Middlebury Institute *of*
International Studies at Monterey
FORMERLY THE MONTEREY INSTITUTE OF INTERNATIONAL STUDIES

Nuclear Power: Present Status, Future Trends, and Proliferation

George M. Moore PhD, JD, PE

U.S. Naval Postgraduate School
November 28, 2023

What We'll Cover

- **Nuclear Reactors (Worldwide and U.S.)**
  - **Electrical Generation - Nuclear Power Plants (NPPs)**
  - **Research Reactors/Training Reactors/Propulsion Reactors/ Space Reactors**
  - **Is there a "Nuclear Renaissance?" – New builds, Problems for developers, Generation IV**
  - **Small Modular Reactors – where are we and why**
- **Nuclear Fuel Cycles and Waste**
- **Military Reactors - Reactors in War - Zaporizhzhia, the Geneva Protocols and AUKUS**

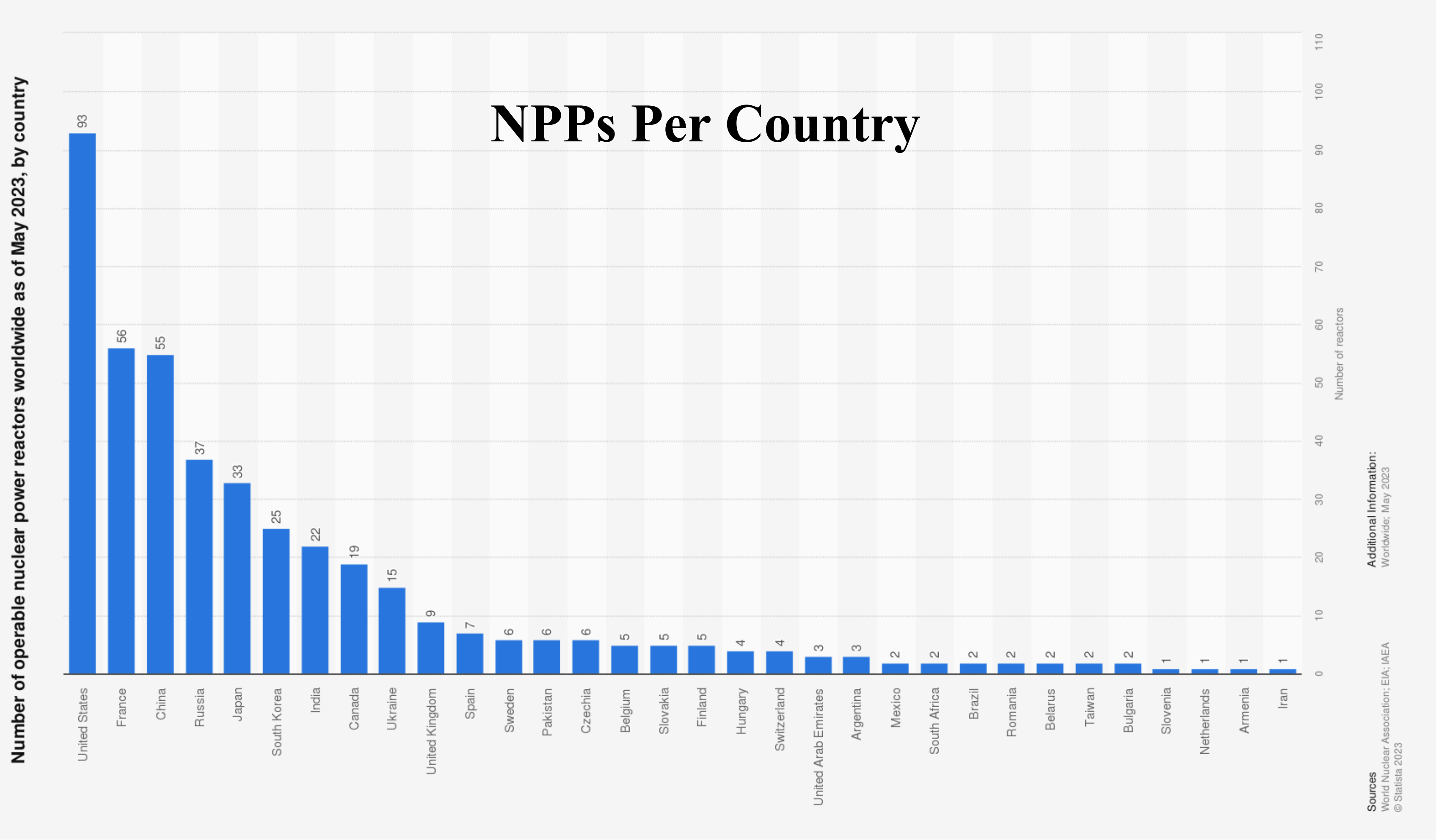
Numbers of NPPs

Worldwide NPPs

- ~ 436 reactors in 32 countries
- 92 reactors operating in U.S. in 28 states
  - ~ 92 GigaWatts (GW)
  - Rule of thumb ~ 33% efficient

Middlebury Institute *of*
International Studies at Monterey
FORMERLY THE MONTEREY INSTITUTE OF INTERNATIONAL STUDIES

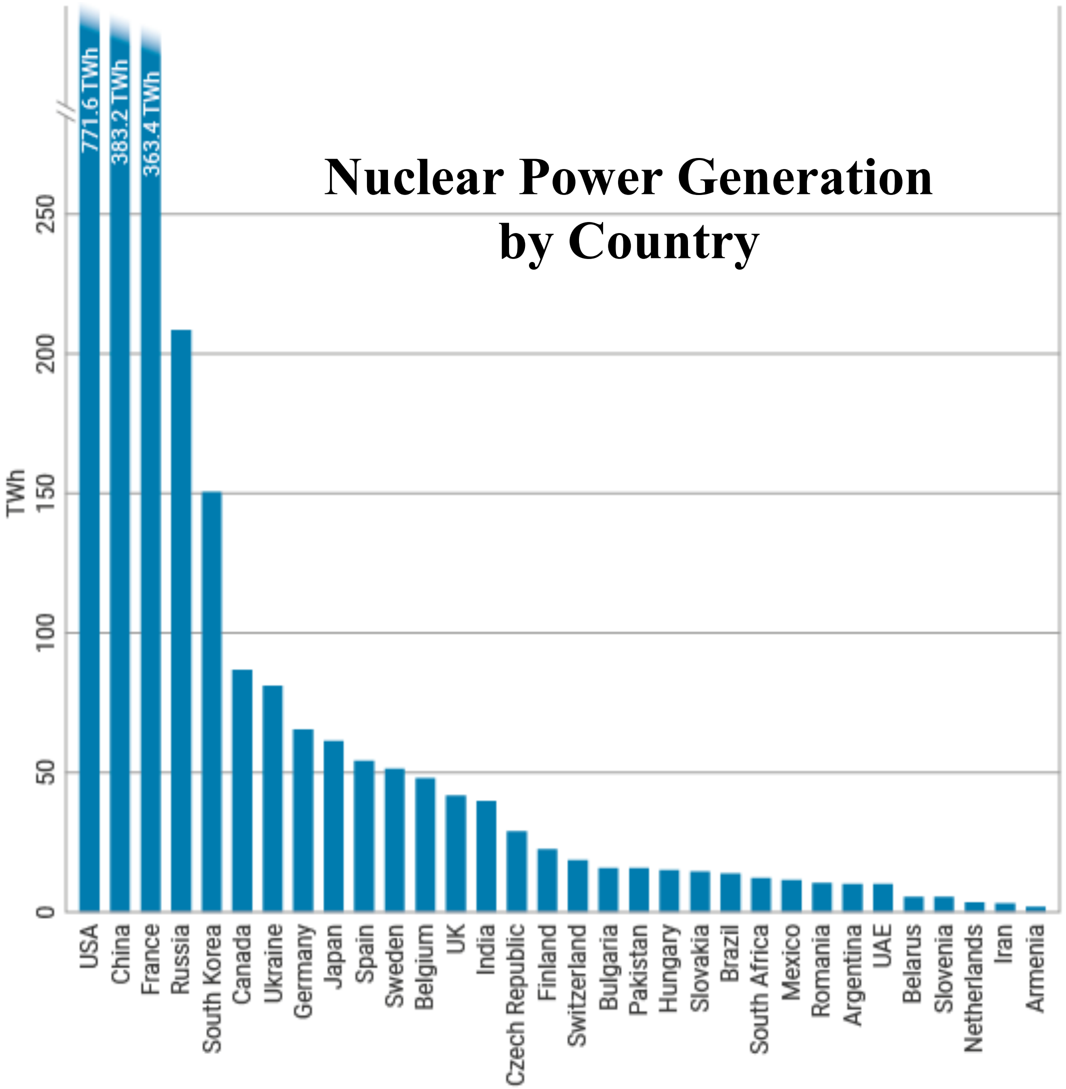
NPPs Per Country



Additional Information:
Worldwide; May 2023

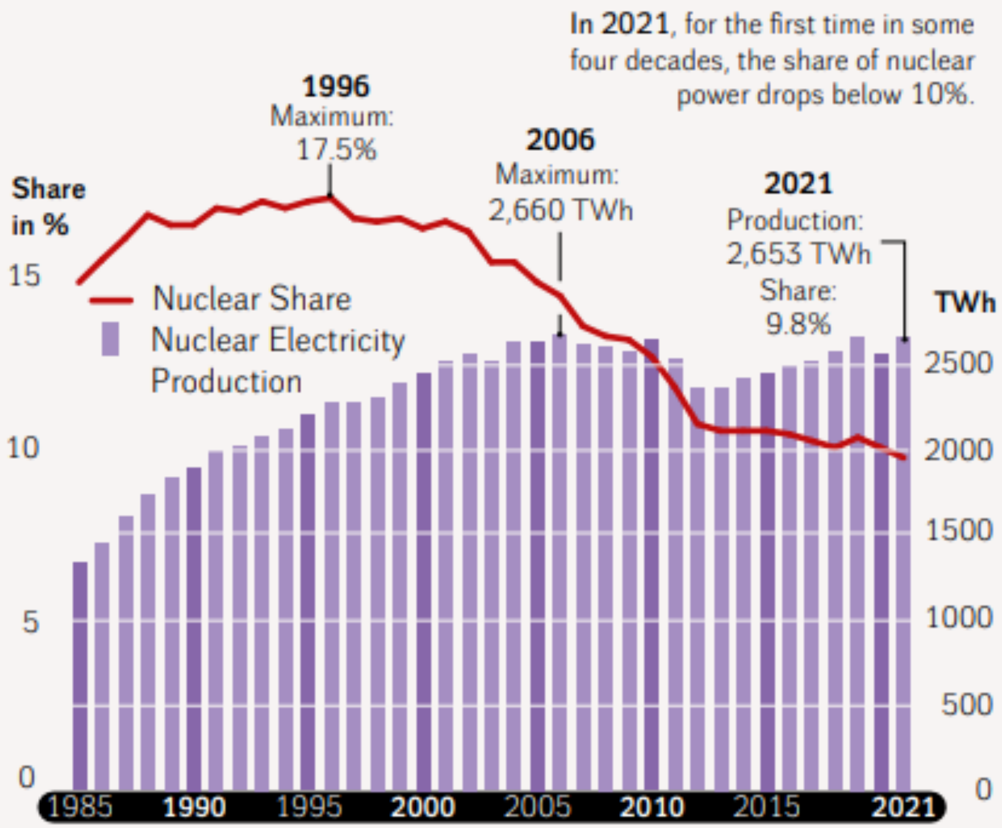
Sources
World Nuclear Association; EIA; IAEA
© Statista 2023

Nuclear Power Generation by Country



Nuclear Electricity Production 1985–2021 in the World…

in TWh (net) and Share in Electricity Generation (gross)



In 2021, for the first time in some four decades, the share of nuclear power drops below 10%.

1996
Maximum:
17.5%

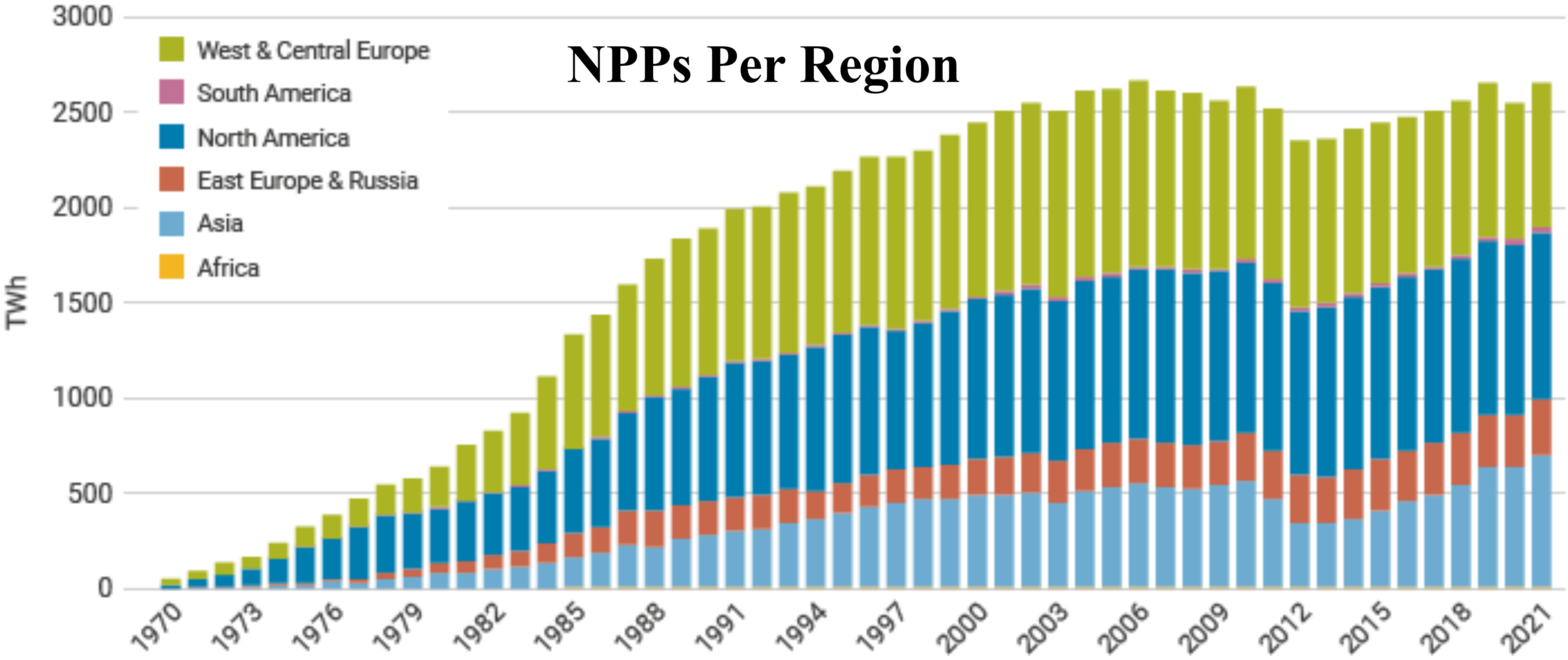
2006
Maximum:
2,660 TWh

2021
Production:
2,653 TWh
Share:
9.8%

© WNISR - Mycle Schneider Consulting

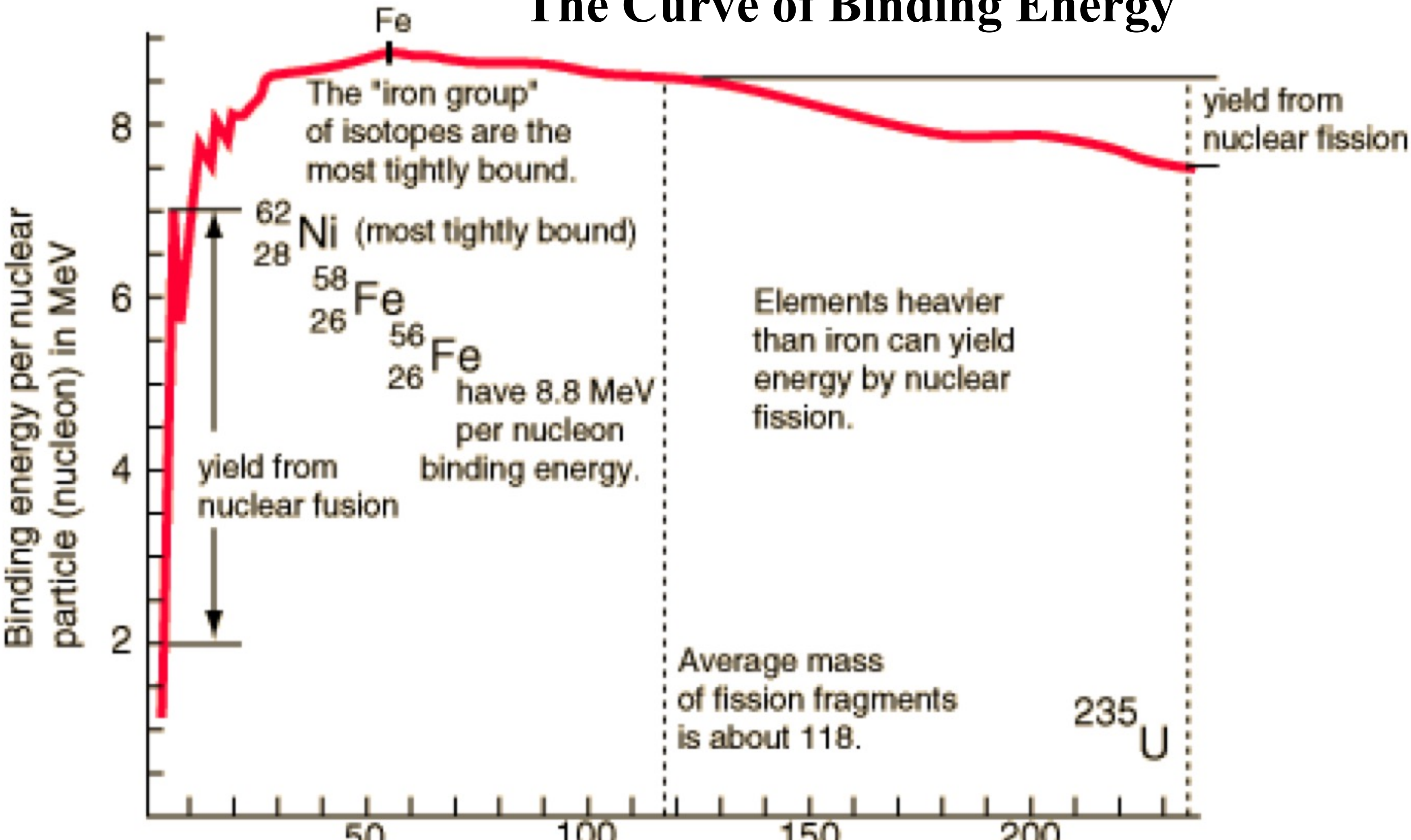
Middlebury Institute *of*
International Studies at Monterey
FORMERLY THE MONTEREY INSTITUTE OF INTERNATIONAL STUDIES

NPPs Per Region



Fission or Fusion?
Thermal or Fast Neutrons?

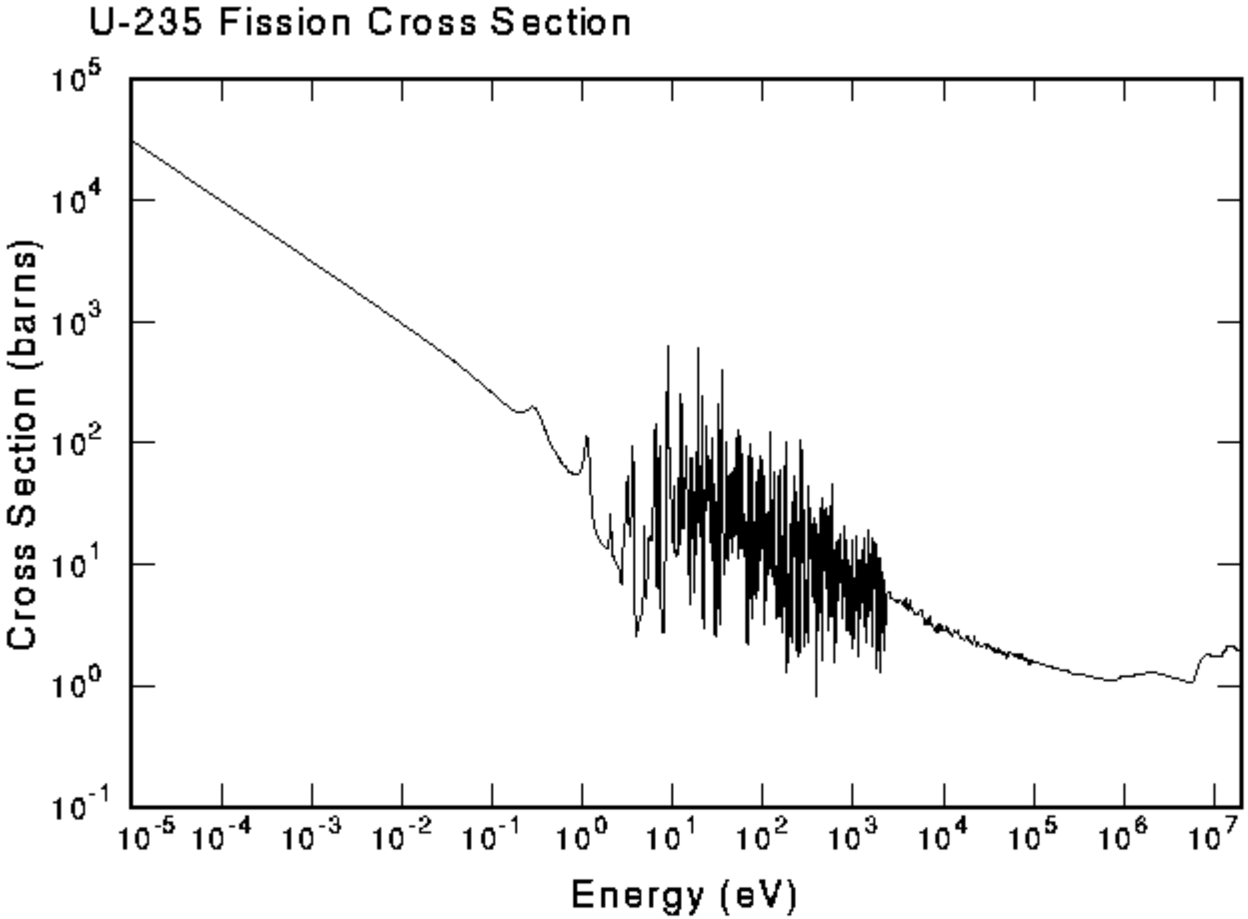
The Curve of Binding Energy

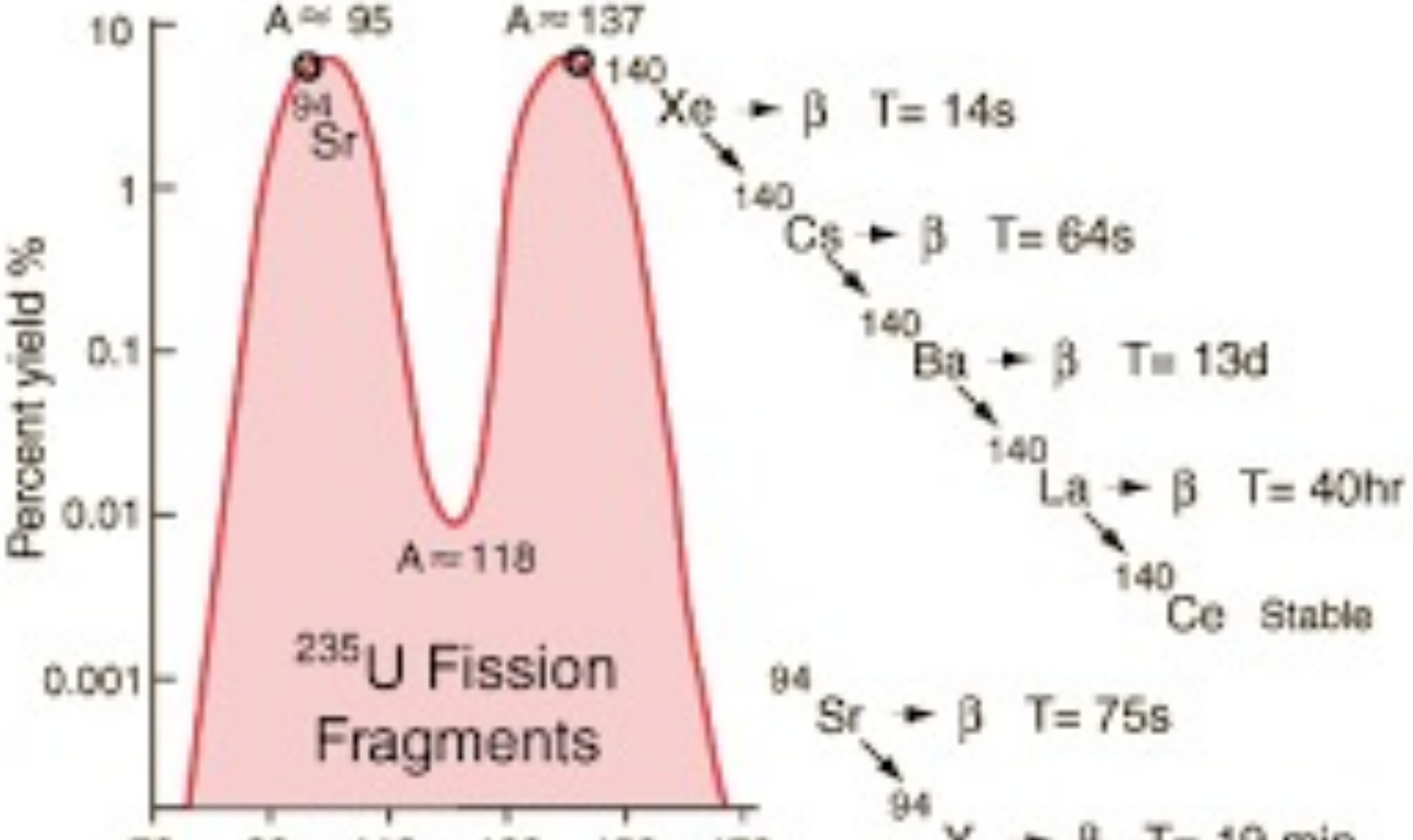



Pu235 24.3m
Pu236 2.85y
Pu237 45.6d
Pu238 87.8y
Pu239 2.439x10⁴y
Pu240 6540y
Pu241 15y
Pu242 3.87x10⁵y
Np234 4.4d
Np235 396d
Np236 22.5h 1.3x10⁶y
Np237 2.14x10⁶y
Np238 2.12d
Np239 2.350d
Np240 7.5m 65m
Np241 16.0m
U233 1.58x10⁵y
U234 0.0055
U235 0.720
U236 2.342x10⁷y
U237 6.75d
U238 99.28
U239 23.5m
U240 14.1h
Pa232 1.32d
Pa233 27.0d
Pa234 UX₂ UZ 1.17m 6.67h
Pa235 24.1m
Pa236 9.1m
Pa237 8.7m
Pa238 2.3m
Th231 UY 25.52h
Th232 Th 100
Th233 22.2m
Th234 UX₁ 24.10d
Th235 6.9m
Ac230
Ac231

Reactors—It's All About the Neutrons and the Nucleus

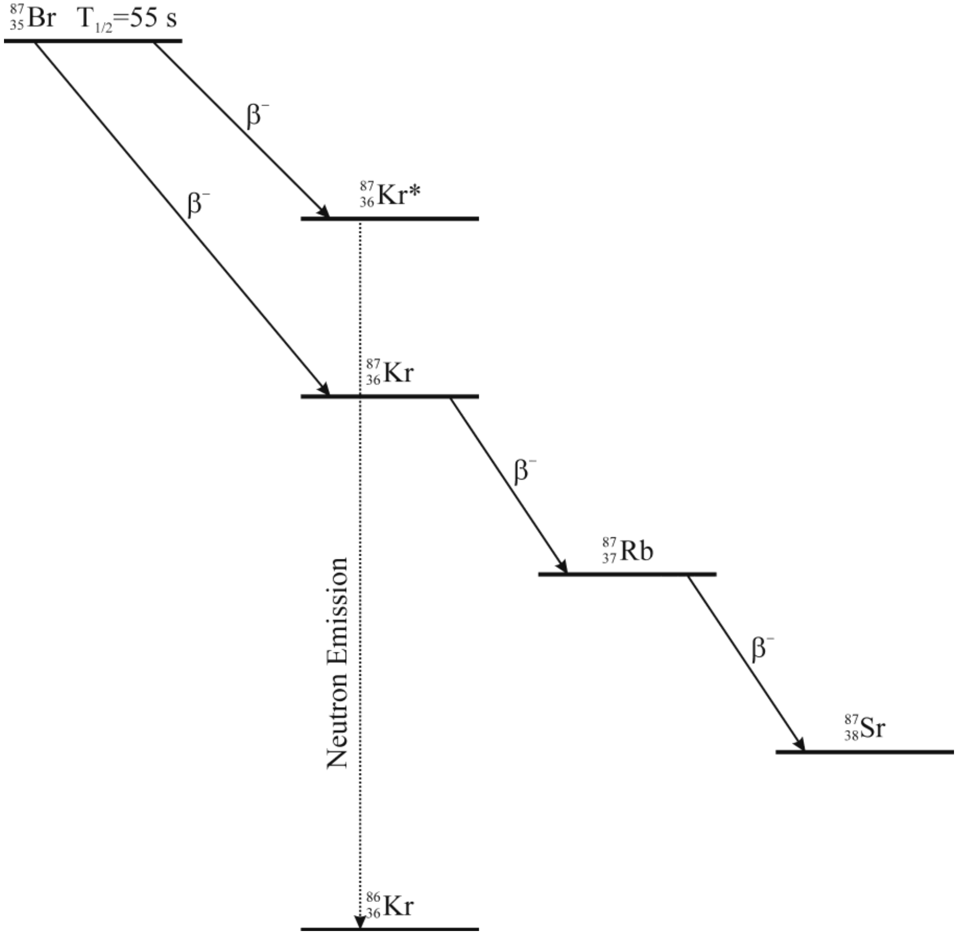
- Fast—Fission Energy (~2 MeV)
  - Must be slowed for a thermal reactor to work
- Prompt neutrons
- Delayed—make reactor possible

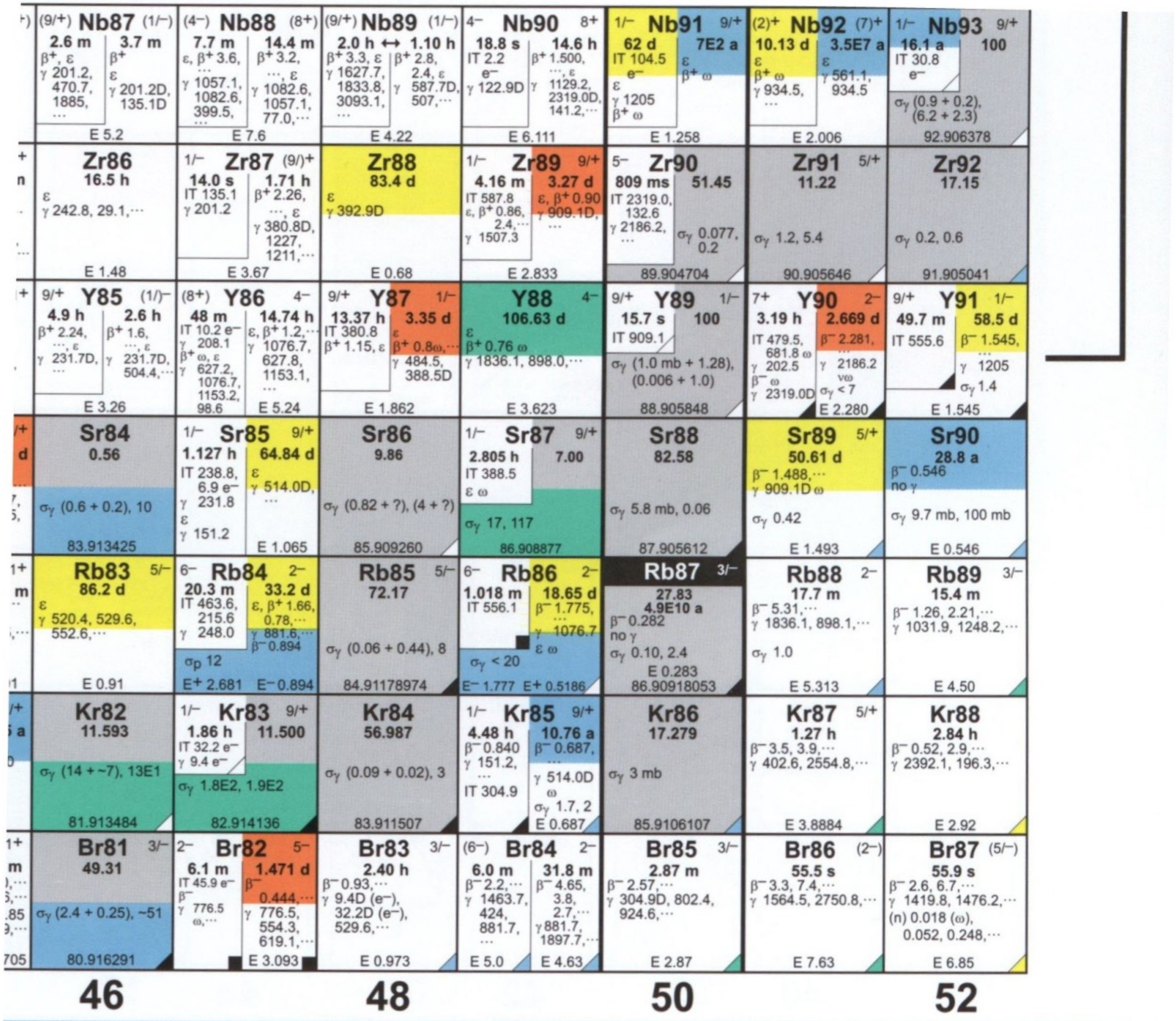

U-235 Fission Cross Section
Cross Section (barns)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV)


Percent yield %
10
1
0.1
0.01
0.001
A ≈ 95
A ≈ 137
A ≈ 118
^{94}Sr
^{235}U Fission Fragments
^{140}Xe → β T= 14s
^{140}Cs → β T= 64s
^{140}Ba → β T= 13d
^{140}La → β T= 40hr
^{140}Ce Stable
^{94}Sr → β T= 75s
94

How Reactors Work

Delayed 87 Br example



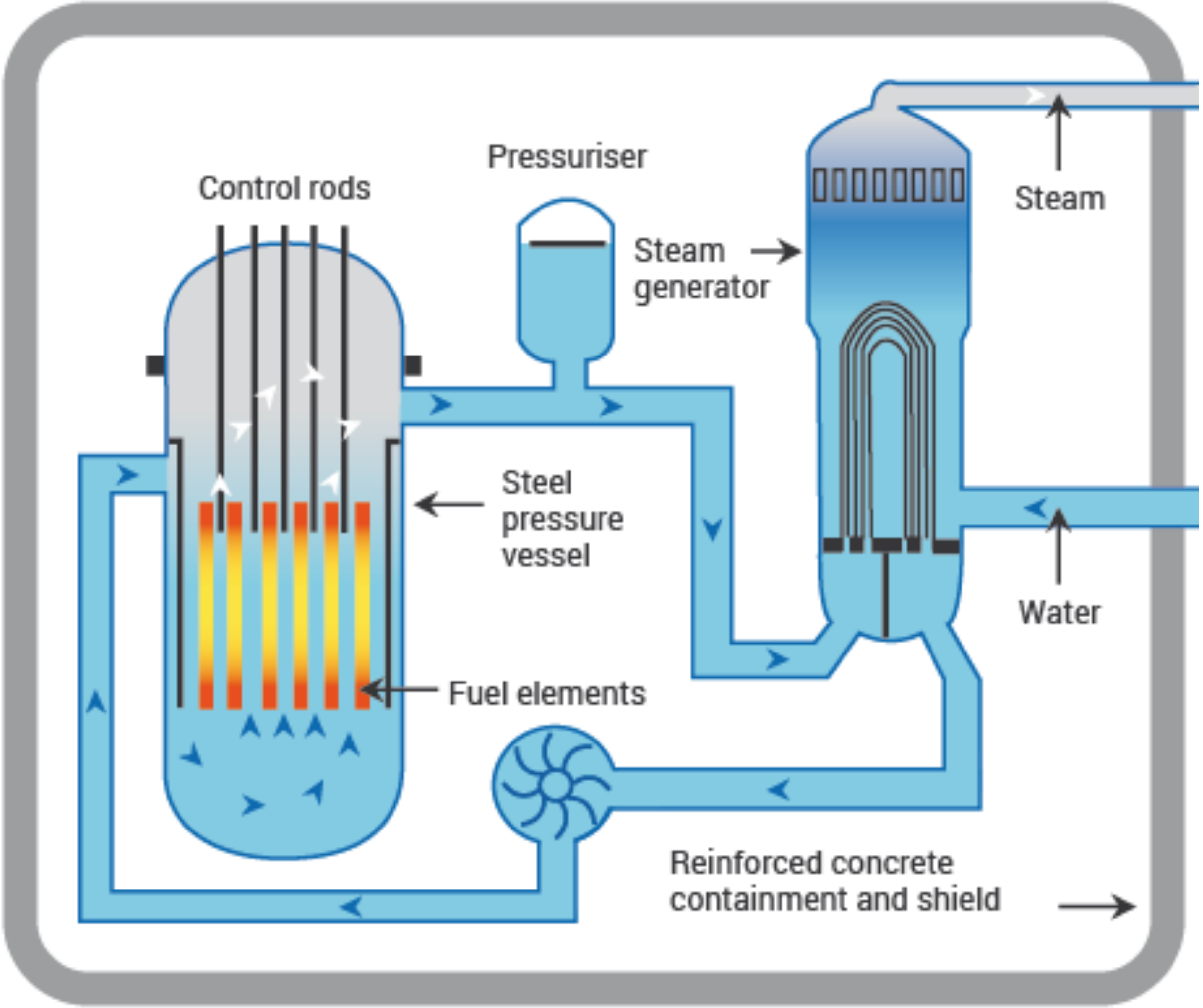


(9/+) **Nb87** (1/−) 2.6 m: β^+, ε γ 201.2, 470.7, 1885, … 3.7 m: β^+ ε γ 201.2D, 135.1D E 5.2	(4−) **Nb88** (8+) 7.7 m: ε, β^+ 3.6, … γ 1057.1, 1082.6, 399.5, … 14.4 m: β^+ 3.2, …, ε γ 1082.6, 1057.1, 77.0, … E 7.6	(9/+) **Nb89** (1/−) 2.0 h ↔ 1.10 h β^+ 3.3, ε γ 1627.7, 1833.8, 3093.1, … β^+ 2.8, 2.4, ε γ 587.7D, 507, … E 4.22	4− **Nb90** 8+ 18.8 s: IT 2.2 e^- γ 122.9D 14.6 h: β^+ 1.500, …, ε γ 1129.2, 2319.0D, 141.2, … E 6.111	1/− **Nb91** 9/+ 62 d: IT 104.5 e^- ε γ 1205 β^+ ω 7E2 a: ε β^+ ω E 1.258	(2)+ **Nb92** (7)+ 10.13 d: ε β^+ ω γ 934.5, … 3.5E7 a: ε γ 561.1, 934.5 E 2.006	1/− **Nb93** 9/+ 16.1 a: IT 30.8 e^- 100 σ_γ (0.9 + 0.2), (6.2 + 2.3) 92.906378
Zr86 16.5 h ε γ 242.8, 29.1, … E 1.48	1/− **Zr87** (9/)+ 14.0 s: IT 135.1 γ 201.2 1.71 h: β^+ 2.26, …, ε γ 380.8D, 1227, 1211, … E 3.67	**Zr88** 83.4 d ε γ 392.9D E 0.68	1/− **Zr89** 9/+ 4.16 m: IT 587.8 ε, β^+ 0.86, 2.4, … γ 1507.3 3.27 d: ε, β^+ 0.90 γ 909.1D, … E 2.833	5− **Zr90** 809 ms: IT 2319.0, 132.6 γ 2186.2, … 51.45 σ_γ 0.077, 0.2 89.904704	**Zr91** 5/+ 11.22 σ_γ 1.2, 5.4 90.905646	**Zr92** 17.15 σ_γ 0.2, 0.6 91.905041
9/+ **Y85** (1/)− 4.9 h: β^+ 2.24, …, ε γ 231.7D, … 2.6 h: β^+ 1.6, …, ε γ 231.7D, 504.4, … E 3.26	(8+) **Y86** 4− 48 m: IT 10.2 e^- γ 208.1 β^+ ω, ε γ 627.2, 1076.7, 1153.2, 98.6 14.74 h: ε, β^+ 1.2, … γ 1076.7, 627.8, 1153.1, … E 5.24	9/+ **Y87** 1/− 13.37 h: IT 380.8 β^+ 1.15, ε 3.35 d: ε β^+ 0.8ω, … γ 484.5, 388.5D E 1.862	**Y88** 4− 106.63 d ε β^+ 0.76 ω γ 1836.1, 898.0, … E 3.623	9/+ **Y89** 1/− 15.7 s: IT 909.1 100 σ_γ (1.0 mb + 1.28), (0.006 + 1.0) 88.905848	7+ **Y90** 2− 3.19 h: IT 479.5, 681.8 ω γ 202.5 β^- ω γ 2319.0D 2.669 d: β^- 2.281, … γ 2186.2 $\nu\omega$ σ_γ < 7 E 2.280	9/+ **Y91** 1/− 49.7 m: IT 555.6 58.5 d: β^- 1.545, … γ 1205 σ_γ 1.4 E 1.545
Sr84 0.56 σ_γ (0.6 + 0.2), 10 83.913425	1/− **Sr85** 9/+ 1.127 h: IT 238.8, 6.9 e^- γ 231.8 ε γ 151.2 64.84 d: ε γ 514.0D, … E 1.065	**Sr86** 9.86 σ_γ (0.82 + ?), (4 + ?) 85.909260	1/− **Sr87** 9/+ 2.805 h: IT 388.5 ε ω 7.00 σ_γ 17, 117 86.908877	**Sr88** 82.58 σ_γ 5.8 mb, 0.06 87.905612	**Sr89** 5/+ 50.61 d β^- 1.488, … γ 909.1D ω σ_γ 0.42 E 1.493	**Sr90** 28.8 a β^- 0.546 no γ σ_γ 9.7 mb, 100 mb E 0.546
Rb83 5/− 86.2 d ε γ 520.4, 529.6, 552.6, … E 0.91	6− **Rb84** 2− 20.3 m: IT 463.6, 215.6 γ 248.0 33.2 d: ε, β^+ 1.66, 0.78, … γ 881.6, … β^- 0.894 σ_p 12 E^+ 2.681 E^- 0.894	**Rb85** 5/− 72.17 σ_γ (0.06 + 0.44), 8 84.91178974	6− **Rb86** 2− 1.018 m: IT 556.1 18.65 d: β^- 1.775, … γ 1076.7 ε ω σ_γ < 20 E^- 1.777 E^+ 0.5186	**Rb87** 3/− 27.83 4.9E10 a β^- 0.282 no γ σ_γ 0.10, 2.4 E 0.283 86.90918053	**Rb88** 2− 17.7 m β^- 5.31, … γ 1836.1, 898.1, … σ_γ 1.0 E 5.313	**Rb89** 3/− 15.4 m β^- 1.26, 2.21, … γ 1031.9, 1248.2, … E 4.50
Kr82 11.593 σ_γ (14 + ~7), 13E1 81.913484	1/− **Kr83** 9/+ 1.86 h: IT 32.2 e^- γ 9.4 e^- 11.500 σ_γ 1.8E2, 1.9E2 82.914136	**Kr84** 56.987 σ_γ (0.09 + 0.02), 3 83.911507	1/− **Kr85** 9/+ 4.48 h: β^- 0.840 γ 151.2, … IT 304.9 10.76 a: β^- 0.687, … γ 514.0D ω σ_γ 1.7, 2 E 0.687	**Kr86** 17.279 σ_γ 3 mb 85.9106107	**Kr87** 5/+ 1.27 h β^- 3.5, 3.9, … γ 402.6, 2554.8, … E 3.8884	**Kr88** 2.84 h β^- 0.52, 2.9, … γ 2392.1, 196.3, … E 2.92
Br81 3/− 49.31 σ_γ (2.4 + 0.25), ~51 80.916291	2− **Br82** 5− 6.1 m: IT 45.9 e^- β^- γ 776.5 ω, … 1.471 d: β^- 0.444, … γ 776.5, 554.3, 619.1, … E 3.093	**Br83** 3/− 2.40 h β^- 0.93, … γ 9.4D (e^-), 32.2D (e^-), 529.6, … E 0.973	(6−) **Br84** 2− 6.0 m: β^- 2.2, … γ 1463.7, 424, 881.7, … E 5.0 31.8 m: β^- 4.65, 3.8, 2.7, … γ 881.7, 1897.7, … E 4.63	**Br85** 3/− 2.87 m β^- 2.57, … γ 304.9D, 802.4, 924.6, … E 2.87	**Br86** (2−) 55.5 s β^- 3.3, 7.4, … γ 1564.5, 2750.8, … E 7.63	**Br87** (5/−) 55.9 s β^- 2.6, 6.7, … γ 1419.8, 1476.2, … (n) 0.018 (ω), 0.052, 0.248, … E 6.85
46		48		50		52

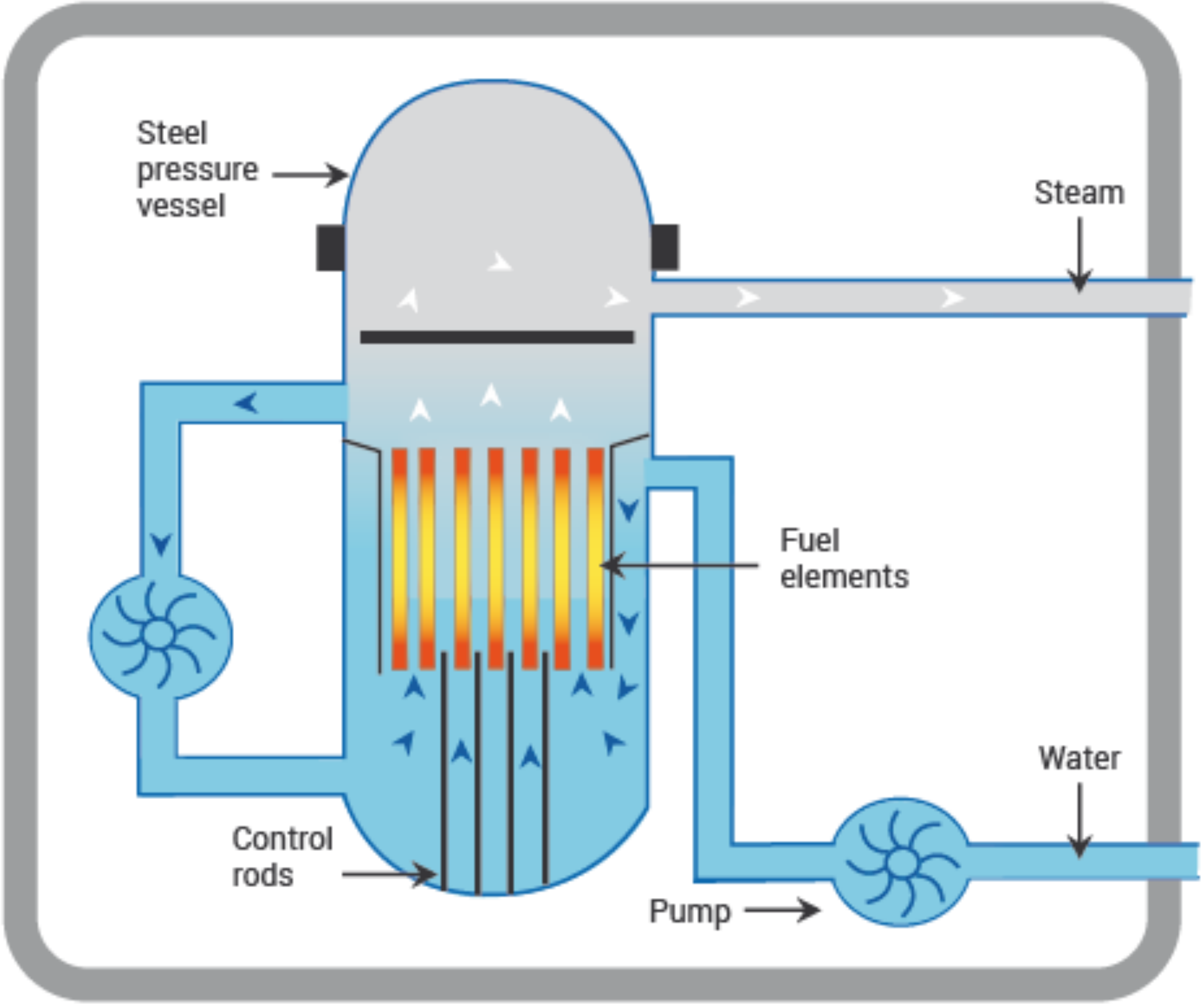
What types of Reactors Are in Use?

- **Power Reactors (thermal vs. fast)**
  - **Pressurized Water (PWR) a type of LWR**
  - **Boiling Water (BWR) also an LWR**
  - **CANDU**
  - **Gas Cooled**
- **Research Reactors and Test Reactors**
- **Propulsion Reactors**
- **Space Reactors + nuclear aircraft, cruise missiles and cars**

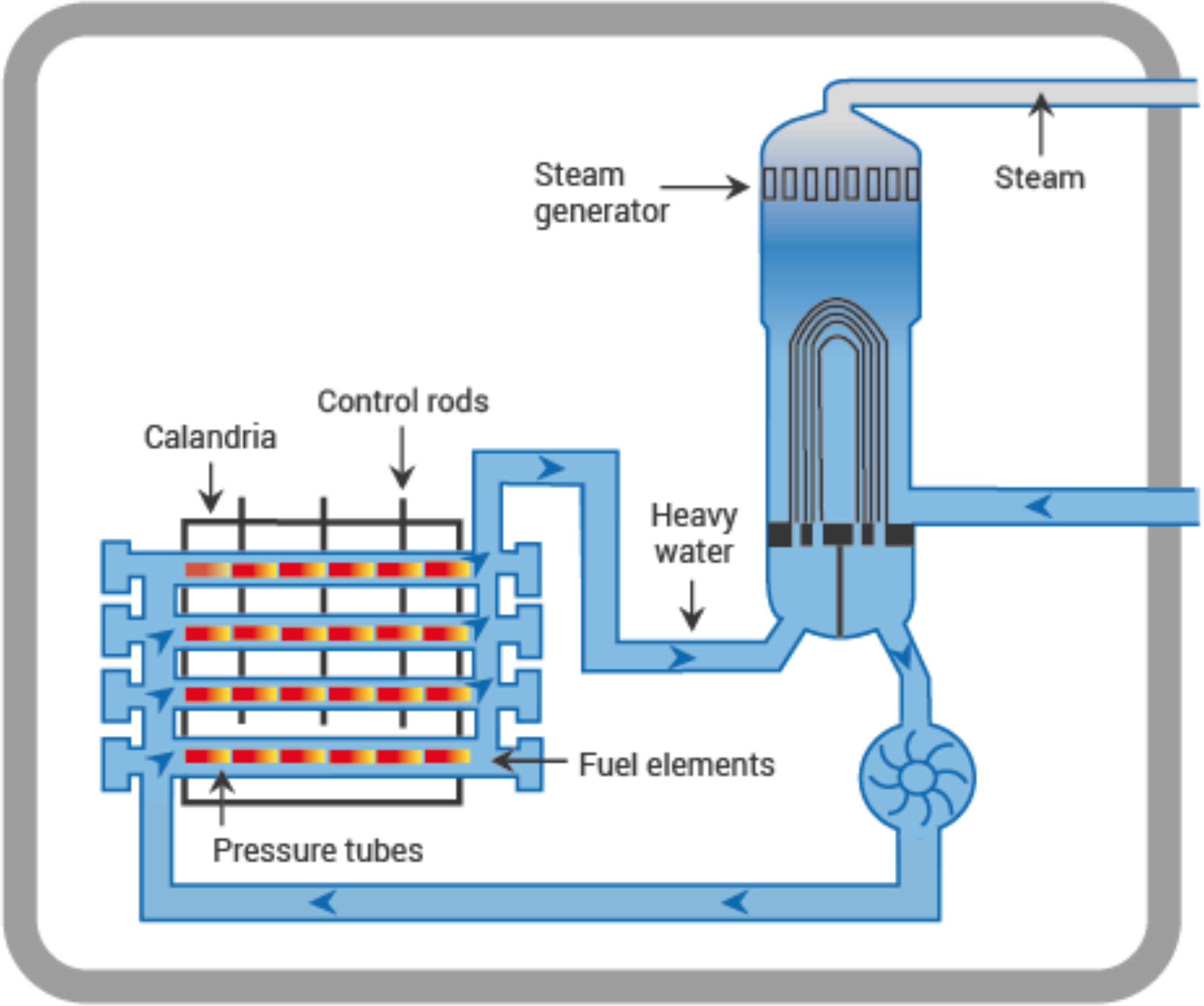
Pressurized Water Reactors (PWR)


Control rods
Pressuriser
Steam generator
Steam
Steel pressure vessel
Water
Fuel elements
Reinforced concrete containment and shield

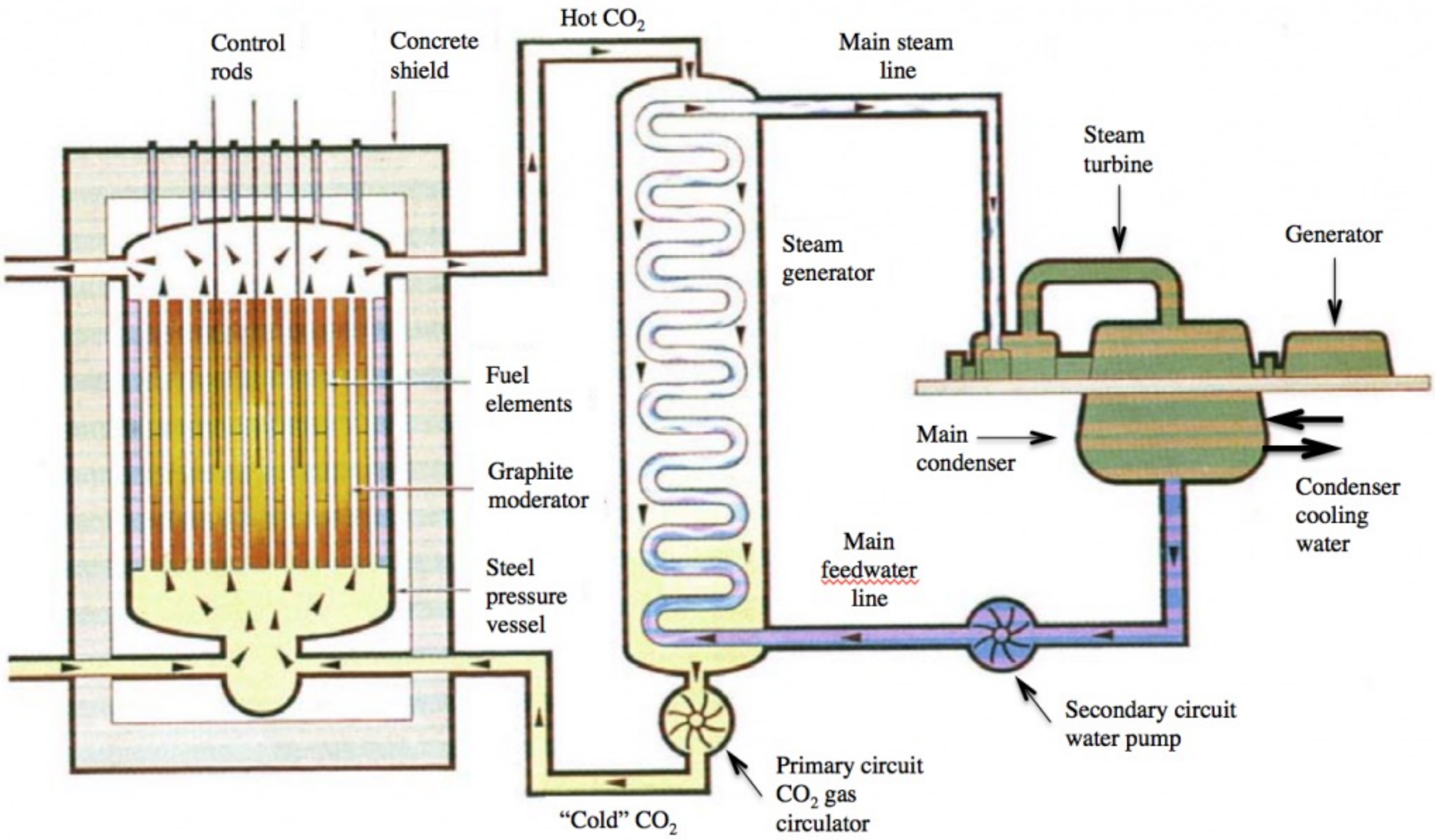
Boiling Water Reactors (BWR)

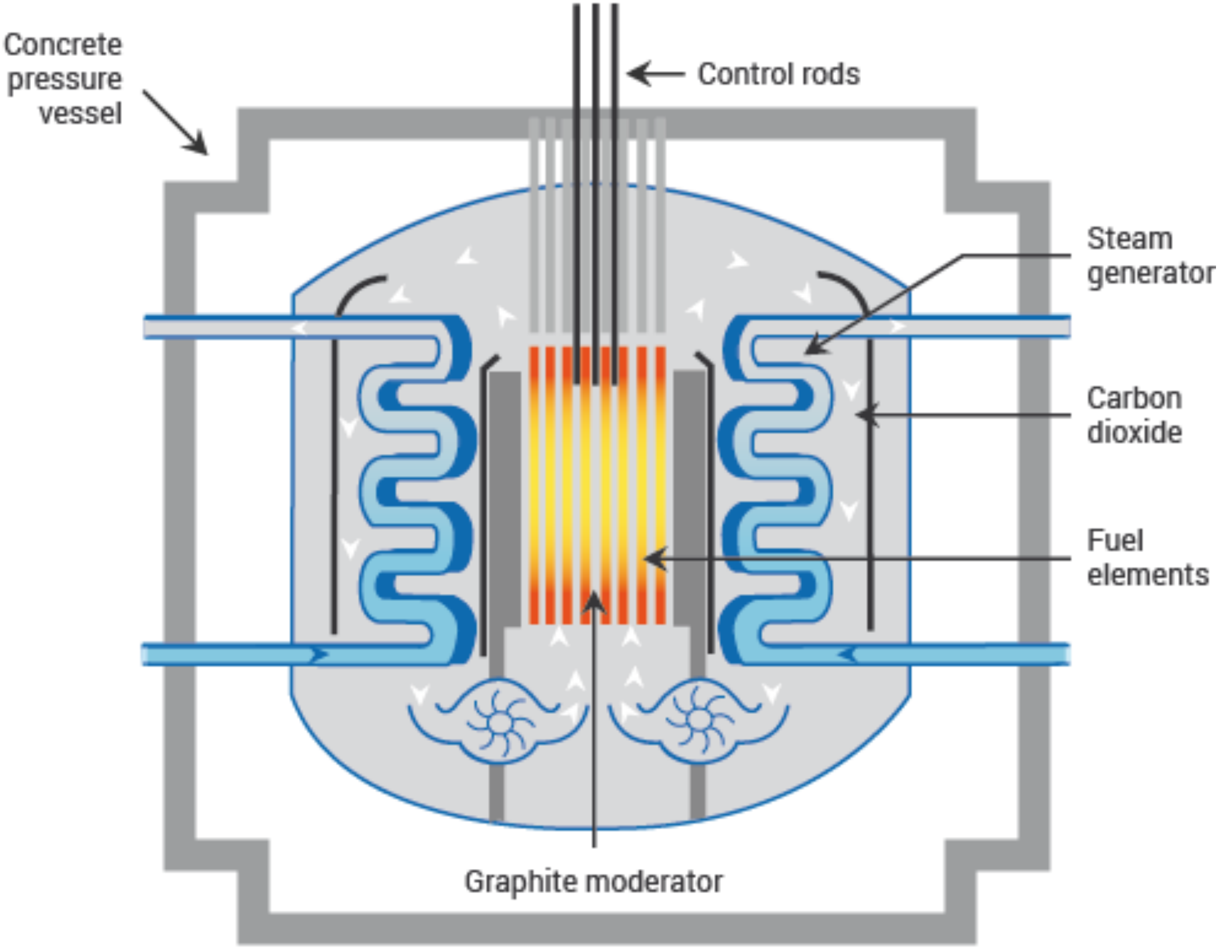

Steel pressure vessel
Steam
Fuel elements
Water
Control rods
Pump

CANDU (HWR)


Steam generator
Steam
Control rods
Calandria
Heavy water
Fuel elements
Pressure tubes

Gas Cooled Reactors


Hot CO_2
Control rods
Concrete shield
Main steam line
Steam turbine
Generator
Steam generator
Fuel elements
Graphite moderator
Steel pressure vessel
Main condenser
Condenser cooling water
Main feedwater line
Secondary circuit water pump
Primary circuit CO_2 gas circulator
"Cold" CO_2



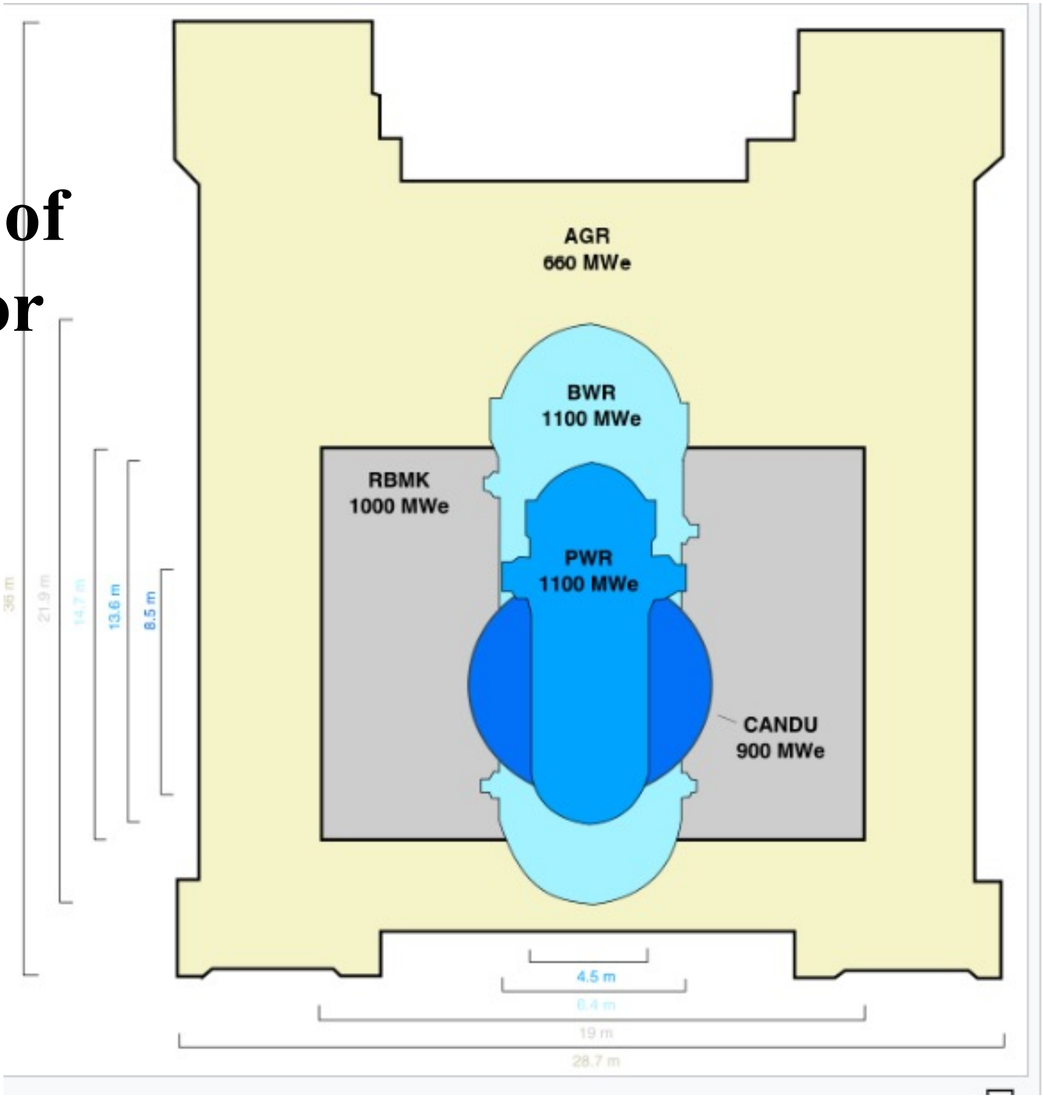
Concrete pressure vessel
Control rods
Steam generator
Carbon dioxide
Fuel elements
Graphite moderator

Operable nuclear power plants

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	307	292.8	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	47	24.3	natural UO_2	heavy water	heavy water
Light water graphite reactor (LWGR)	Russia	11	7.4	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		436	391.7			

For reactors under construction, see information page on Plans for New Reactors Worldwide.

Size Comparisons of Five Power Reactor Types



In all of these reactor types we need to consider how they can be safeguarded and their risk for proliferation.

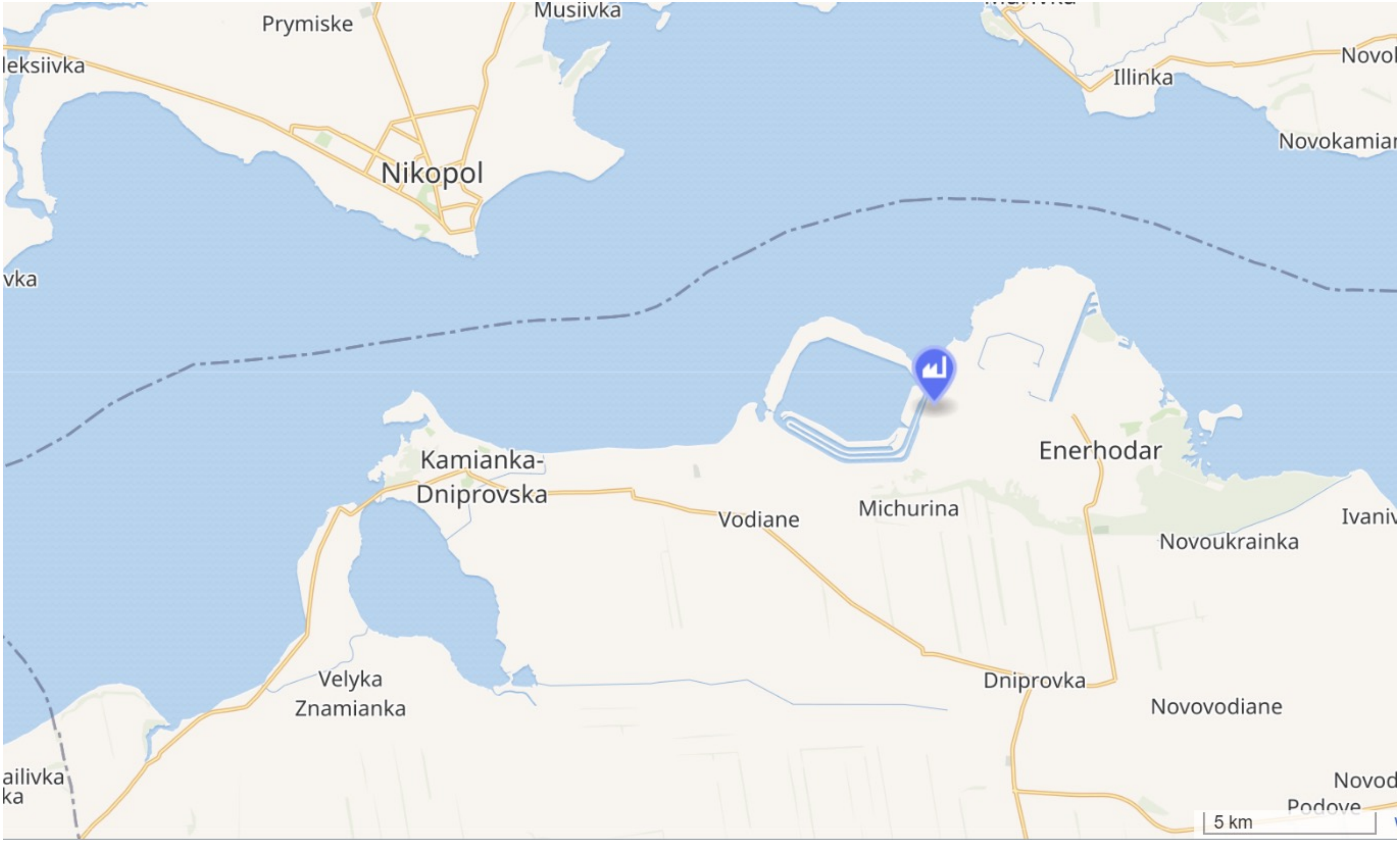
Generally, the risks depend on fuel type and ease of diversion. Don’t forget that proliferation has a human aspect and that there are dual use aspects inherent in any nuclear power program.

Zaporizhzhia

Zaporizhzhia

- VVER-1000 6 units—current status
- Dnieper River Cooling (note cooling towers)
- Connection to Ukrainian Power Grid
- Emergency Diesels (days of fuel?)
- IAEA onsite - Rosatom onsite
- Vulnerabilities?


© 2022 Google


Prymiske
Musiivka
leksiivka
Nikopol
Illinka
Novol
Novokamian
vka
Kamianka-
Dniprovska
Vodiane
Michurina
Enerhodar
Ivaniv
Novoukrainka
Velyka
Znamianka
Dniprovka
Novovodiane
ailivka
ka
Novod
Podove
5 km

Additional Protocol I

vs.

DOD Law of War Manual

AP I

Article 56 of Protocol I reads as follows:

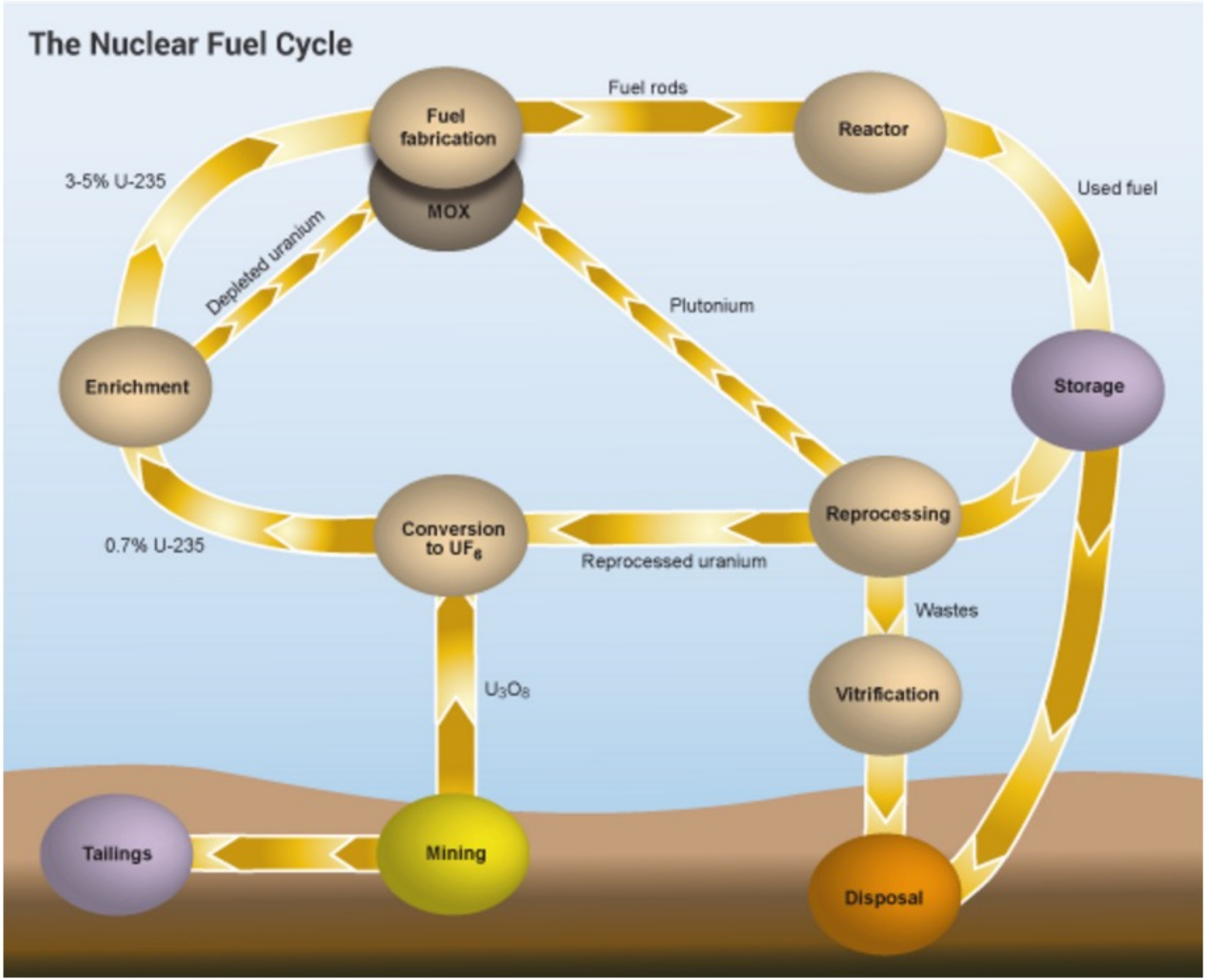
Protection of works and installations containing dangerous forces

1. Works or installations containing dangerous forces, namely dams, dykes and nuclear electrical generating stations, **shall not be made the object of attack, even where these objects are military objectives, if such attack may cause the release of dangerous forces and consequent severe losses among the civilian population.** Other military objectives located at or in the vicinity of these works or installations shall not be made the object of attack if such attack may cause the release of dangerous forces from the works or installations and consequent severe losses among the civilian population. (emphasis added)

Fuel Cycle

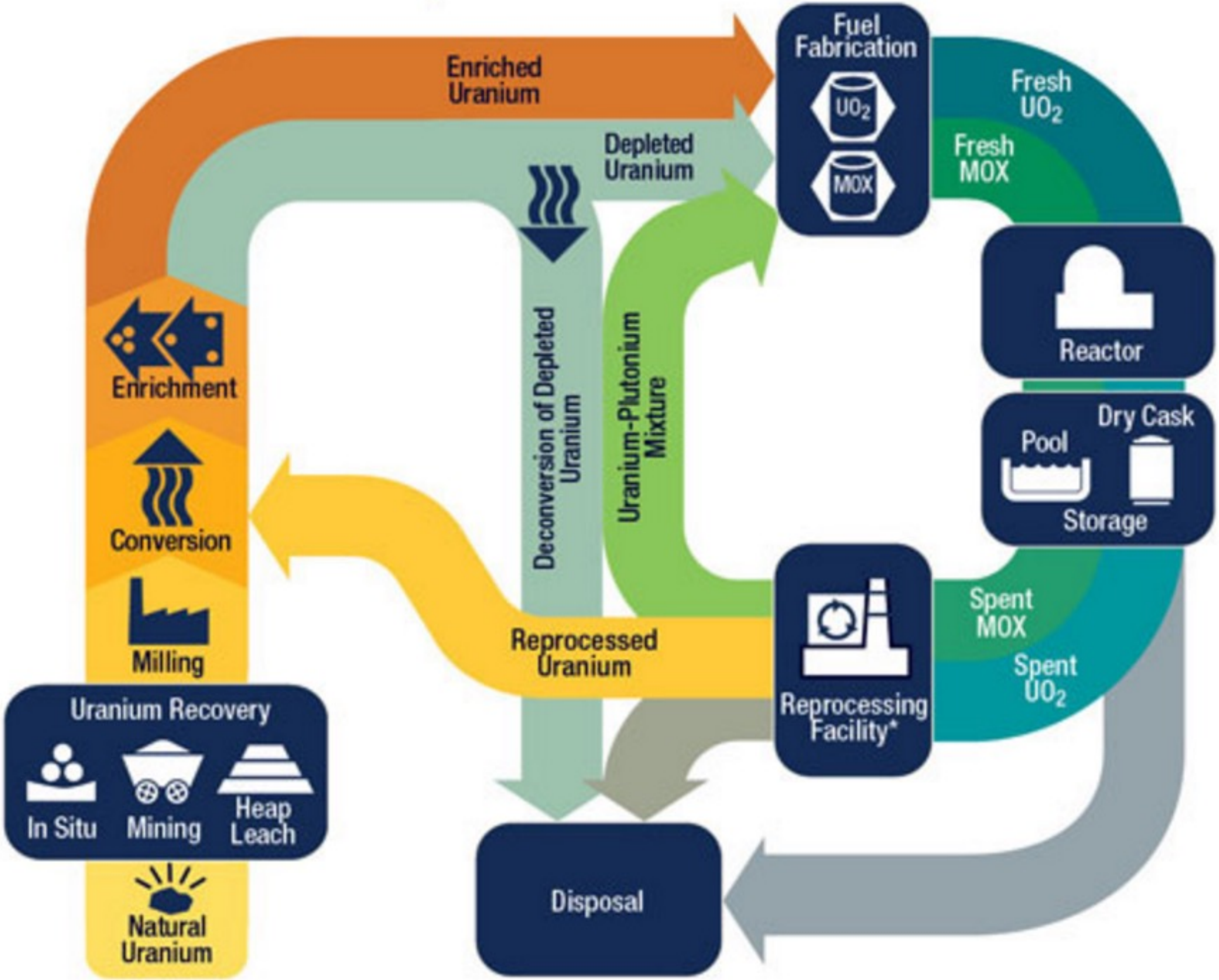
Uranium

What about Thorium?



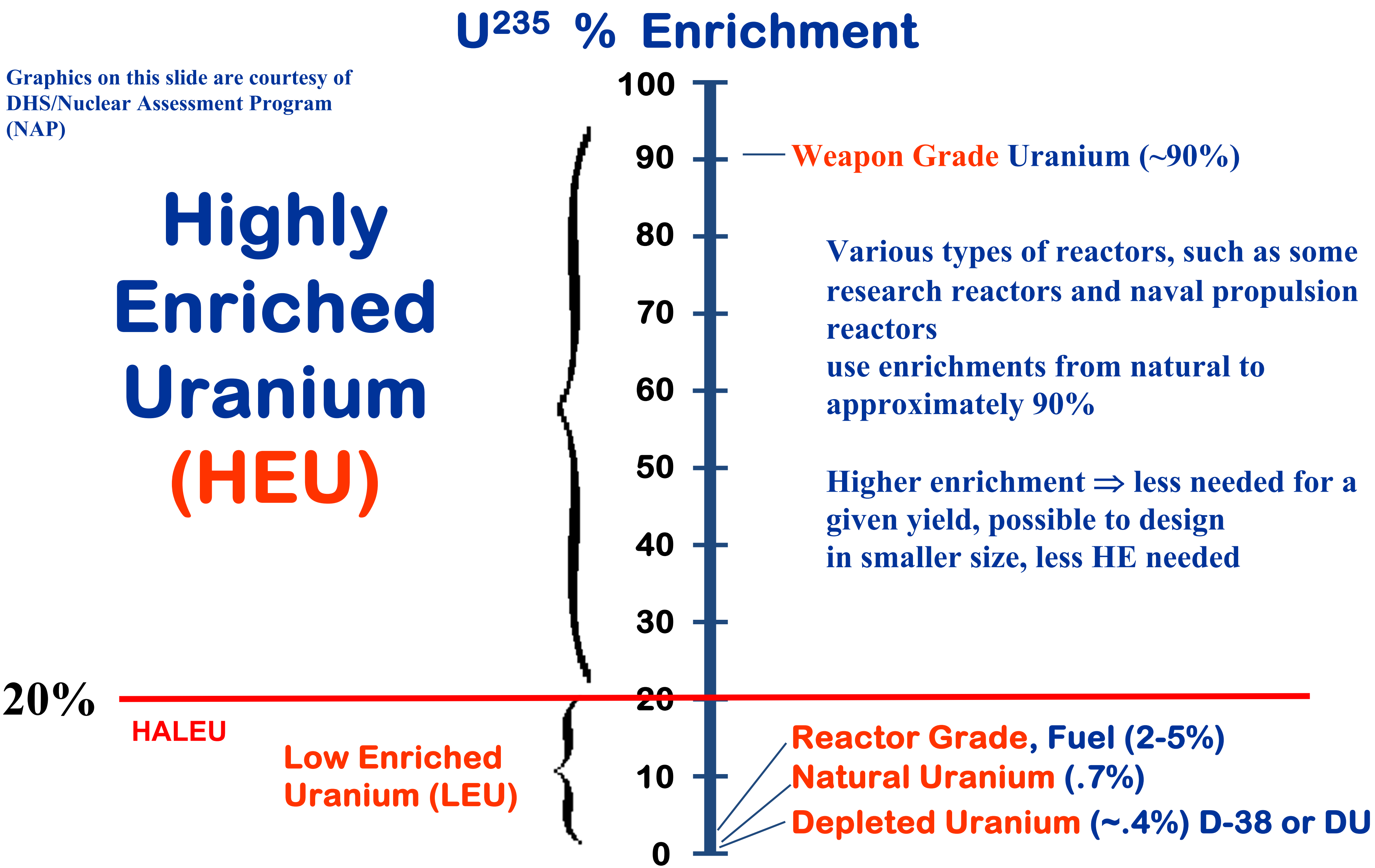
The Nuclear Fuel Cycle

The Nuclear Fuel Cycle



Uranium enrichment terms

Graphics on this slide are courtesy of
DHS/Nuclear Assessment Program
(NAP)



U^{235} % Enrichment

Highly Enriched Uranium (HEU)

Weapon Grade Uranium (~90%)

Various types of reactors, such as some research reactors and naval propulsion reactors
use enrichments from natural to approximately 90%

Higher enrichment ⇒ less needed for a given yield, possible to design
in smaller size, less HE needed

20%

HALEU

Low Enriched Uranium (LEU)

Reactor Grade, Fuel (2-5%)

Natural Uranium (.7%)

Depleted Uranium (~.4%) D-38 or DU

Mine	Country	Main owner	Type	(tU)	world
McArthur River	Canada	Cameco	underground	7356	13
Tortkuduk & Moinkum	Kazakhstan	Katco JV/Areva, Kazatomprom	ISL	4322	8
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3351	6
SOMAIR	Niger	Areva	open pit	2331	5
Budenovskoye 2	Kazakhstan	Karatau JV/Kazatomprom, Uranium One	ISL	2084	4
South Inkai	Kazakhstan	Betpak Dala JV/Uranium One, Kazatomprom	ISL	2002	4
Priagunsky	Russia	ARMZ	underground	1970	4
Langer Heinrich	Namibia	Paladin	open pit	1947	4
Inkai	Kazakhstan	Inkai JV/Cameco, Kazatomprom	ISL	1922	3
Central Mynkuduk	Kazakhstan	JSC Ken Dala, Kazatomprom	ISL	1790	3
Top 10 total				**29,075**	**54%**

Uranium mines operate in some 20 countries, though in 2014 some 54% of world production

Thorium Explained

Accidents

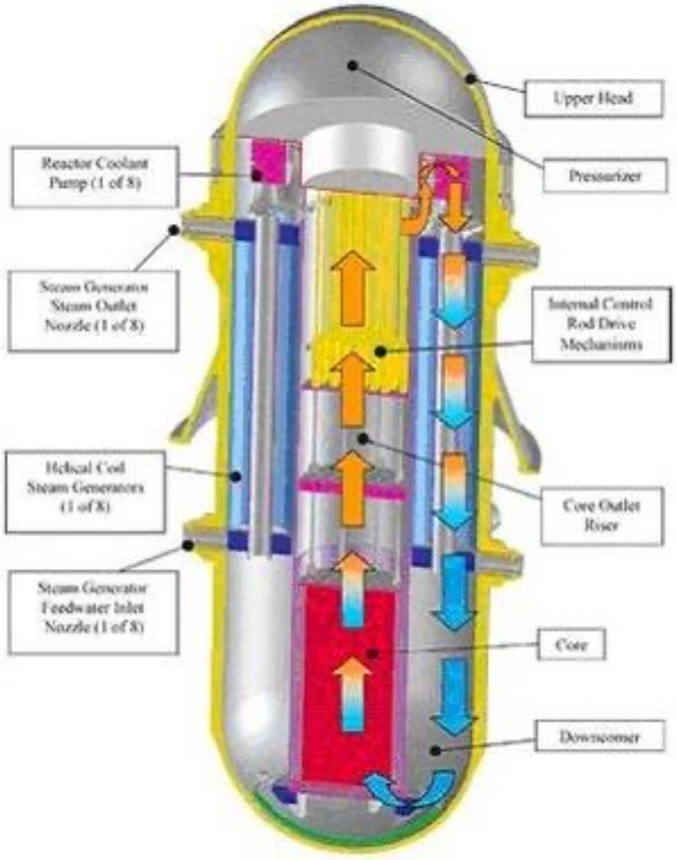
- **Fukushima**
- **Windscale**
- **Chernobyl**
- **Three Mile Island**
- **SL-1**

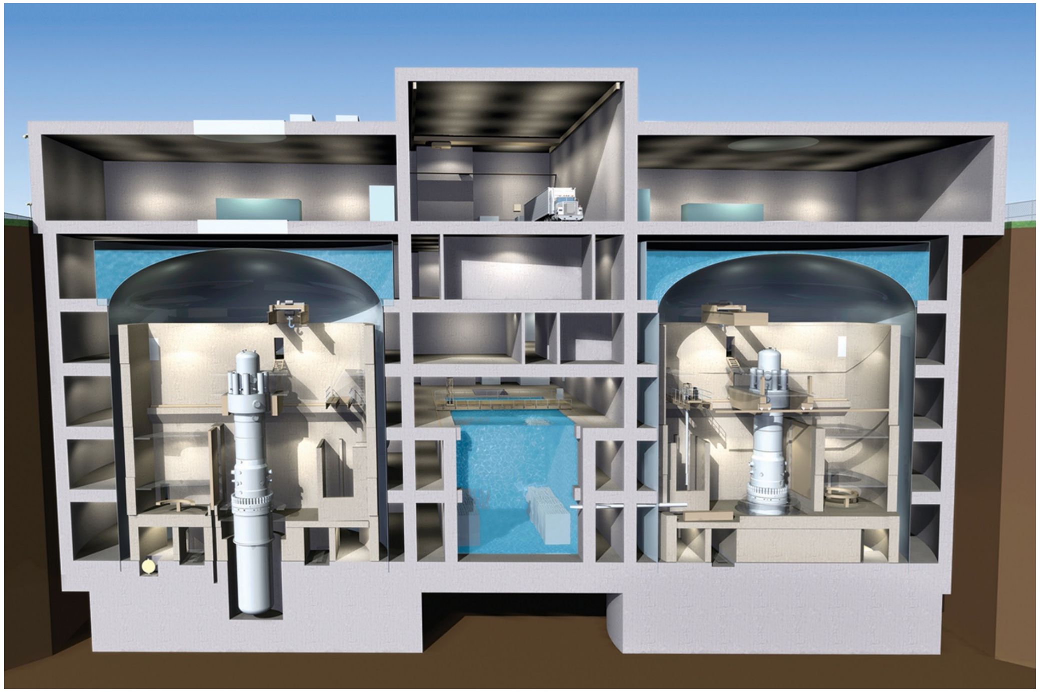
The New Kids
On the Block
(SMRs and Gen IV)

Small Modular Reactors

SMRs range in size up to 300 megawatts electrical (MWe), employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly. SMRs can employ light water coolant or any of a number of non-light water coolants.

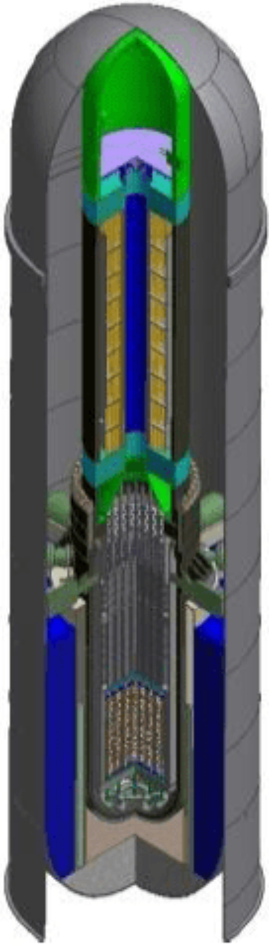
- SMRs offer many advantages such as relatively small size, reduced capital investment, ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. SMRs also offer distinct safeguards, security and nonproliferation advantages.
- Well, maybe if you get by NIMBY and other concerns


Upper Head
Reactor Coolant Pump (1 of 8)
Pressurizer
Steam Generator Steam Outlet Nozzle (1 of 8)
Internal Control Rod Drive Mechanisms
Helical Coil Steam Generators (1 of 8)
Core Outlet Riser
Steam Generator Feedwater Inlet Nozzle (1 of 8)
Core
Downcomer



Newly announced Westinghouse SMR

- Replaces IRIS as Westinghouse's SMR design
- Integral PWR configuration
- 225 MWe capacity
- Standard 17x17 pin fuel assemblies
- Heavy reliance on AP-1000 and past reactor experience
- Internal control rod drive mechanisms
- Straight tube steam generator
- External primary coolant pump motors
- Small volume containment vessel



Advanced Reactor Designs

Fast Reactors

EBR-1 and -2

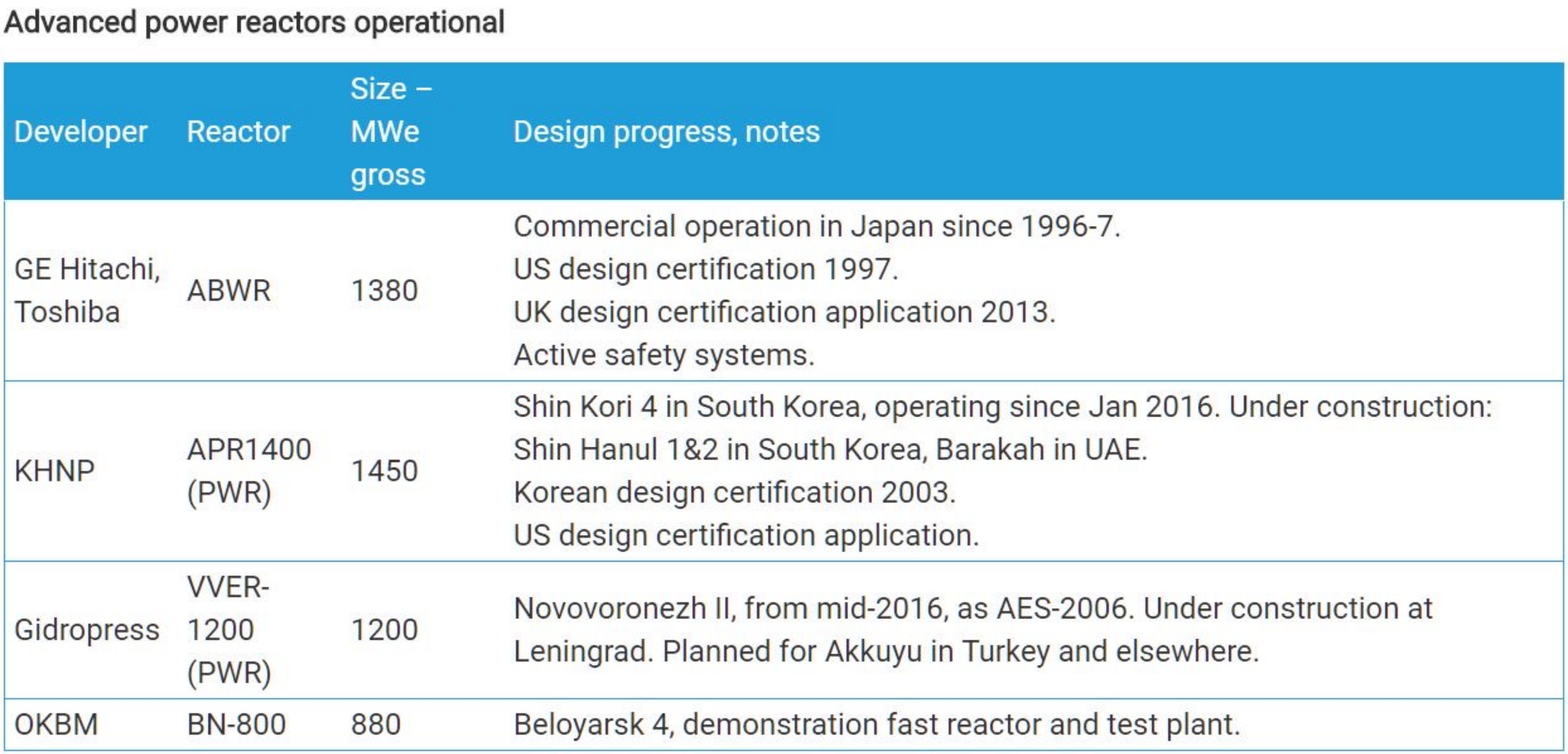
https://www.youtube.com/watch?v=cBThTwFhRlA

A pro nuclear power “rant”
https://www.youtube.com/watch?v=c1QmB5bW_WQ

Generation I reactors were developed in 1950-60s, and the last one shut down in the UK in 2015.

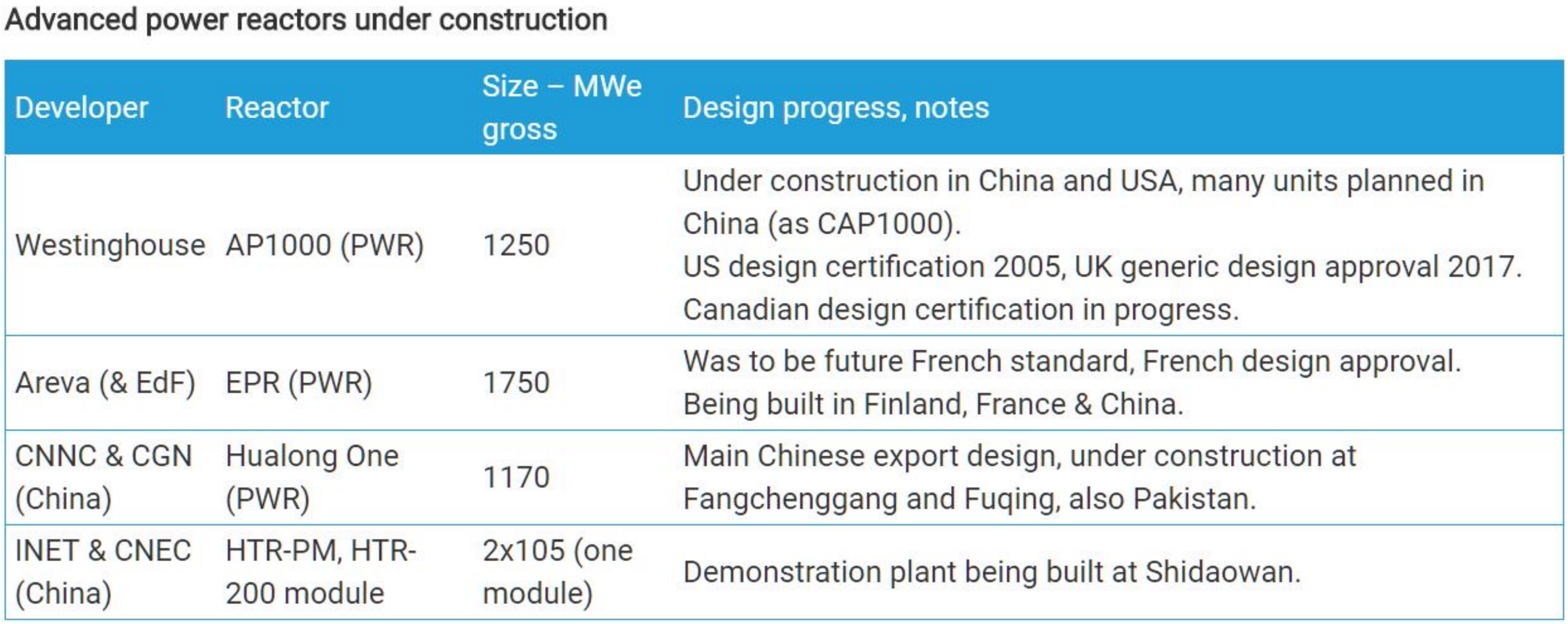
Generation II reactors are typified by the present US and French fleets and most in operation elsewhere.

So-called Generation III (and III+) are considered advanced reactor, though the distinction from Generation II is arbitrary. The first ones are in operation in Japan and others are under construction in several countries. Most Generation IV designs are still on the drawing board and the first are just under construction.



Advanced power reactors operational

Developer	Reactor	Size – MWe gross	Design progress, notes
GE Hitachi, Toshiba	ABWR	1380	Commercial operation in Japan since 1996-7. US design certification 1997. UK design certification application 2013. Active safety systems.
KHNP	APR1400 (PWR)	1450	Shin Kori 4 in South Korea, operating since Jan 2016. Under construction: Shin Hanul 1&2 in South Korea, Barakah in UAE. Korean design certification 2003. US design certification application.
Gidropress	VVER-1200 (PWR)	1200	Novovoronezh II, from mid-2016, as AES-2006. Under construction at Leningrad. Planned for Akkuyu in Turkey and elsewhere.
OKBM	BN-800	880	Beloyarsk 4, demonstration fast reactor and test plant.



Advanced power reactors under construction

Developer	Reactor	Size – MWe gross	Design progress, notes
Westinghouse	AP1000 (PWR)	1250	Under construction in China and USA, many units planned in China (as CAP1000). US design certification 2005, UK generic design approval 2017. Canadian design certification in progress.
Areva (& EdF)	EPR (PWR)	1750	Was to be future French standard, French design approval. Being built in Finland, France & China.
CNNC & CGN (China)	Hualong One (PWR)	1170	Main Chinese export design, under construction at Fangchenggang and Fuqing, also Pakistan.
INET & CNEC (China)	HTR-PM, HTR-200 module	2x105 (one module)	Demonstration plant being built at Shidaowan.

Advanced power reactors ready for deployment

Developer	Reactor	Size – MWe gross	Design progress, notes
GE Hitachi	ESBWR	1600	Planned for Fermi and North Anna in USA. Developed from ABWR, but passive safety systems. Design certification in USA Sept 2014.
Mitsubishi	APWR	1530	Planned for Tsuruga in Japan. US design certification application for US-APWR, but delayed. EU design approval for EU-APWR Oct 2014.
Areva & Mitsubishi	Atmea1 (PWR)	1150	Planned for Sinop in Turkey. French design approval Feb 2012. Canadian design certification in progress.
Candu Energy	EC6 (PHWR)	750	Improved CANDU-6 model. Canadian design certification June 2013.
Gidropress	VVER-TOI (PWR)	1300	Planned for Kursk II, Nizhny Novgorod and many more in Russia. Russian design certification in progress for EUR.
	VVER-600	600	Planned for Kola.

Nonproliferation And Nuclear Weapons

Murrah Building, Oklahoma City

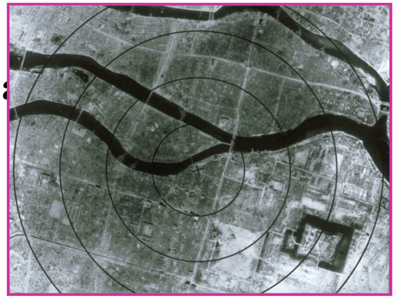
5000 lbs. of ANFO
~1.5 ton equivalent (0.0015 kT)
Fatalities – 168

World Trade Center, New York City

2 aircraft, ~180 tons each @ ~500 mph
~20,000 total gallons of jet fuel
~2 kiloton (kT) of TNT equivalent
Fatalities - 2980

Nuclear Weapons Dropped on Japan

Little Boy: 12.5 kT (~6 times larger)
Small yield compared to modern arsena
Fatalities
48 hours - 66,000
1945 - 145,000
1950 – 200,000



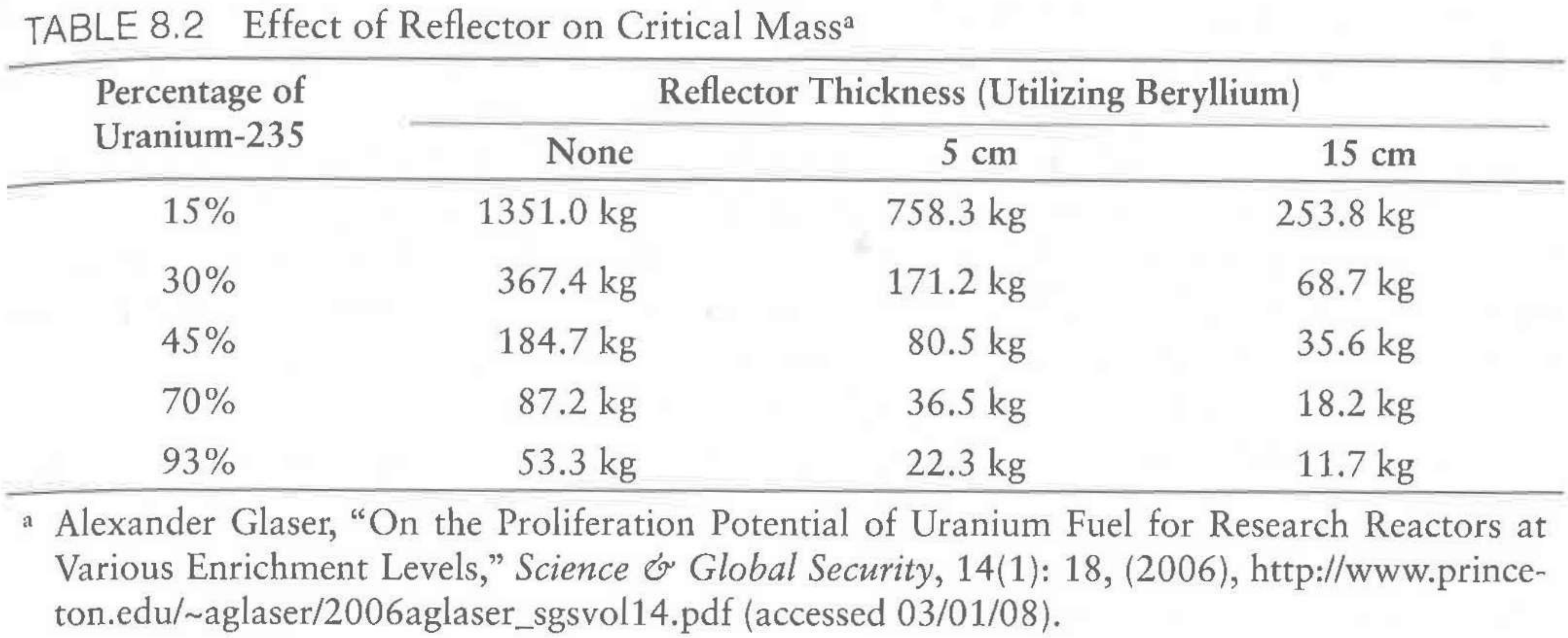


TABLE 8.2 Effect of Reflector on Critical Mass[a]

Percentage of Uranium-235	Reflector Thickness (Utilizing Beryllium)		
	None	5 cm	15 cm
15%	1351.0 kg	758.3 kg	253.8 kg
30%	367.4 kg	171.2 kg	68.7 kg
45%	184.7 kg	80.5 kg	35.6 kg
70%	87.2 kg	36.5 kg	18.2 kg
93%	53.3 kg	22.3 kg	11.7 kg

[a] Alexander Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science & Global Security*, 14(1): 18, (2006), http://www.princeton.edu/~aglaser/2006aglaser_sgsvol14.pdf (accessed 03/01/08).

Spontaneous fission rates

Spontaneous fission rates:[2]

Nuclide	Half-life	Fission prob. per decay	Neutrons per fission	Neutrons per gram-second
^{235}U	7.04x10^{8} years	7.0x10^{-11}	1.86	1.0x10^{-5}
^{238}U	4.47x10^{9} years	5.4x10^{-7}	2.07	0.0136
^{239}Pu	2.41x10^{4} years	4.4x10^{-12}	2.16	2.2x10^{-2}
^{240}Pu	6569 years	5.0x10^{-8}	2.21	920
^{250}Cm	8300 years	0.80	3.3	2x10^{10}
^{252}Cf	2.638 years	3.09x10^{-2}	3.73	2.3x10^{12}

In practice ^{239}Pu will invariably contain a certain amount of ^{240}Pu due to the tendency of ^{239}Pu to absorb an additional neutron during production. ^{240}Pu's high rate of spontaneous fission events makes it an undesirable contaminant. Weapons-grade plutonium contains no more than 7.0% ^{240}Pu.

The rarely-used gun-type atomic bomb has a critical insertion time of about one millisecond, and the probability of a fission during this time interval should be small. Therefore only ^{235}U is suitable. Almost all nuclear bombs use some kind of implosion method.

- Proliferation by material access
- Proliferation by technology access
- Proliferation by education

Let’s Talk a little about bombs and designs

- Gun vs. Implosion
- Timing and mechanics
- Effects are largely design independent

Single stage fission devices

- –Relationship to nuclear reactors
  - •Neutron energies
  - •Timing
  - •Lack of reliance on delayed neutrons
  - •Can a reactor explode like a bomb?
- –Timing: one “shake” is 10^{-8} seconds. Device requires approximately 50 to 60 shakes or about 0.5 μs to produce a yield on the order of 1 kt

Weapons-grade materials

- –Plutonium with less than 7% plutonium 240 (typical reactor Pu is 25% Pu 240)
- –Uranium 235 generally the HEU definition of greater than 20% uranium 235 (remember that Oralloy is 93.5%)
- –Uranium 233 has no formal definition for weapons grade, but it is desirable that uranium 232 content is less than 10 ppm

Gun and Implosion Designs

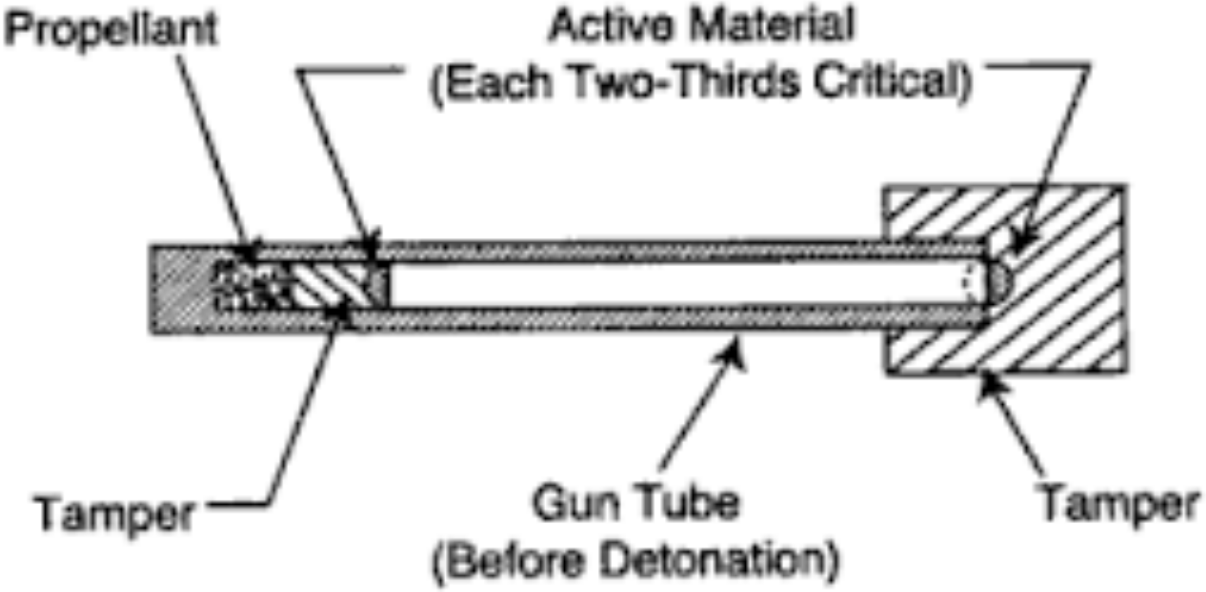
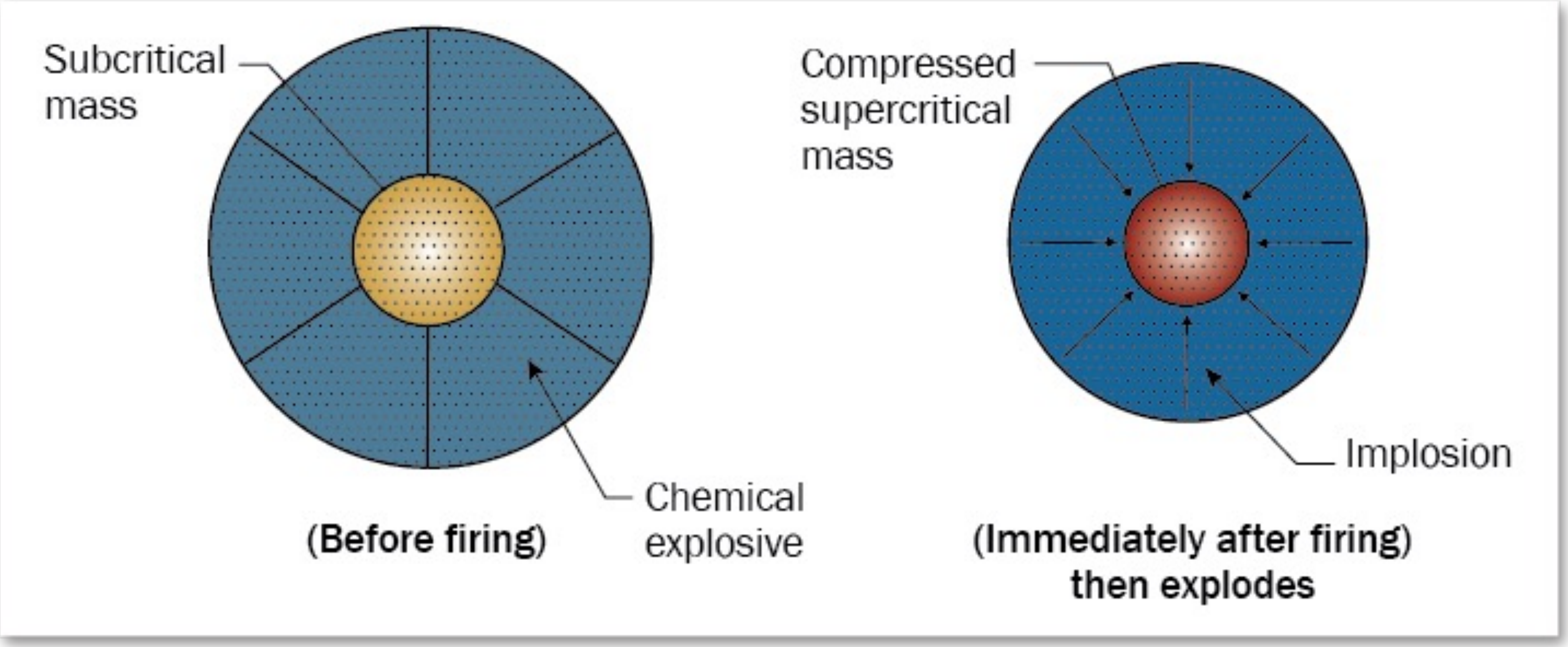


Figure 2-VII. Gun Assembly Principle

Test Firing of “Atomic Cannon” at Nevada Test Site 1953

Gun assembled nuclear weapons

- Initiator with a crushable alpha emitter and a low-Z material, typically beryllium. Polonium 210 was used in early weapons
- Spontaneous fission is a problem and can produce a "fizzle" yield. Why a plutonium gun doesn’t work well! Thin Man
- For a 10 kg quantity of 50% uranium 238 the spontaneous fission rate will be about 10^{-4} to 10^{-3} neutrons in about 10 µs. For a 10 kg quantity of weapons grade plutonium there will be approximately 2.5 spontaneous fissions in the 10 µs timeframe
- Uranium 233, bred from thorium 232 is less likely to pre-initiate than a uranium 235 device



(Before firing)

(Immediately after firing) then explodes

Implosion Systems and Boosting

Fusion Reactions

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} = {}^{3}\mathrm{He} + n + 3.2\ \mathrm{MeV},$$

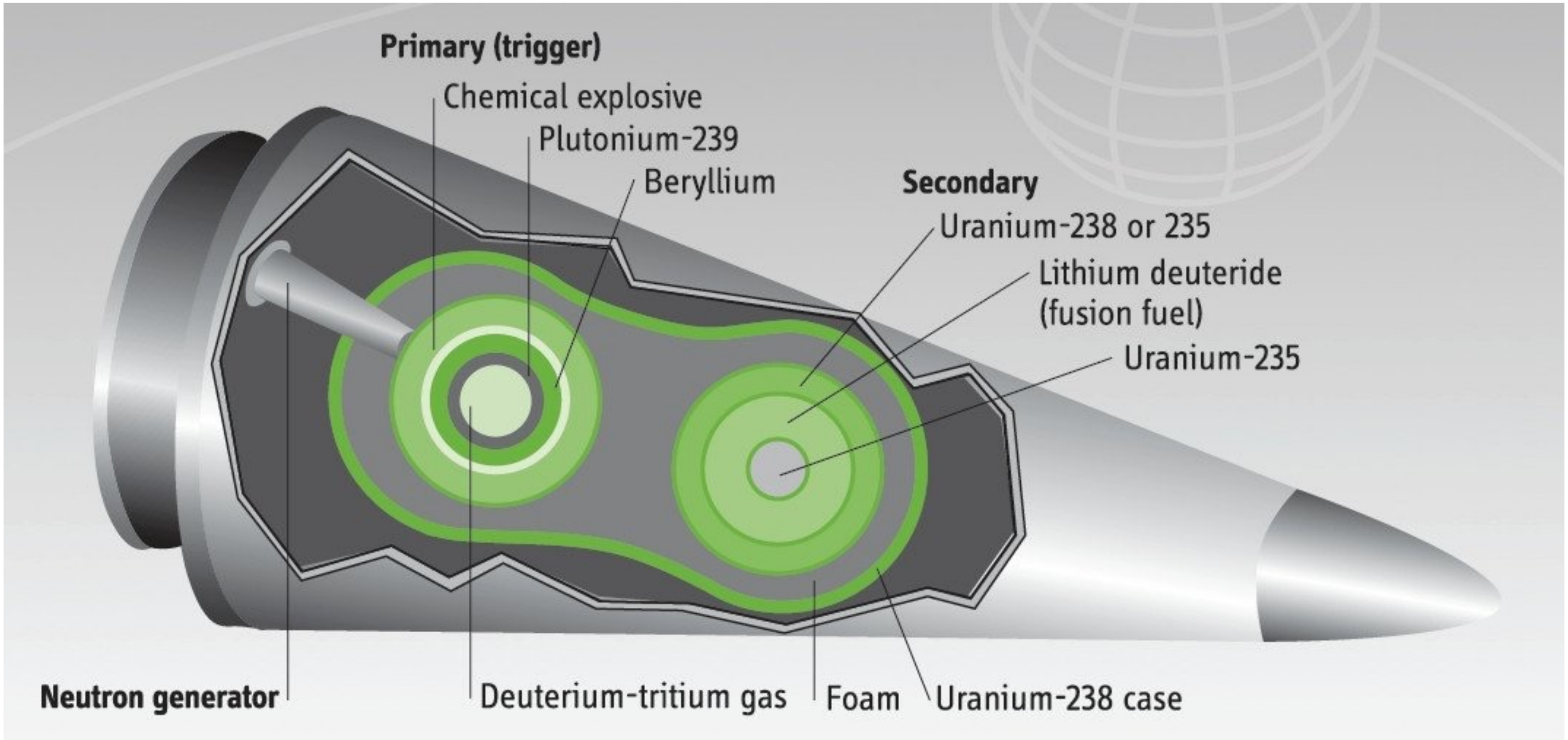
$$^{2}\mathrm{H} + {}^{2}\mathrm{H} = {}^{3}\mathrm{H} + {}^{1}\mathrm{H} + 4.0\ \mathrm{MeV},$$

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} = \mathrm{n} + {}^{4}\mathrm{He} + 17.6\ \mathrm{MeV},$$

$$^{3}\mathrm{H} + {}^{3}\mathrm{H} = {}^{4}\mathrm{He} + 2\mathrm{n} + 11.3\ \mathrm{MeV}.$$

Background for Two-stage nuclear explosive (Hydrogen Bomb or Thermonuclear Bomb)

- Joe-one in 1949
- Oppenheimer security problems
- By mid-1949 two concepts proposed for the hydrogen bomb
  - Alarm Clock
  - Super (Classic super tested in November 1952 10 Mt Mike test using liquid deuterium)


Primary (trigger)
Chemical explosive
Plutonium-239
Beryllium
Secondary
Uranium-238 or 235
Lithium deuteride (fusion fuel)
Uranium-235
Neutron generator
Deuterium-tritium gas
Foam
Uranium-238 case

Finally AUKUS

What We’ll Cover

- **Nuclear Reactors (Worldwide and U.S.)**
  - **Electrical Generation- Nuclear Power Plants (NPPs)j**
  - **Research Reactors/Training Reactors/Propulsion Reactors/ Space Reactors**
  - **Is there a “Nuclear Renaissance?” – New builds, Problems for Developers Generation IV**
  - **Small Modular Reactors– where are we and why**
- **Nuclear Fuel Cycles and Waste**
- **Military Reactors- Reactors in War- Zaporizhia and Geneva Protocols and AUKUS**