Reactor

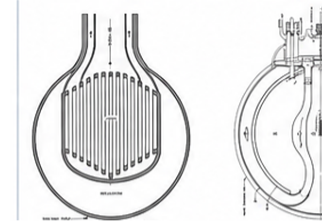


Molten-fluoride fuel proposed:
NaF-ZrF₄-UF₄ with HEU.

3

1952–1953

Early Designs for
Aircraft Fluoride Reactor

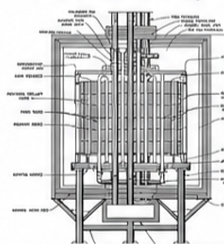


Preliminary reactor concepts and layouts developed for aircraft application.

4

1954

Aircraft Reactor Experiment
(ARE) Built and Operated

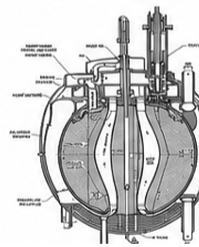


World's first circulating molten-salt reactor.
Produced 2.5 MWth at 860 °C.

5

1955

60 MWth Aircraft Reactor Test
(ART) "Fireball" Proposed

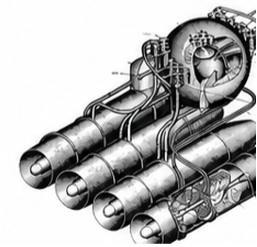


High-power (60 MWth) reactor concept
for aircraft propulsion.

6

1961

ANP Program Cancelled
in Favor of ICBMs



Focus shifts to intercontinental ballistic
missiles (ICBMs) and nuclear submarines.



Outcome: Pioneering research at ORNL advanced molten-salt reactor technology and informed future nuclear energy and propulsion programs.



- **1940s:** The idea of sodium-cooled reactors was explored during the Manhattan Project, **1951:** The first experimental sodium-cooled reactor, the **Experimental Breeder Reactor I (EBR-I)**, was constructed and operated at the (now) U.S. Idaho National Laboratory.
- **1946 - 1950s:** The molten salt reactor (MSR) concept was proposed and developed at the U.S. Oak Ridge National Laboratory (ORNL).
- **Atoms for Peace** was initiated by President Eisenhower on **December 8, 1953**
- The first nuclear-powered submarine, **USS Nautilus (SSN-571)**, construction: **1952, launch: 1954**
- The first civilian nuclear power plant in the United States was the **Shippingport, Pennsylvania, 1957, use water as moderator and water as coolant - Light Water Reactor (LWR)**



"That light water would be the main line for commercial development was a surprise to me even though I had proposed this system for submarine propulsion. In the early days, other systems had their proponents. But the LWR had one overwhelming advantage: it has already proven itself as a reliable power plant for Nautilus." —pg 133

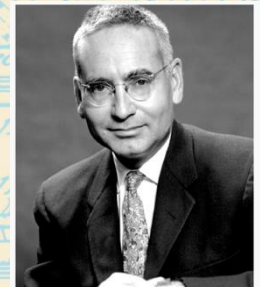
"Why didn't the molten-salt system, so elegant and so well thought-out, prevail? It was a successful technology that was dropped because it was too different from the main lines of reactor development...I hope that in a second nuclear era, the technology will be resurrected." —pg 130-131

"I knew this was untrue: pressurized water had been chosen to power submarines because such reactors are compact and simple. Their advent on land was entirely due to Rickover's dominance in reactor development the 1950s, and once established, the light-water reactor could not be displaced by a competing reactor. To claim that light-water reactors were chosen because of their superior safety belied an ignorance of how the technology had actually evolved." —pg 231

THE FIRST NUCLEAR ERA

The Life and Times of a Technological Fixer

1994



Alvin Weinberg, c. 1960

M. WEINBERG



Vice Admiral H. G. Rickover, USN
author of EDUCATION AND PERSONALITY
1970/71

Admiral Rickover



From Many Paths to One Standard

— Key Milestones in Reactor Development and the Rise of the Light Water Reactor —

	YEAR	MILESTONE	SIGNIFICANCE
	1942	Chicago Pile-1	Demonstrated the first controlled nuclear chain reaction, launching the reactor age.
	1943–1945	Hanford Production Reactors	Established large-scale reactor engineering for plutonium production.
	1947–1953	ORNL & Argonne develop multiple reactor concepts	Parallel development of PWR, BWR, sodium fast, molten salt, gas-cooled, and homogeneous reactors.
	1949–1954	Rickover develops the Naval PWR	Massive U.S. Navy investment matures PWR technology years ahead of competitors.
	1951	EBR-I (Fast Reactor)	First reactor to generate electricity, proving breeder reactor feasibility.
	1954	USS <i>Nautilus</i>	First nuclear-powered submarine demonstrates PWR reliability.
	1957	Shippingport PWR	First U.S. commercial nuclear power plant; naval technology enters civilian service.
	1958–1968	Utilities adopt PWRs and BWRs	Standardization, supply chains, and licensing begin favoring LWRs.
	1965–1969	Molten Salt Reactor Experiment (MSRE)	Successfully validates molten salt reactor technology but is not commercialized.
	1972–1977	Advanced reactor programs lose support	Weinberg leaves ORNL; MSR funding ends while LWR deployment continues.
	1983	Clinch River Breeder Reactor canceled	U.S. commercial fast reactor program effectively ends.
	1990s	LWR becomes the global standard	Nearly all Western commercial reactors are PWRs or BWRs.

This timeline was created with generative AI assistance and is for interpretive summary only, not a definitive historical chronology.



Key takeaway from Weinberg's book:

The Light Water Reactor won the commercialization race before alternative reactor concepts had the opportunity to fully mature.

The commercialization of reactor technologies was shaped less by a direct technical competition than by a sequence of decisions:

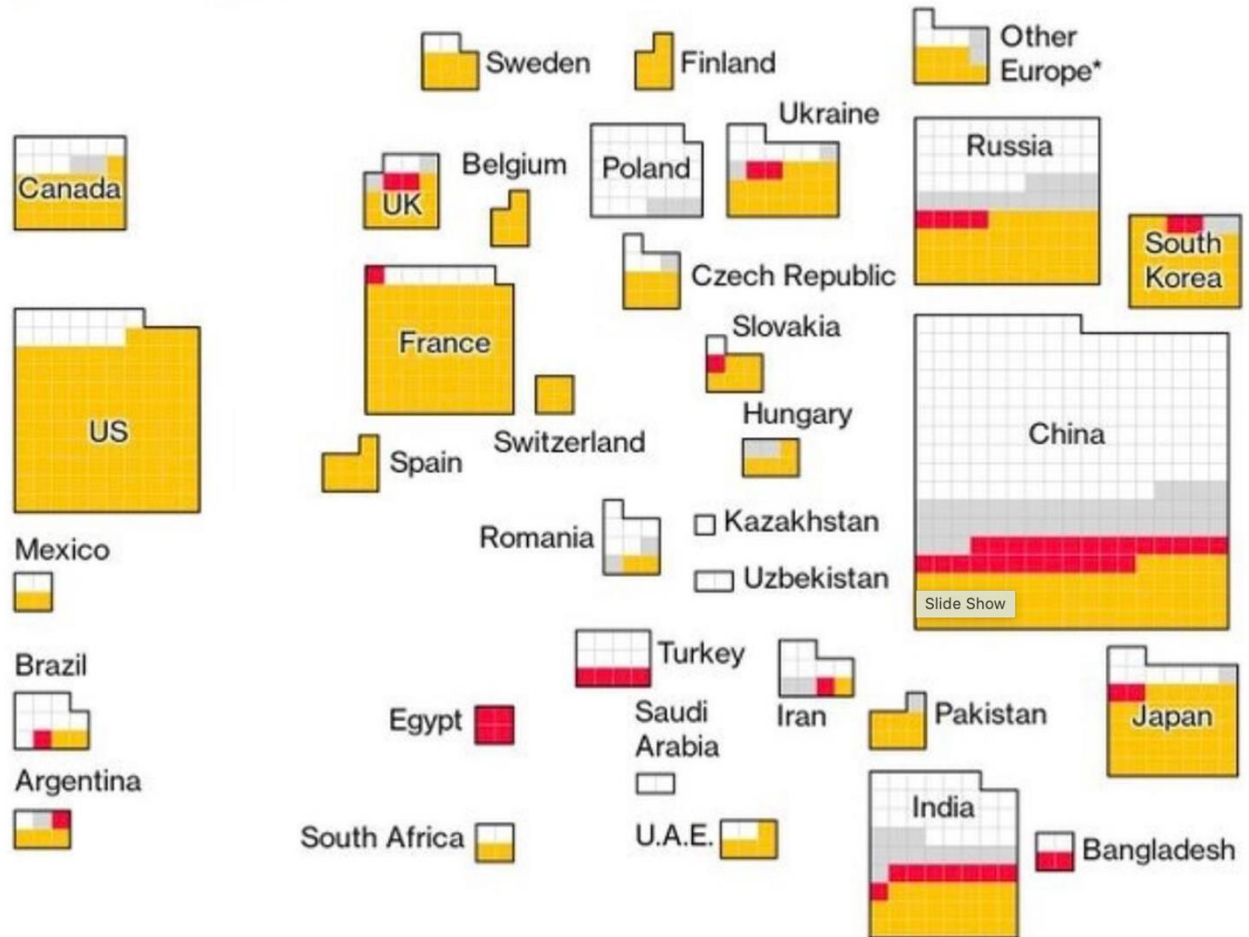
- 1. Naval propulsion** gave the PWR a 10-year engineering head start.
- 2. Shippingport** demonstrated that a naval reactor could be adapted for civilian electricity generation.
- 3. Utilities and vendors** standardized on LWRs, creating economies of scale.
- 4. Regulatory frameworks** evolved around LWR technology.
- 5. Advanced reactors (MSR, SFR, HTGR)** remained successful demonstrations but never received comparable commercial investment.



- China and India are leading with massive investments in nuclear reactors constructions.
- The US, France, Russia, and South Korea are also expanding their nuclear infrastructure.
- US has a surging interests in bringing nuclear energy to power AI/data centers

Nuclear reactors

■ Operating ■ Under construction ■ Planned □ Proposed



Source: World Nuclear Association

*Other Europe includes Armenia, Belarus, Bulgaria, Netherlands and Slovenia

Note: Reactor construction in Brazil, Ukraine and Japan is currently suspended

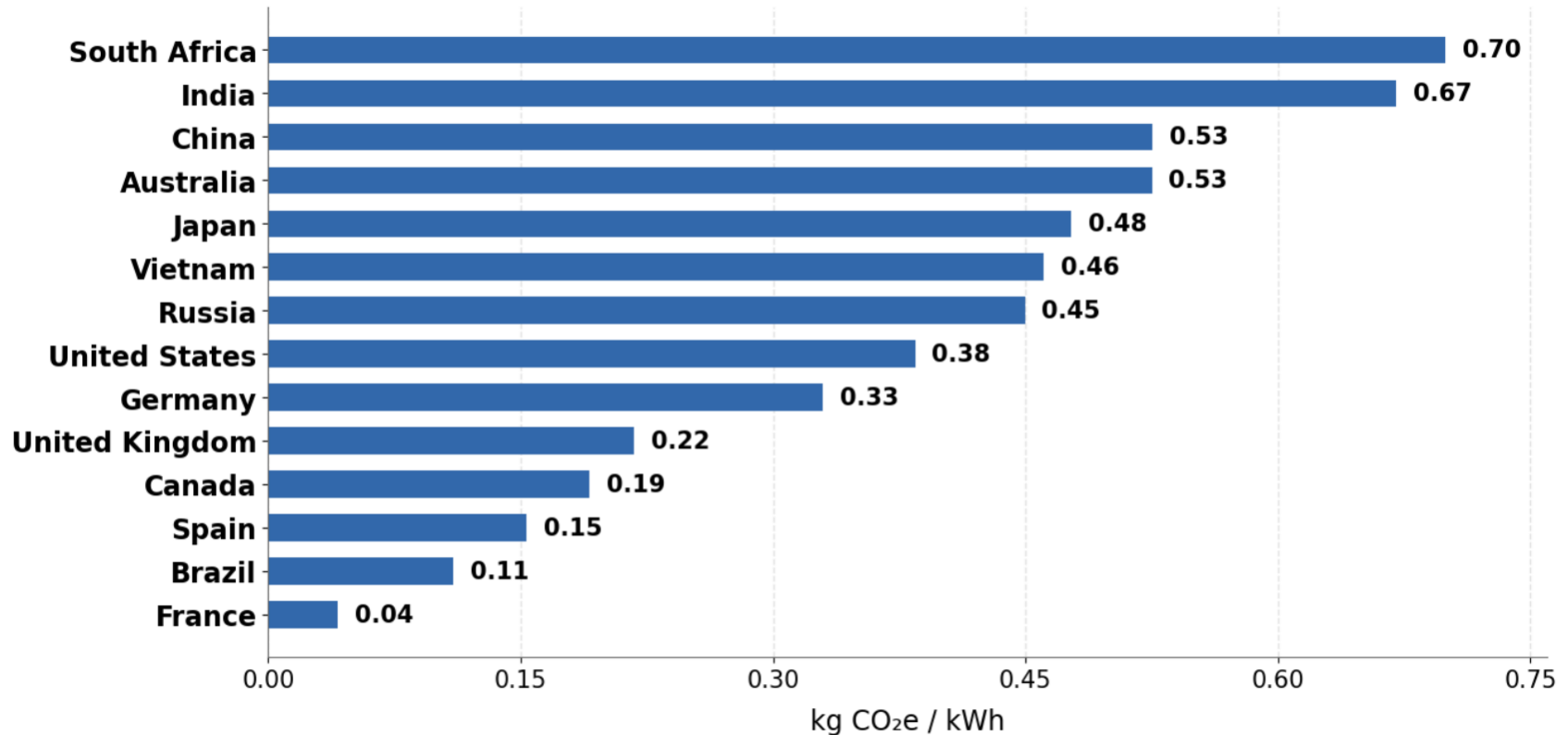


Operable nuclear power plants

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	310	296.7	enriched UO ₂	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	60	60.9	enriched UO ₂	water	water
Pressurized heavy water reactor (PHWR)	Canada, India	48	25.0	natural UO ₂	heavy water	heavy water
Light water graphite reactor (LWGR)	Russia	10	6.5	enriched UO ₂	water	graphite
Advanced gas-cooled reactor (AGR)	UK	8	4.7	natural U (metal), enriched UO ₂	CO ₂	graphite
Fast neutron reactor (FNR)	Russia	2	1.4	PuO ₂ and UO ₂	liquid sodium	none
High temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO ₂	helium	graphite
TOTAL		439	395.4			



Electricity production and CO₂ emissions (kg CO₂e/kWh): a world comparison — 2025

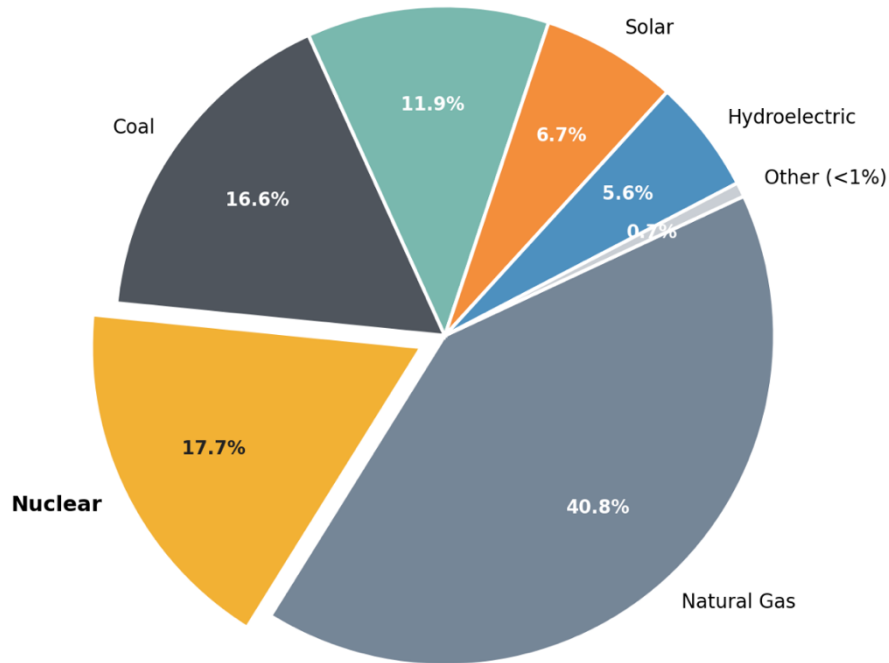


Note: Operational carbon intensity of electricity generation. Values are shown in kg CO₂e per kWh.
Source: Our World in Data energy dataset, based primarily on Ember Yearly Electricity Data.



U.S. Electricity Generation Mix, 2025

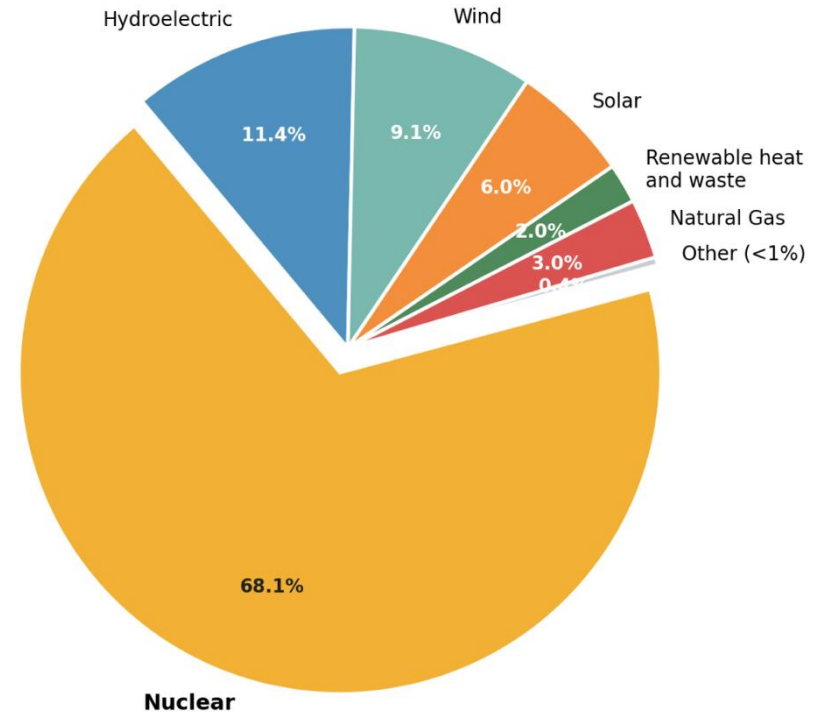
Nuclear highlighted; minor sources grouped as "Other (<1%)"
Wind



Source: U.S. Energy Information Administration, Electric Power Monthly, Table 1.1.
Utility-scale net generation; total: 4,429.5 TWh.

France Electricity Generation Mix, 2025

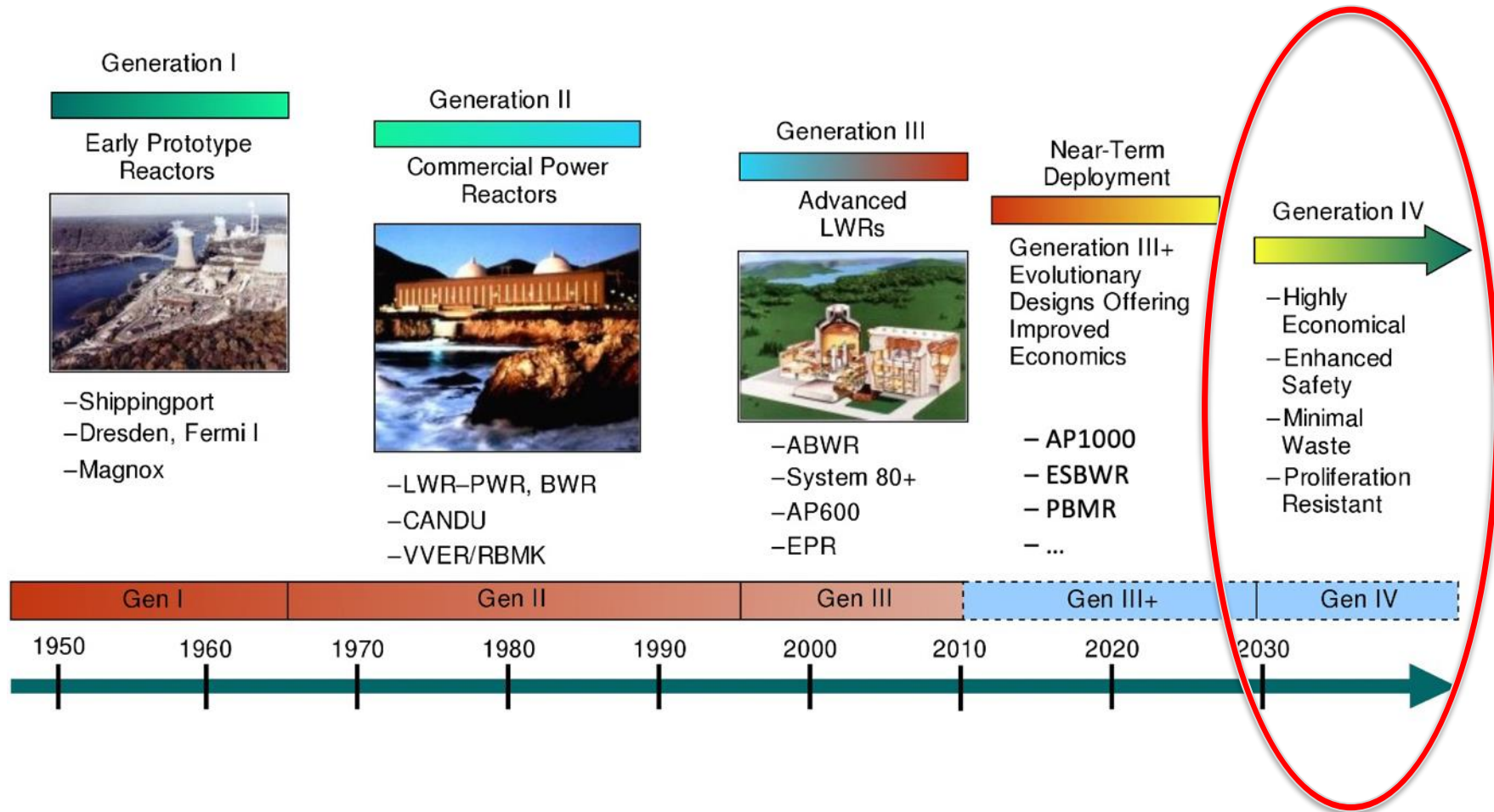
Nuclear highlighted; coal, oil, and miscellaneous generation grouped as "Other (<1%)"



Source: RTE, Annual Electricity Review 2025. Total generation: 547.5 TWh.



- This Nuclear Generation Chart is a bit outdated, but still relevant, proposed in 2000s
- Microreactors, SMRs, and advanced reactor concepts were not introduced back then





- **US nuclear capacity has the potential to triple from ~100 GW in 2024 to ~300 GW by 2050**

Advanced nuclear includes reactor types of all sizes across two generations

	Gen III+	Gen IV		
Coolant	Light water	Gas	Liquid metal	Molten salt
Examples	• Pressurized water reactor • Boiling water reactor	• High temperature gas reactor • Gas fast reactor	• Sodium fast reactor • Lead fast reactor	• Fluoride high temperature reactor • Molten chloride fast reactor
Typical fuel	LEU, LEU+	HALEU	HALEU	HALEU
Outlet temperature	~300°C	~750°C	~550°C	~750°C
Power output	Large, small	Small, micro	Small, micro	Small
Example reactor designers	• GE Hitachi • Holtec • NuScale • Westinghouse	• BWXT • General Atomics • Radiant • X-energy	• ARC • TerraPower • Oklo	• Kairos • Terrestrial

<https://liftonn.energy.gov/advanced-nuclear/>

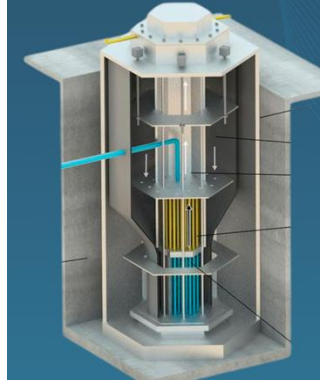


SMR and Microreactor



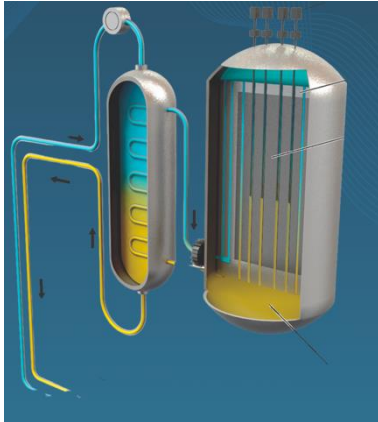
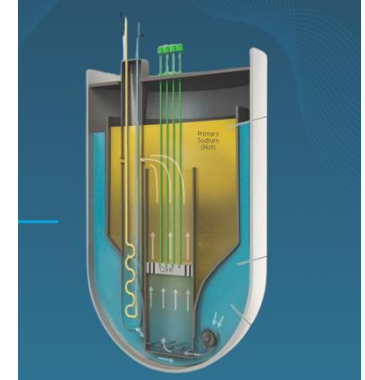
1.) Advanced Light Water Reactors

- Existing light-water reactor systems
- Use enhanced safety systems



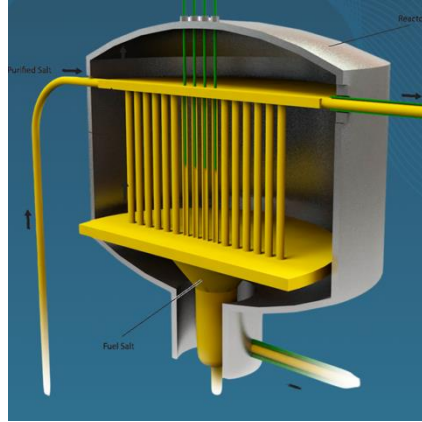
2.) Liquid Metal Fast Reactor

- Na or Pb
- High temperature
- Low pressure



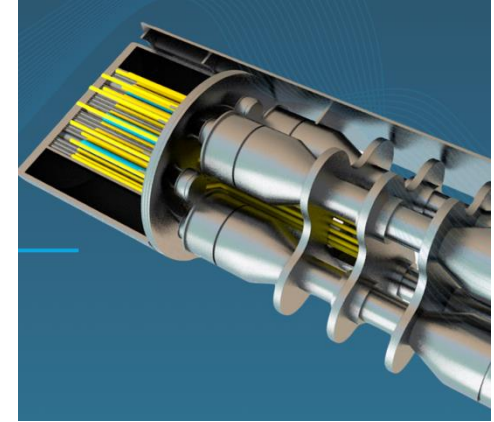
3.) High-Temperature Gas Reactor

- (750 - 900 Celsius)
- TRISO fuel



4.) Molten-salt Reactor

- Atmospheric pressure
 - On-line refueling



5.) Heat-pipe Reactor

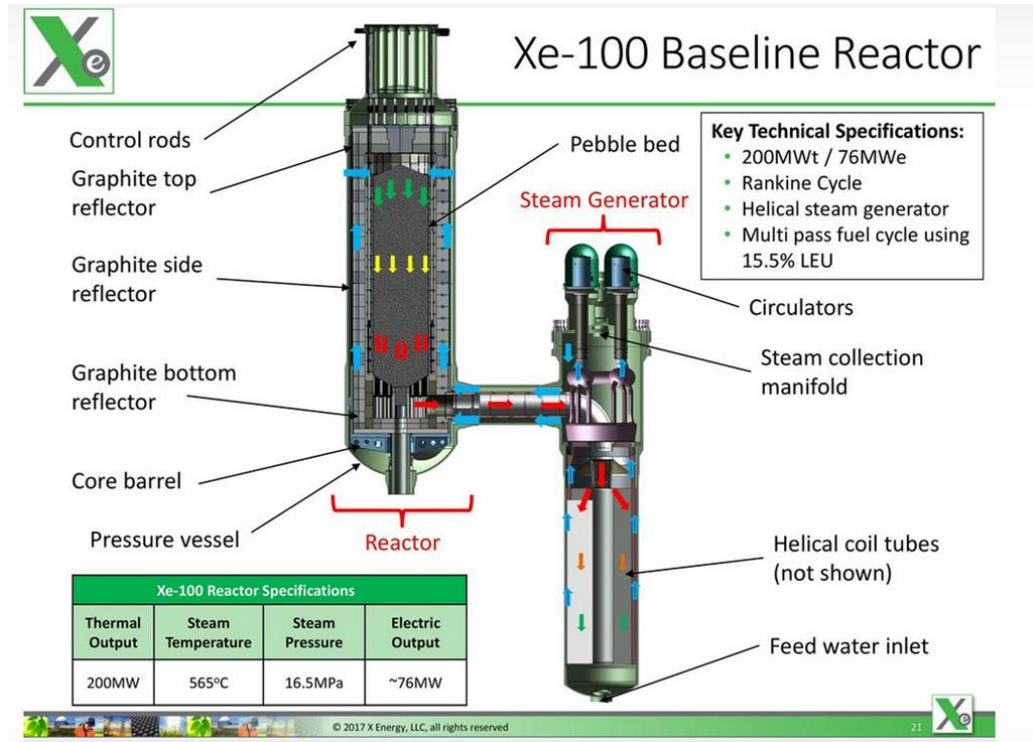
- No pumps or moving parts



- In the U.S., X-energy is working on pebble-fueled Xe-100 design (80-MWe high-temperature, gas-cooled reactor) that can be scaled into a four-pack to make a 320-MWe power plant.
- Kairos Power also has a version of molten salt coolant (Flibe, contains fluorine, lithium, and beryllium), TRISO fuel-based reactor.

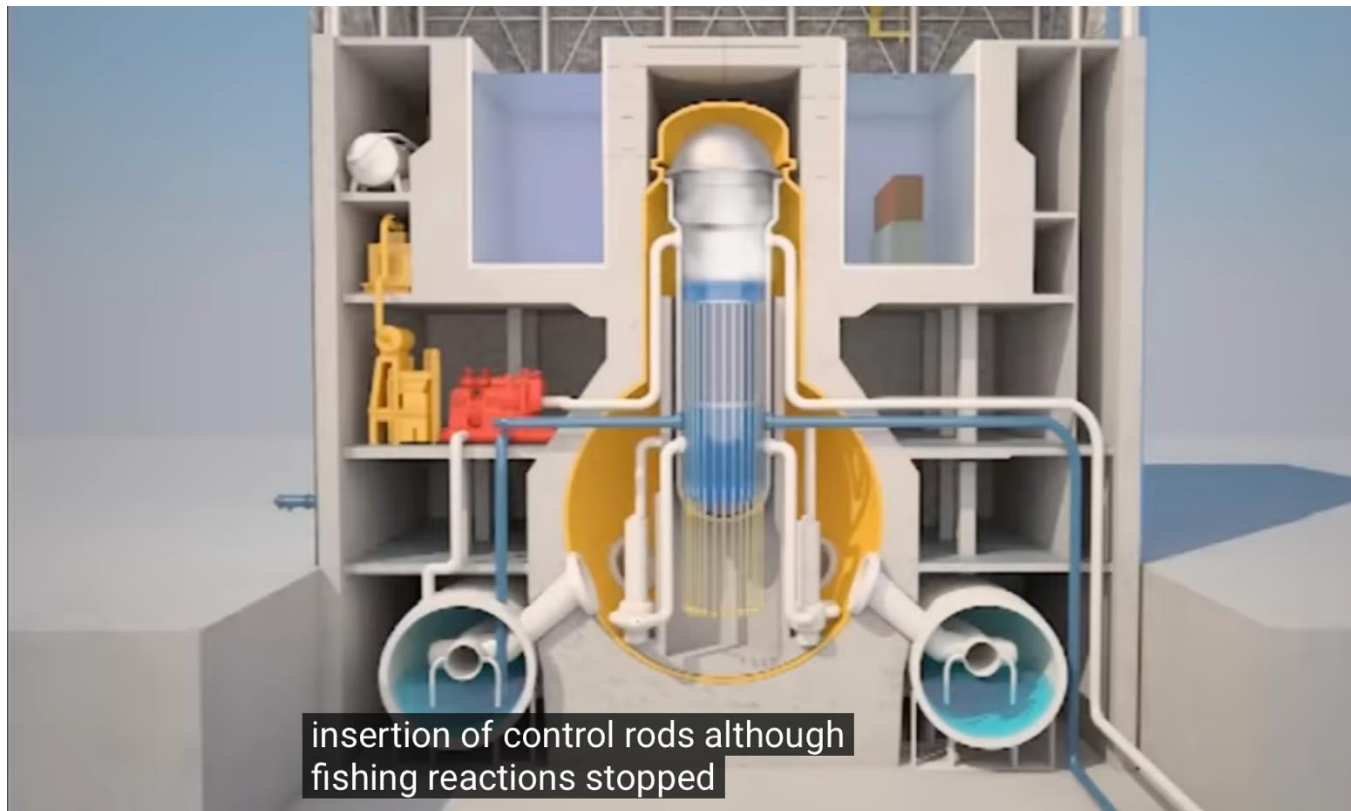
In the prismatic reactor,
no flowing balls

Thousands of
hexagonal blocks are
stacked and their
TRISO fuel sticks
replaced periodically.



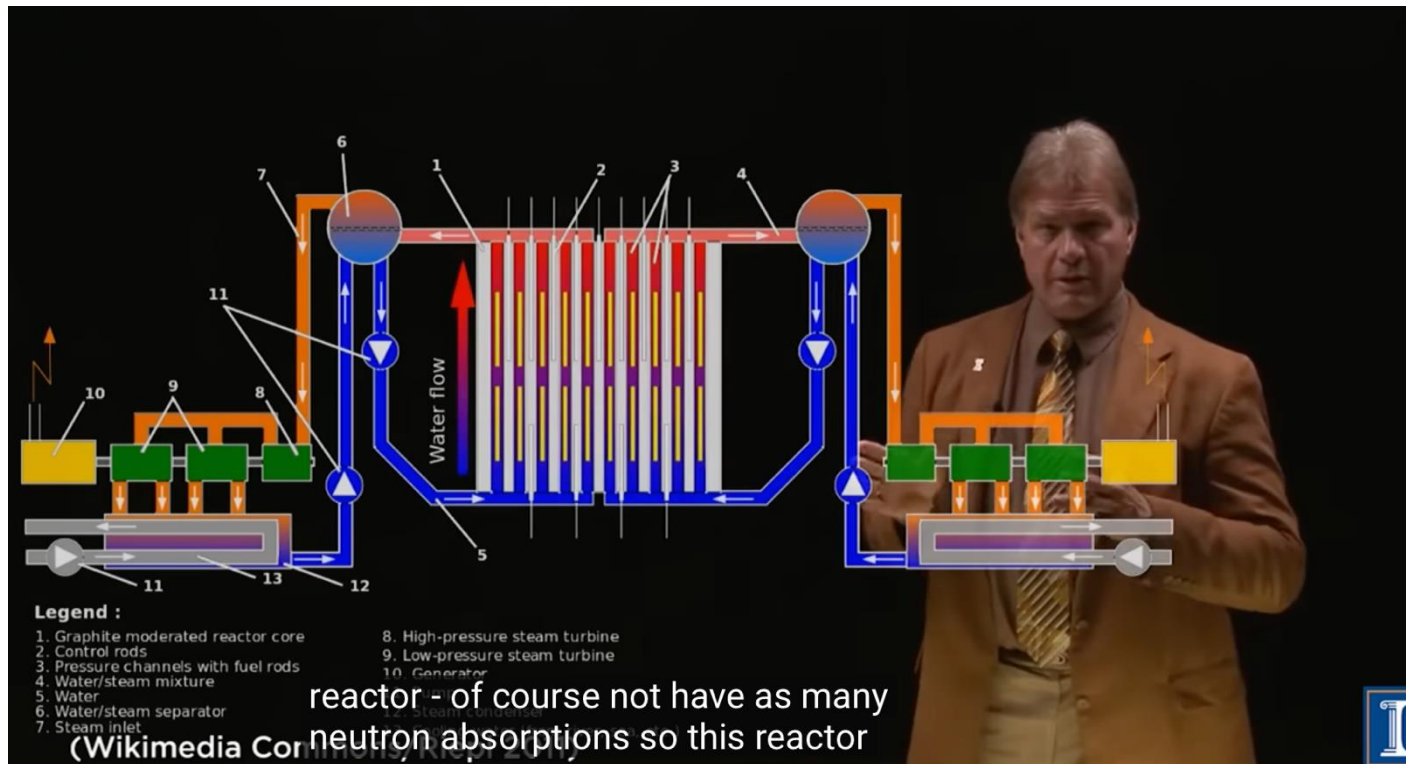


An overview of nuclear accident in Fukushima Japan



<https://www.youtube.com/watch?v=YBNFvZ6Vr2U>

Chernobyl Visually Explained



https://www.youtube.com/watch?v=bCbms6umE_o



The Three Nuclear Eras

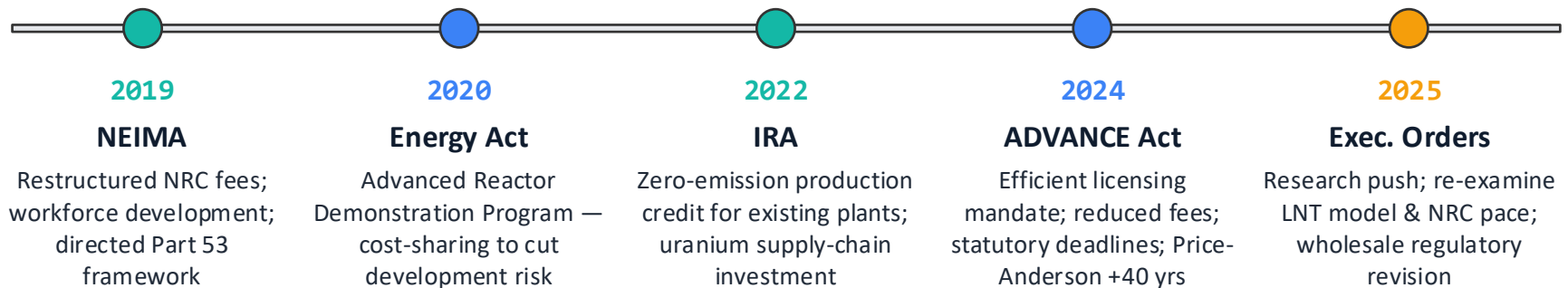
ERA	APPROXIMATE YEARS	CHARACTERISTICS
 FIRST NUCLEAR ERA	 1942–1990s	• Manhattan Project kicks off the nuclear age • Rapid reactor innovation and technology breakthroughs • Commercial nuclear build-out and industry optimism • Challenges emerge: Three Mile Island (1979), Chernobyl (1986) • Era ends with industry stagnation 
 INTERREGNUM ("NUCLEAR WINTER")	 1990–2015	• Very few new reactor orders in the U.S. and Europe • Aging nuclear fleets • Low natural gas prices • Post-Chernobyl and post-Fukushima skepticism • Cancellation of many advanced reactor programs 
 SECOND NUCLEAR ERA	 ~2015– PRESENT	• Climate change drives clean energy solutions • Advanced reactors re-emerge • SMRs and microreactors are developed • Private investment and innovation accelerate due to AI and data center boom • Nuclear is increasingly viewed as part of clean energy and energy security 



2015–Present:

Accelerated by advanced reactor concepts, major legislation, and rising demands from AI data centers.

KEY POLICY MILESTONES



Part 53 Milestone

Completion of the Part 53 licensing framework marks the first concrete achievement of this latest renaissance push.



AI Data Center Demand

Exogenous momentum from large language model data centers seeking reliable, carbon-free baseload power — sustainability of the renaissance still uncertain.