Power from Nuclear Transmutation
Gen III-IV Fission Reactors

The Diablo Canyon NPPT produced CO_2-free electricity at 2¢/kwh, half the state's (CA) average cost.

Agenda

- Nuclear stability & particle radiation
  Potential biological hazards

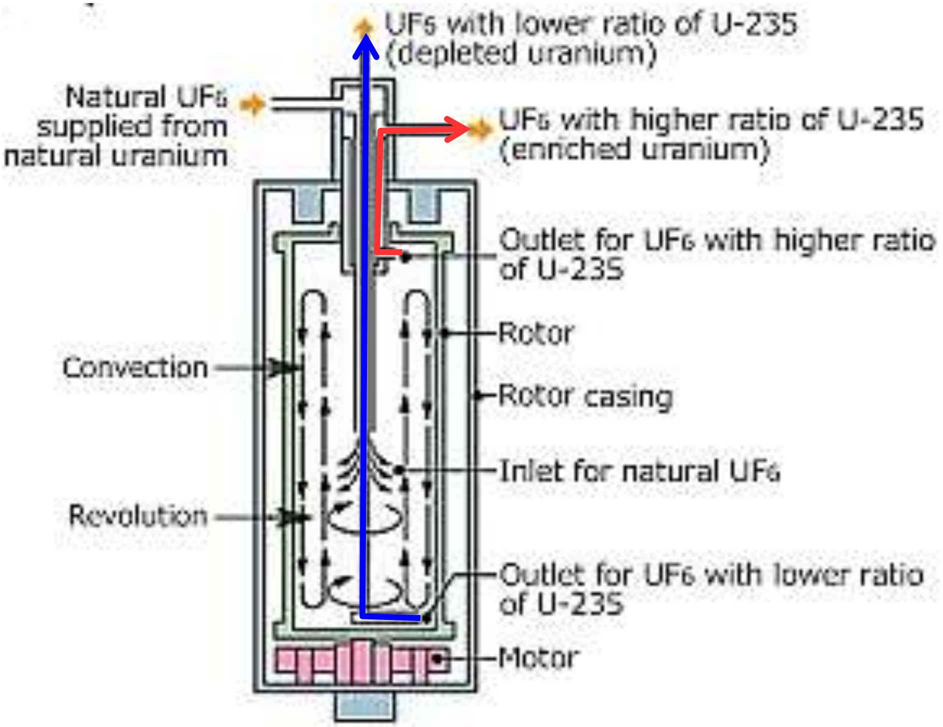
- Energy Generation from Nuclear Fission
  - U.S./World trends,
  - Nuclear fuel resources (U.S.),
  - Fission chain reaction and reactor control,
  - Reactor types,
  - Fuel cycles, radioactive waste & storage.

- New Nukes: Advanced Nuclear Energy Technologies
  - Small modular reactors (SMR plants),
  - Advanced (Gen II+, Gen IV) reactor designs,
  - U & Th breeder reactors, subcritical reactors,
  - Closed fuel cycle,
  - Applications: Radioisotope Thermoelectric Generators (RTG)

- Energy from nuclear fusion reactions
  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

- Strategic Issues for Nuclear Power
  - Sustainability, reliability, scalability, safety, eco-footprint, cost

Gas Diffusion Isotope Enrichment

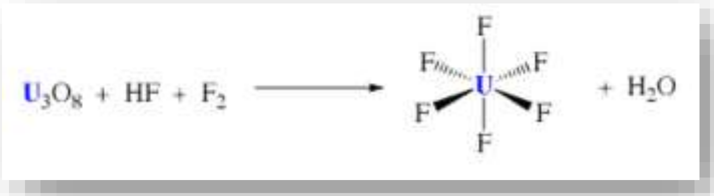


Preferred technology: Gaseous diffusion of UF_6 (^{19}F mono-isotopic)

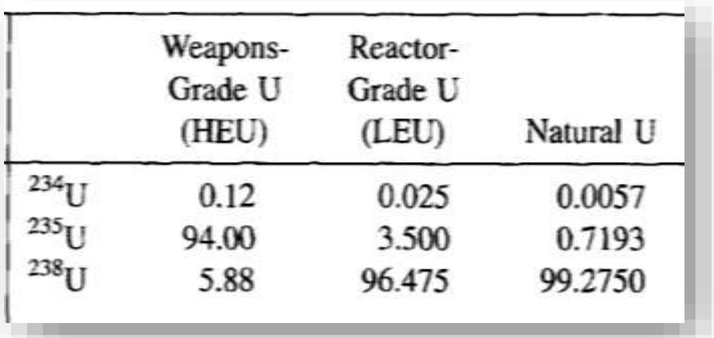
Laser ionization possible, economics

US: NPP (7TWh/a output) needs 250 GWh/a for enrichment

Gasify "Yellow Cake" U_3O_8



NPP (7TWh/a output) needs ≈ 6 GWh/a for 0.7 → 6% ^{235}U



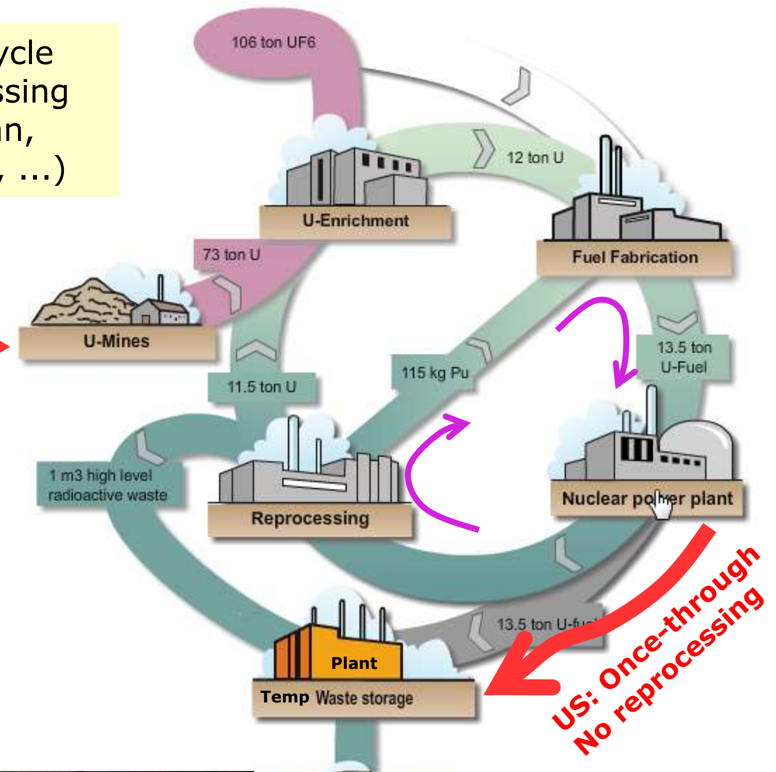
	Weapons-Grade U (HEU)	Reactor-Grade U (LEU)	Natural U
^{234}U	0.12	0.025	0.0057
^{235}U	94.00	3.500	0.7193
^{238}U	5.88	96.475	99.2750

Intermediate enrichment ~20% needed for research & radio-pharma reactors, and for some SMRs.

Uranium (& Thorium) Fuel Cycles

"Spent fuel" still contains "97% nuclear energy" ($^{235,238}U$, $^{239,240}Pu$) + FF & MA

Closed fuel cycle with reprocessing (France, Japan, Russia, India, ...)

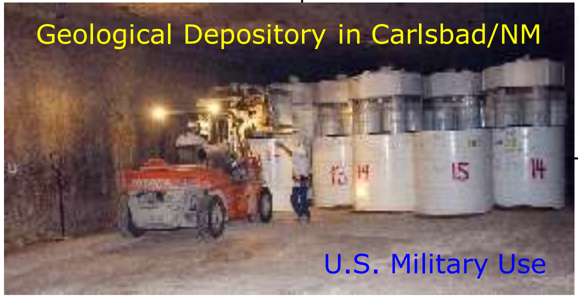


Depository

Worldwide:
5 geological depositories in operation (US: 1)

Yucca Mountain
Stopped in 2010, temporarily?

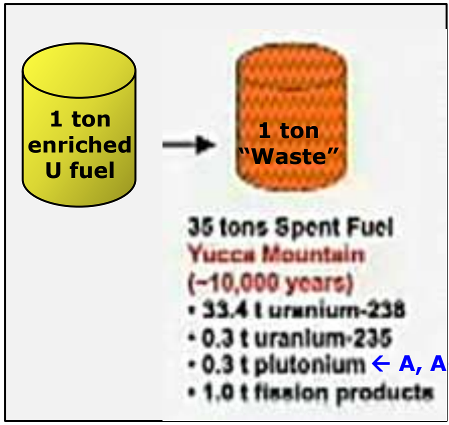
Geological Depository in Carlsbad/NM



U.S. Military Use

Permanent storage of high-level waste already paid by electricity consumers: ¢0.1/kWh.

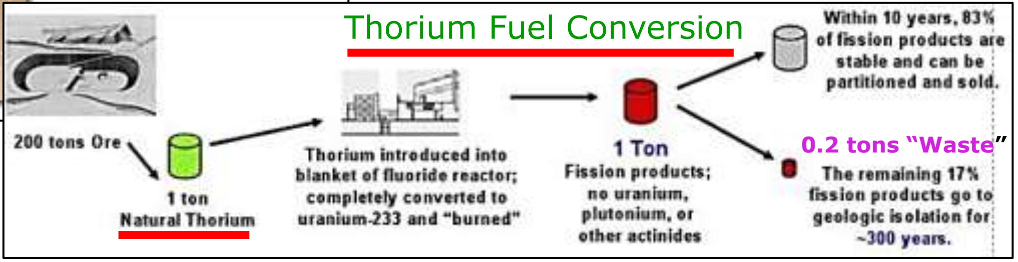
Uranium Fuel Conversion



35 tons Spent Fuel
Yucca Mountain
(~10,000 years)

- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium ← A, A+1,..
- 1.0 t fission products

Thorium Fuel Conversion



200 tons Ore

1 ton
Natural Thorium

Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

1 Ton
Fission products; no uranium, plutonium, or other actinides

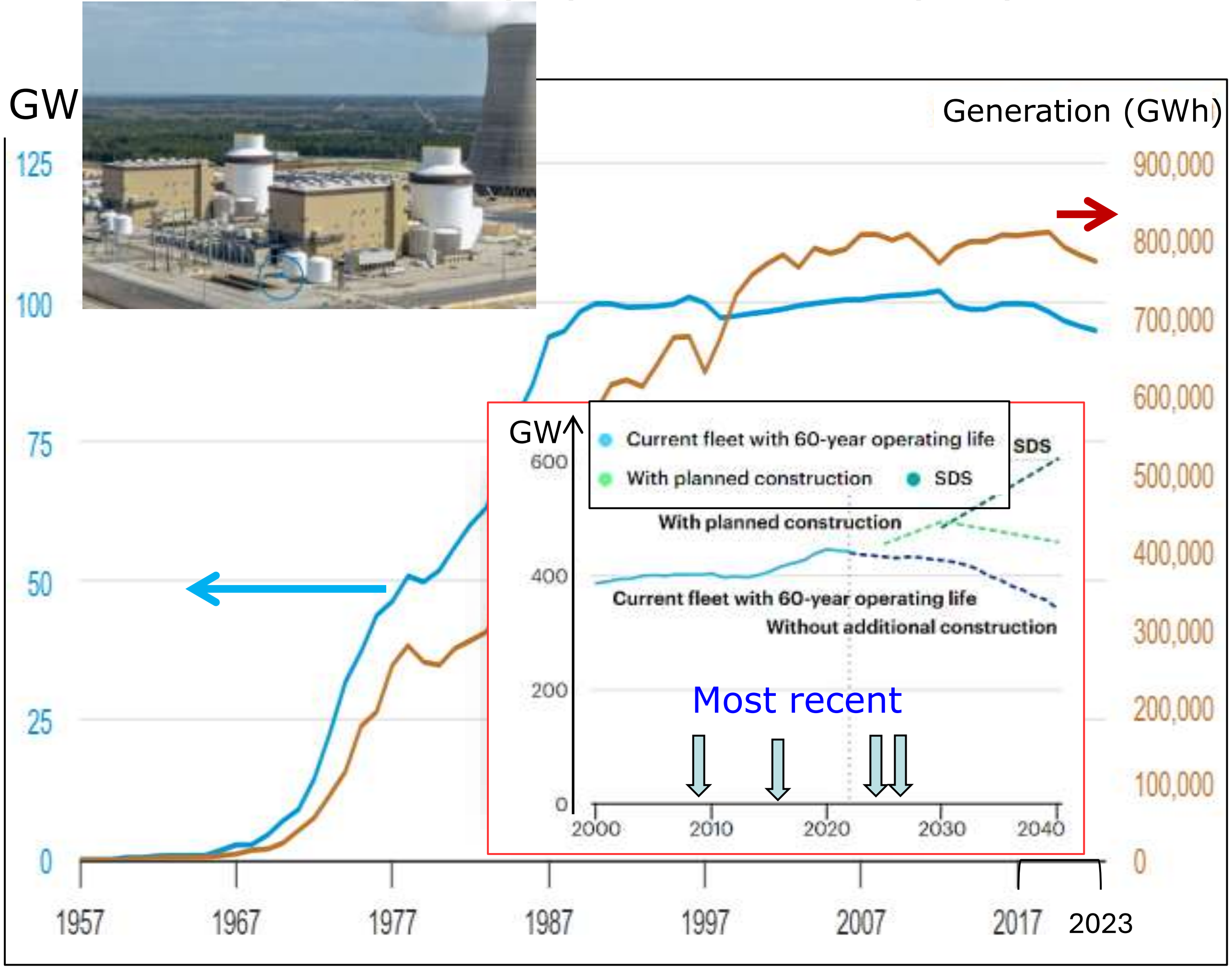
Within 10 years, 83% of fission products are stable and can be partitioned and sold.

0.2 tons "Waste"
The remaining 17% fission products go to geologic isolation for ~300 years.

U.S./World Trends in Nuclear Energy Production

Steady increase of nuclear power output over 30y. Efficiency ε ↗
Now: ε ≧ 90% → equivalent: 24 quads of oil. NPP lifetime 40a → > 60a

World 2023 (US): 440 (92) reactors; 400 (100) GW, 2.5 PWh → Modernize !

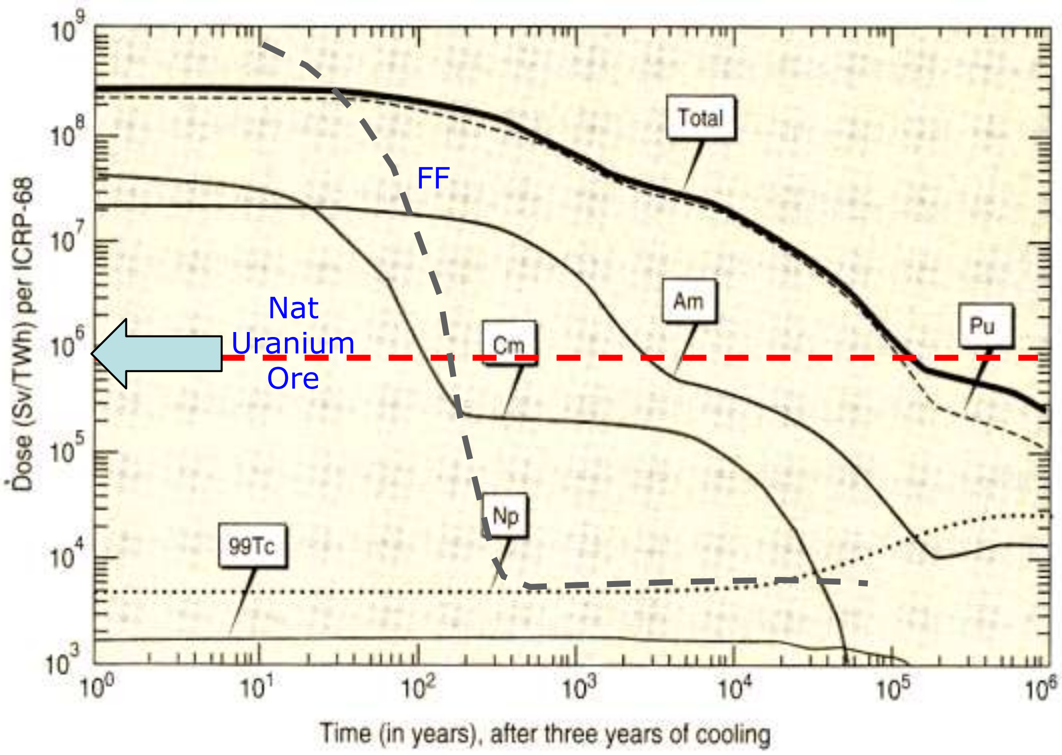


World Trend
>63 under constr
→2050:>600GW
US(>2012):+3-6
> 20 planned (?)
license app, financing risks

US potential:
1.Extend plant lifetime, uprate
2.*New* reactors/a (@ **$**(3-4)**B**/GW$_e$ → (5-10)¢/kWh)

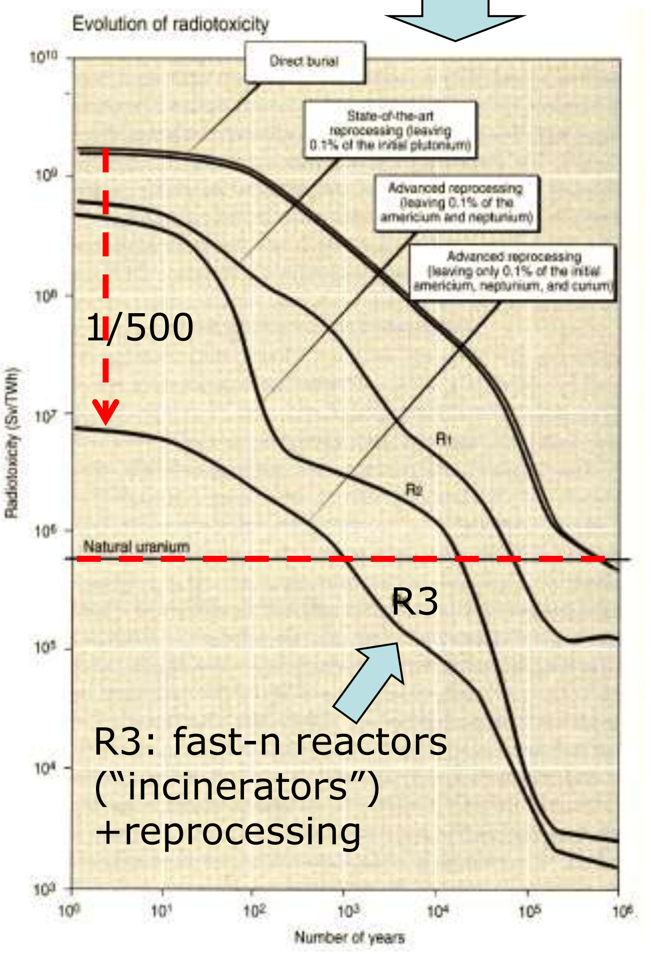
Several new companies → SMR
Na-cooled
Microreactors
Fusion Demos

Nuclear Power Strategic Issue Radioactive Waste



High-level waste depository for geological times → Yucca Mtns/NV ?

Radio-chemical reprocessing



R3: fast-n reactors (“incinerators”) +reprocessing

Very-long-lived ^{99}Tc, ^{129}I >could< dissolve in groundwater → disposal strategies for isolation.

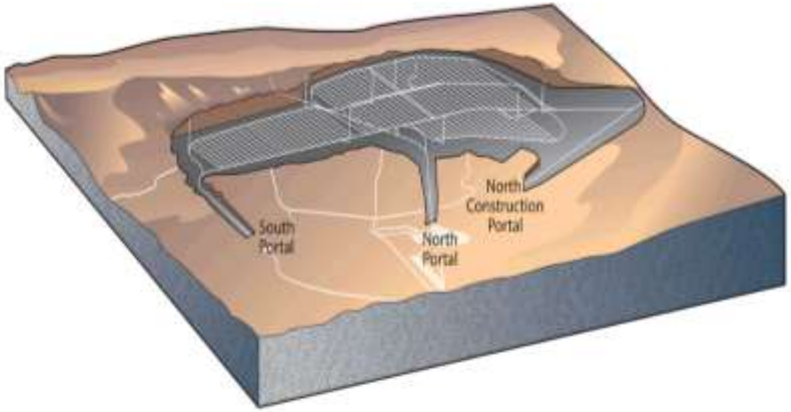
Reprocess @ n-source, fast reactors, transmutation/incineration of ^{99}Tc, ^{129}I, trans-actinides Np, Pu, Am, Cm (exothermic rxns)

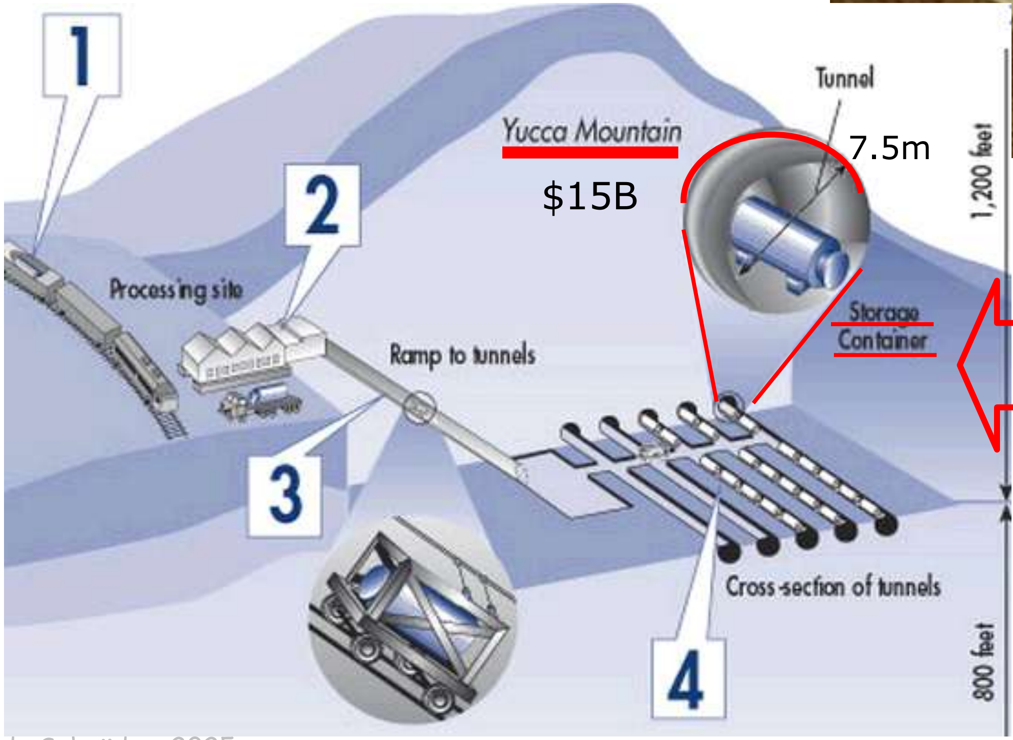
1 Sv (Sievert) = 100 rem, biolog. equivalent to 1J/kg X-rays

Radiotoxicity: R(Sv)=(Dose in Sv/decay), Activity/kg

Yucca Mountain (NV) Depository Project

Permanent storage of high-level waste already paid for by consumers ¢0.1/kWh.



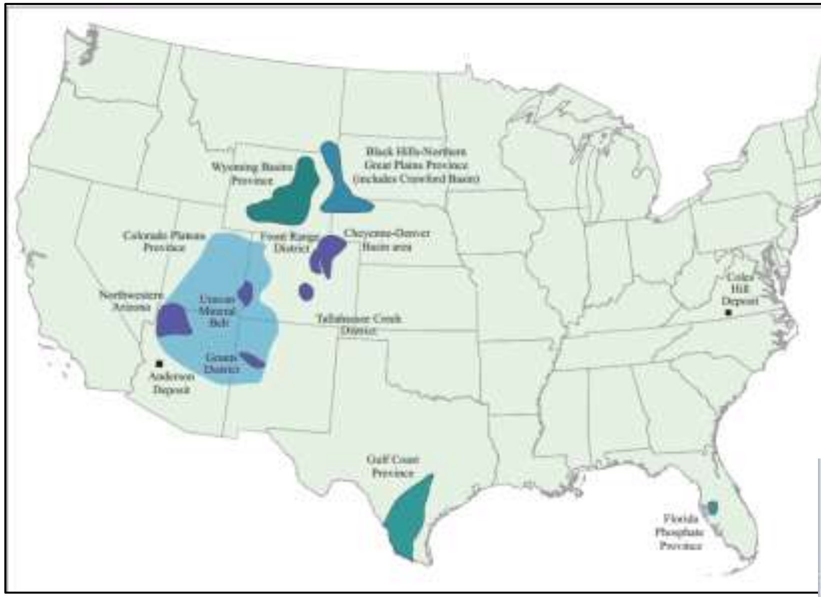


$15B

Spent-fuel sealed in dry casks, are shipped to the site by truck or train. Casks inner tubes with fuel elements are placed in a steel, multilayered storage containers. Automated system manages storage containers in underground tunnels. Containers stored on their side along the tunnels. Retrievable for later use (or not).

Geological depositories: US, Russia, China, Finland, Sweden

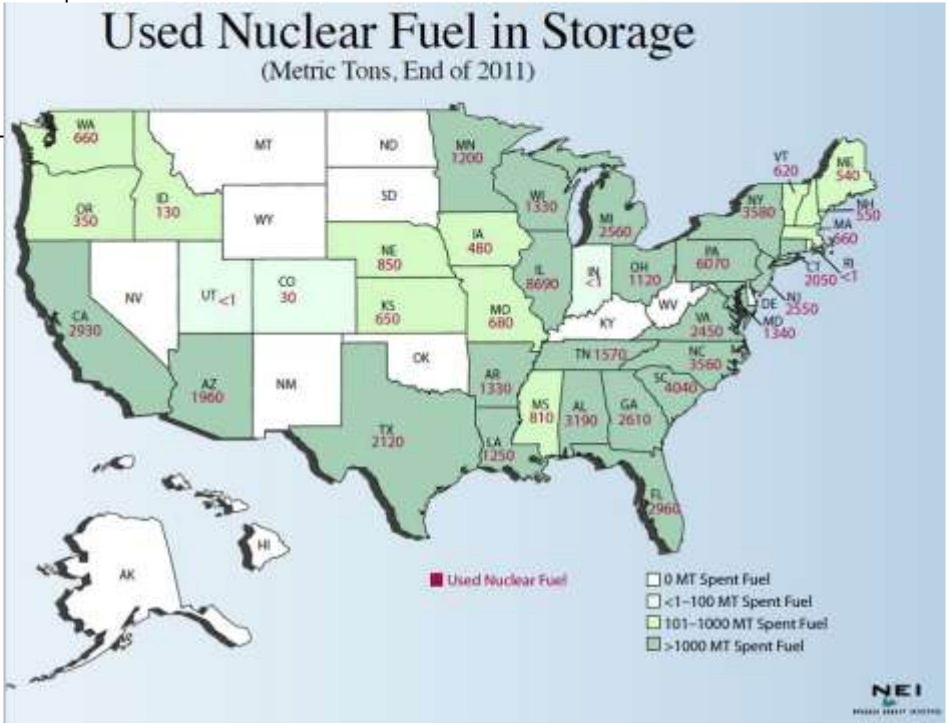
U.S. Uranium Resources/Used Fuel Elements



Used fuel elements in NP stations is U enriched in U-235. Used fuel elements: < 3 % U-235, > 95% U-238= fertile fuel for breeding.

Future small modular ppt, U, Th breeder reactors, Nuclear Magnetic Confinement fusion demos.

1GWe nuclear reactor requires yearly core load of (17.5-20) t low-enriched uranium U_3O_8 (3.5 - 5)% U-235, → 95% U-238


Used Nuclear Fuel in Storage

(Metric Tons, End of 2011)

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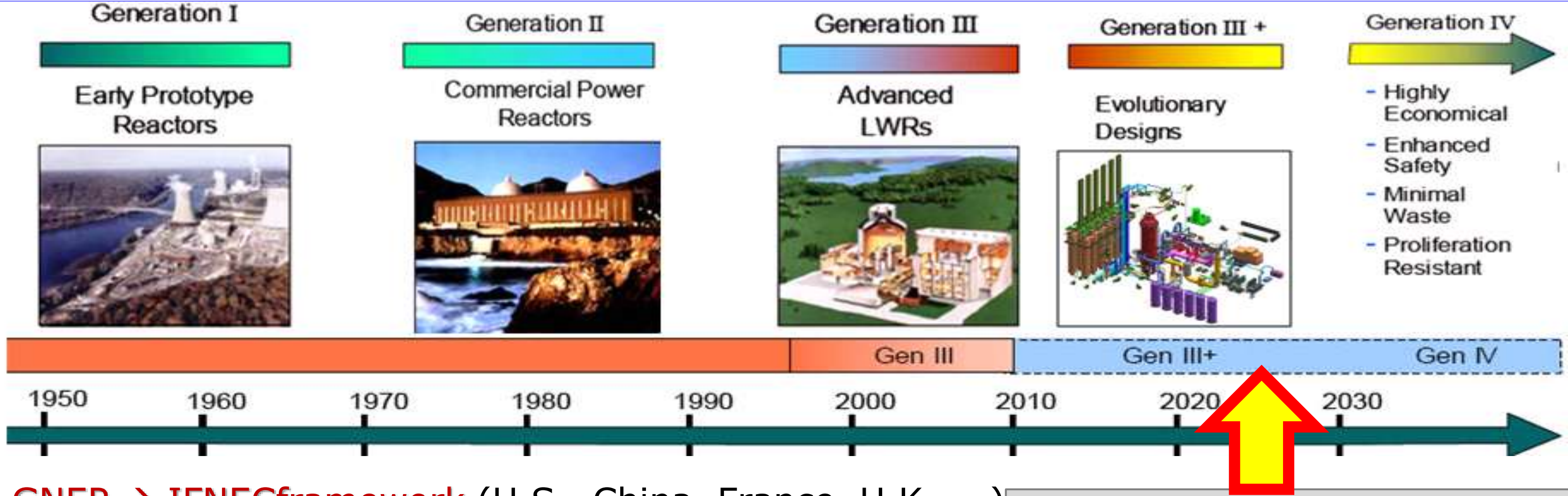
Timeline of Reactor/Fuel Cycle Development



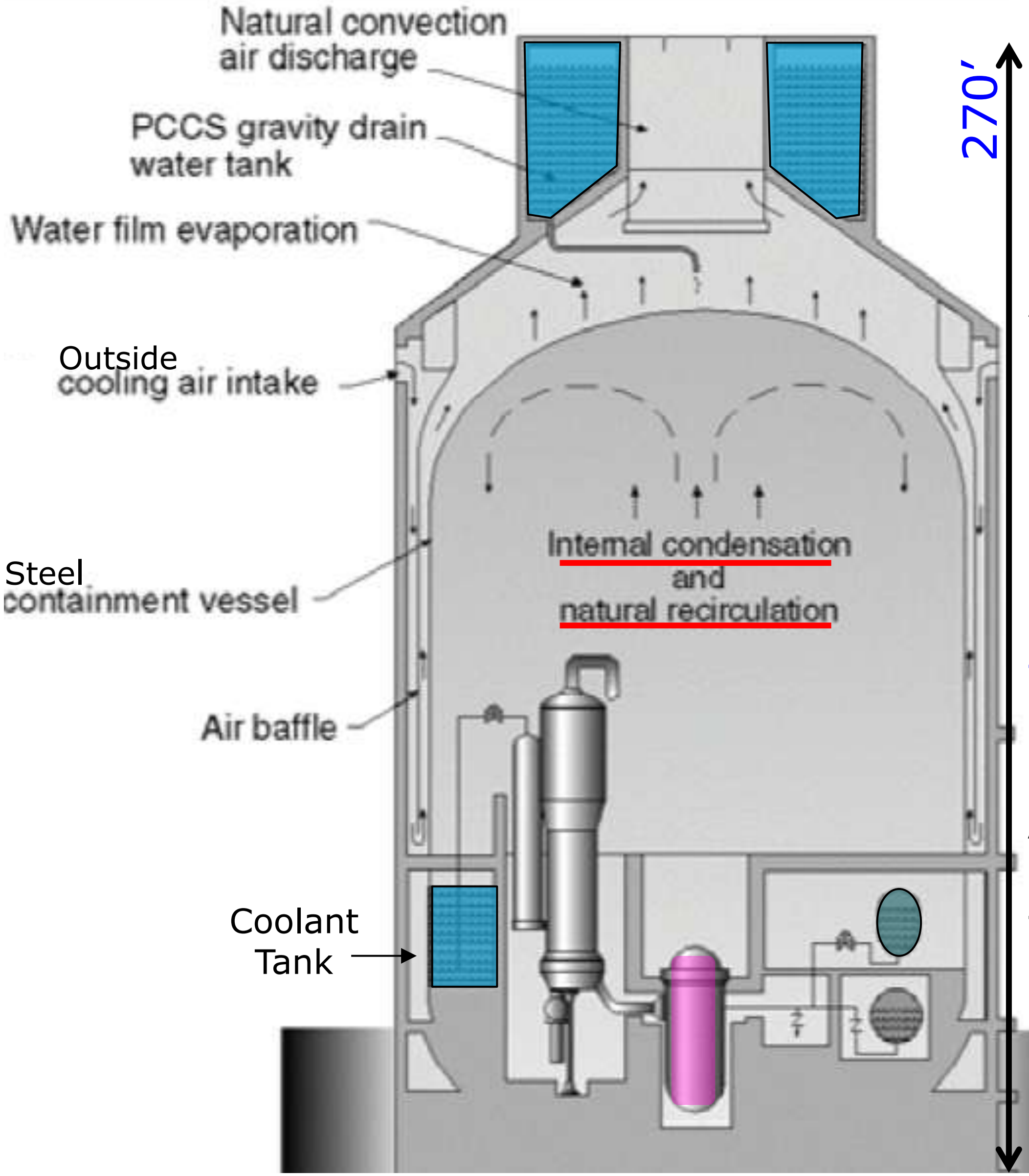
GNEP → IFNECframework (U.S., China, France, U.K., …)
→By 2030: Gen IV designs studied, modelled, tested:

- Simpler, enhanced-safety, prefabricated reactors
- Simple, small, super-safe modular reactors
- Sodium-cooled fast reactors (SFR)
- Gas-cooled fast (high-T) reactors (GFR, HTR)
- Lead-cooled fast breeder reactors (LFR)
- Molten-salt reactors (MSR, LIFTR) ← ORNL
- Accelerator Driven Subcritical (ADS) systems
- Cogeneration of district heat & electricity (EU)

- Operational reactor safety;
- Storage, sequestration of radiotoxic waste;
- Economy of nuclear plant construction, deployment, $$
- ^{235}U/Pu, Th fuel resources.
- Proliferation nuclear materials & technology;

•Russia: fast breeders BN-600/700 operating since 1980.
Also tested Gen IV: France, Japan, S-Korea, China, India.
Current ADS: Belgium "Myrrha"

Gen(III+) Passive Safety Features: Westinghouse AP1000



3,415 MW_{th}=1,110 MW_e,
2017: commissioned US\$7B
Modular prefab construction

Smart use of laws of physics:
Air-cooled! Natural convection cools large-surface shield & steel containment building.

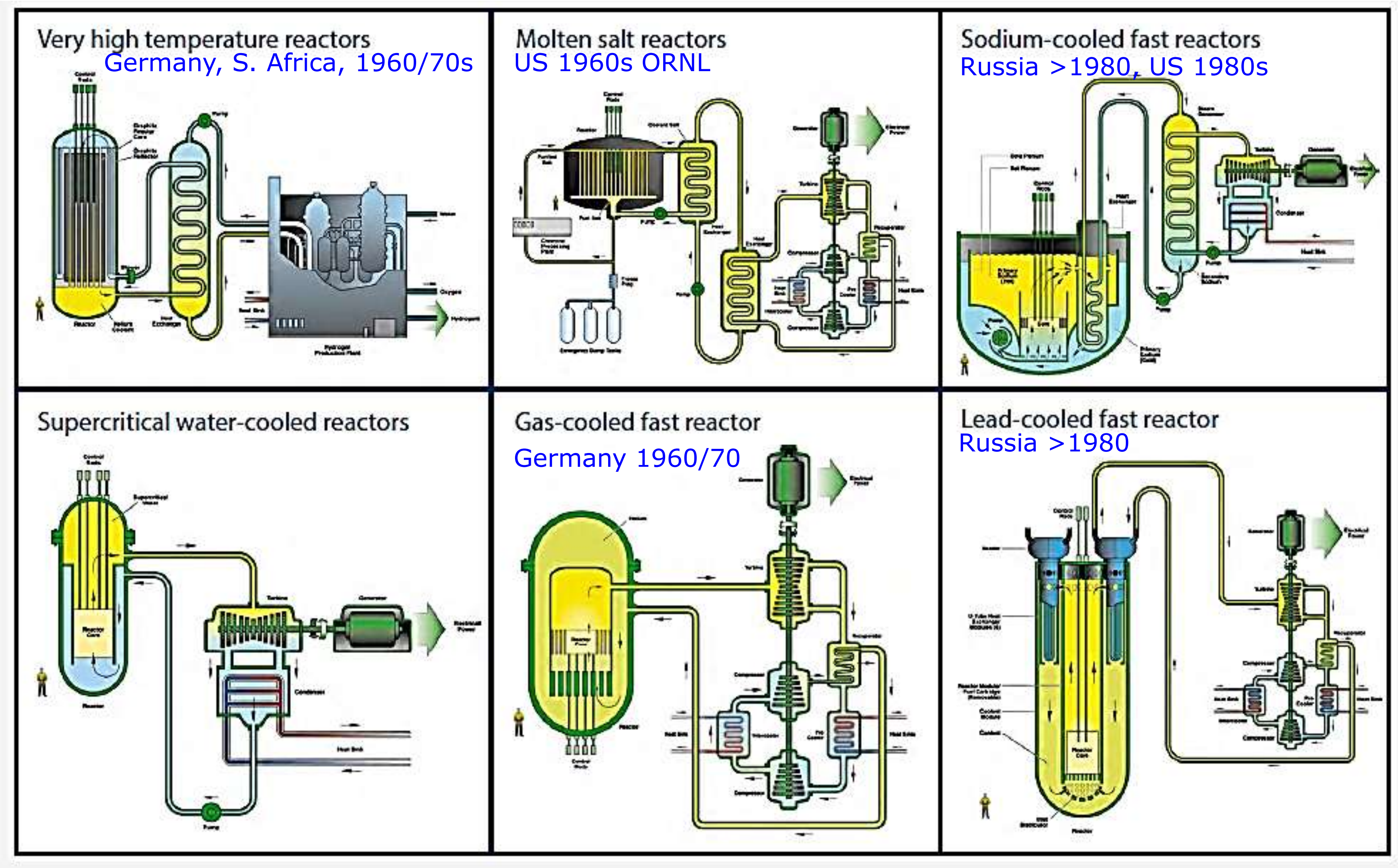
Damage-resistant pressure vessel contains all primary components

Core water cooling by gravity feed → no pumps, no major coolant loss in pipe breaks.

Ancillary water tanks on top can release water → cool containment for up to 3 days.

FOAK → Westinghouse default
China: 2 builds + take over development/license APC1000

Nuclear Reactor Types Gen IV Systems



Very high temperature reactors
Germany, S. Africa, 1960/70s

Molten salt reactors
US 1960s ORNL

Sodium-cooled fast reactors
Russia >1980, US 1980s

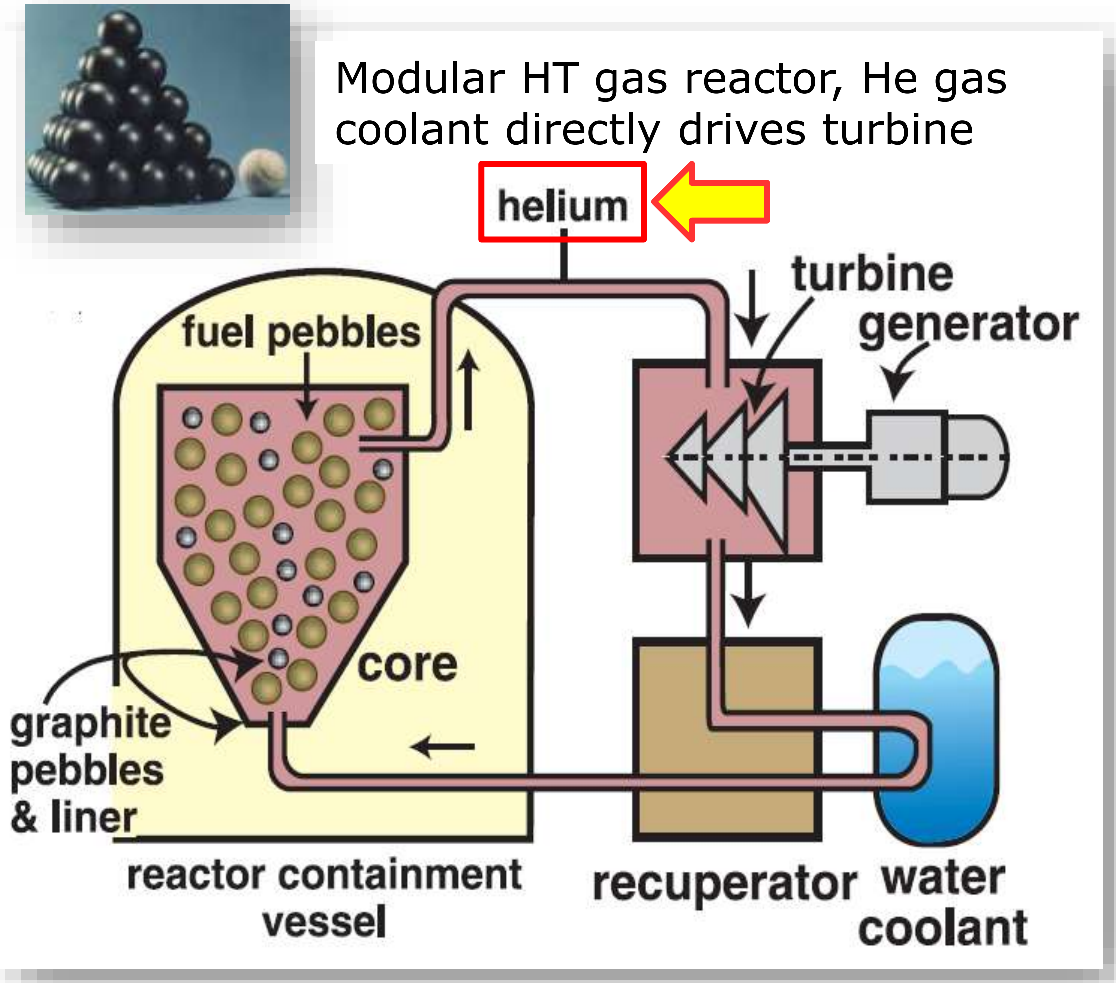
Supercritical water-cooled reactors

Gas-cooled fast reactor
Germany 1960/70

Lead-cooled fast reactor
Russia >1980

Advanced Reactors: Pebble-Bed HTGR

1960/70s Germany, S-Africa, China: Modular (@250MW) → U+Th Mox
Uses Tri-structural-Isotropic (**TRISO**) fuel particles.



Modular HT gas reactor, He gas coolant directly drives turbine

Coolant He (inert gas)
T ~ 950^0C
C-moderator/reflector

Continuous throughput sorting & replacement of "pebble" fuel elements

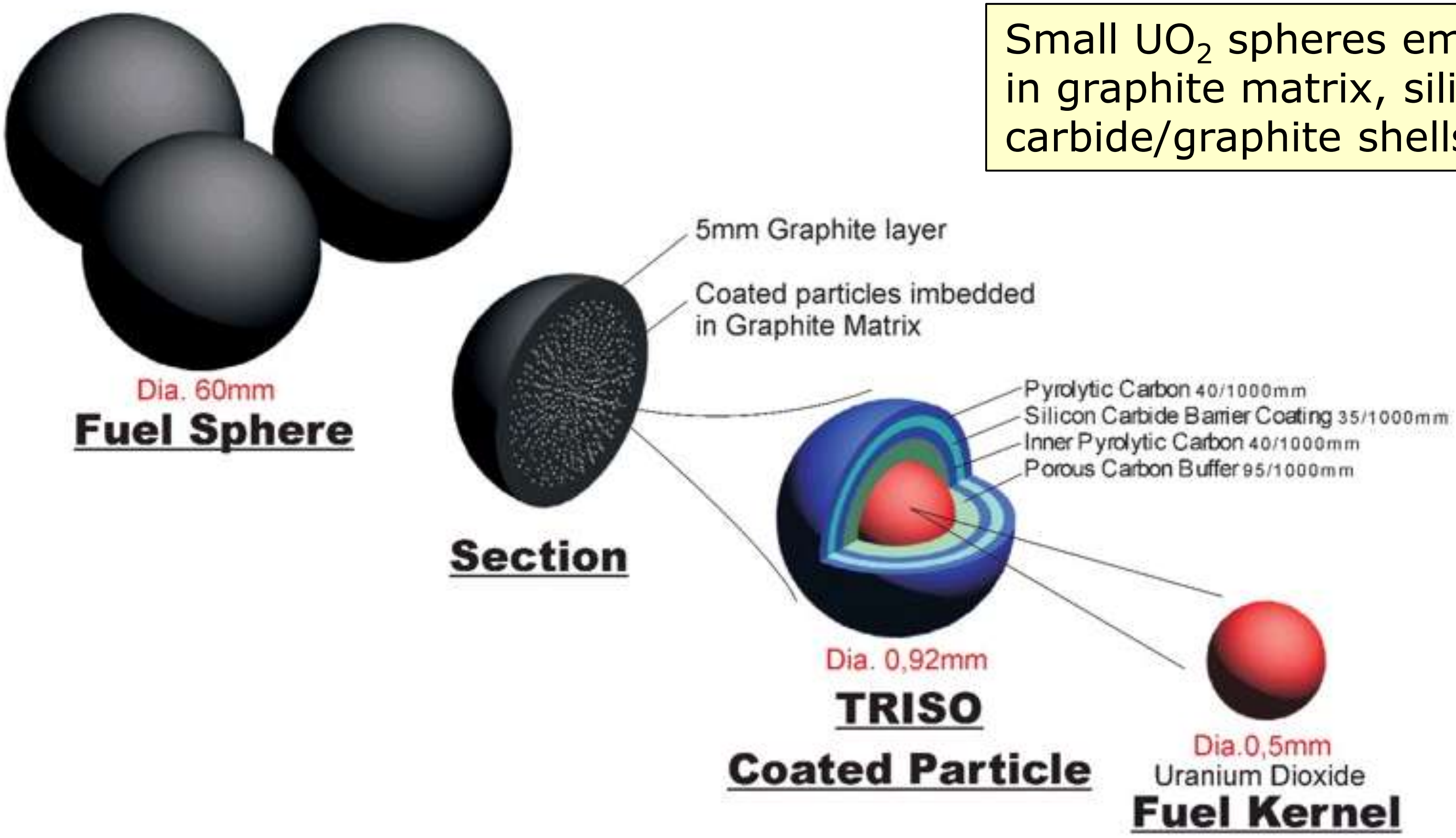
→Strongly negative reactivity

Core has high surface/volume ratio, low power density.

→Fail-safe operation.

Modular Pebble Bed Reactor TRISO Fuel Pebbles

Small UO_2 spheres embedded in graphite matrix, silicon carbide/graphite shells

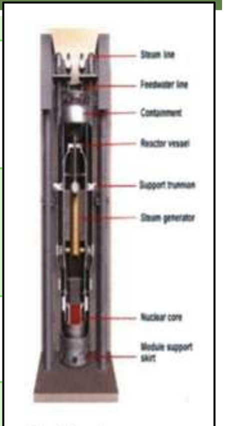


Proliferation resistant → difficult reprocessing, requires national facilities.

Extended test operations (D) terminated for non-technical reasons.

Small (Modular) Nuclear Reactors

Rank	SMR (design / plant)	Country	Nominal electrical power	Technology (type)
1	HTR-PM (Shidao Bay)	China	210 MWe	HTGR, pebble-bed
2	ACP100 'Linglong One' (Changjiang)	China	125 MWe	Integral PWR (LWR)
✸ 3	BWRX-300 (Darlington SMR)	Canada	300 MWe	BWR (LWR)
4	RITM-200N (Ust-Kuyga land-based SMR)	Russia	55 MWe	Integral PWR (water-cooled)
✸ 5	KLT-40S (Akademik Lomonosov, floating)	Russia	70 MWe (2×35)	PWR (marine)
6	BREST-OD-300 (Seversk)	Russia	300 MWe	Lead-cooled fast reactor (LFR)
7	Natrium (Kemmerer Unit 1)	USA	345 MWe (up to 500 MWe w/ storage boost)	Sodium fast reactor (SFR) + molten-salt energy storage
8	Xe-100 (Dow/X-energy, Seadrift TX)	USA	80 MWe (per module)	HTGR, pebble-bed
9	NuScale VOYGR / US460	USA	77 MWe per module (6×77 = 462 MWe)	Integral PWR (LWR)
10	Kairos Power HERMES (test reactor)	USA	0 MWe (35 MWth demo)	FHR (fluoride-salt-cooled, TRISO pebbles)



NuScale

Small Modular NPPT (RF 2019) w. Cogeneration


Akademik Lomonosov has now been fully commissioning (Image: Rosenergoatom)

Two 35-MW reactors KLT-40C,

Outputs:
el. power=70 MW

Heat 50 Gcal/h (210 GJ/h)

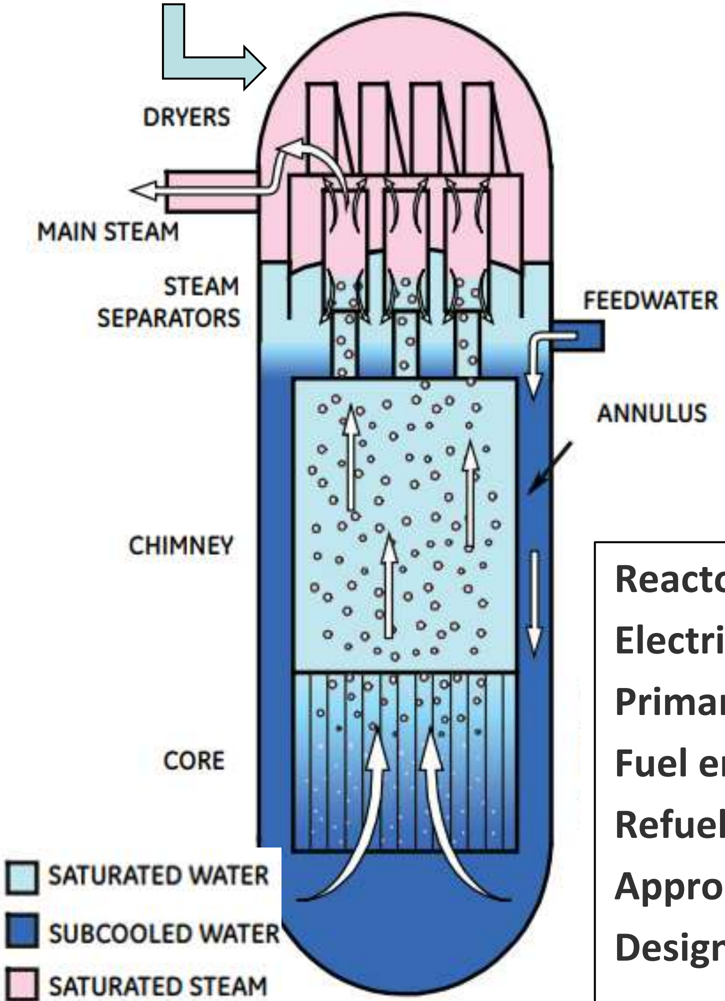
The floating nuclear power plant (FNPP Rosenergoatom) Akademik Lomonosov has been fully commissioned in the town of Pevek (Chukotka region of Russia's Far East). Subsidiary of the state nuclear corporation Rosatom. (WNN 5/22/2020)

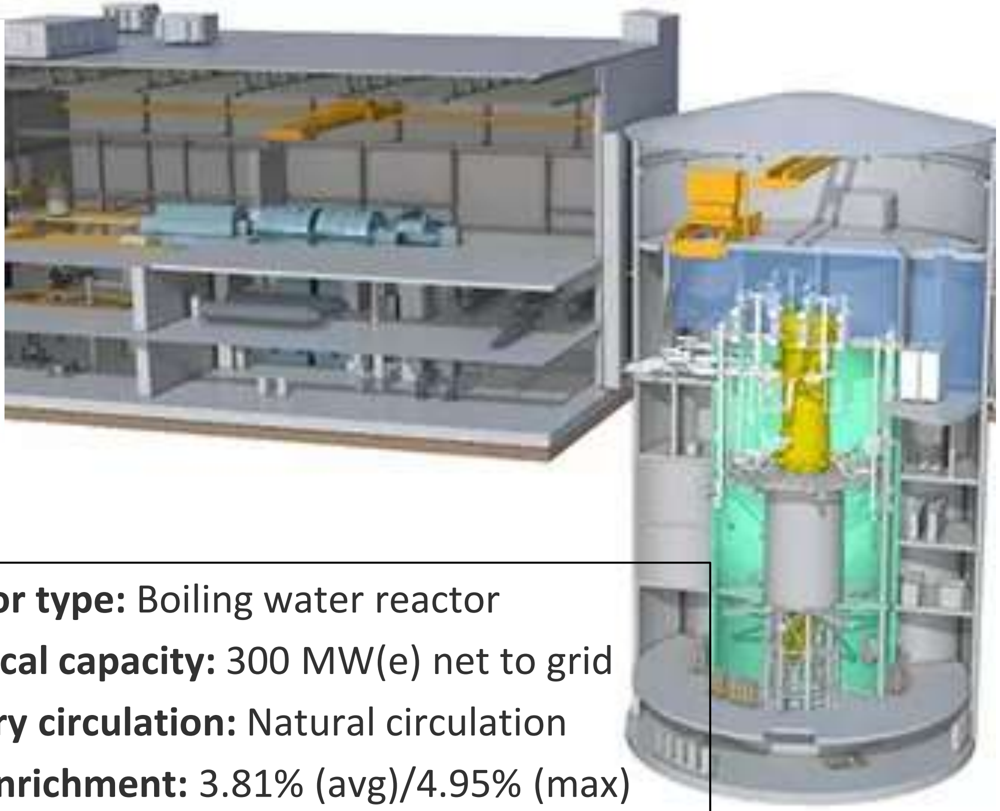
Russian arctic icebreakers are all nuclear powered. US naval fleet: submarines, aircraft carriers

GE-Hitachi Small Modular Type BWRX-300

Under construction in Canada (Ontario), planned by Tennessee Valley Authority

Natural coolant circulation.





Reactor type: Boiling water reactor

Electrical capacity: 300 MW(e) net to grid

Primary circulation: Natural circulation

Fuel enrichment: 3.81% (avg)/4.95% (max)

Refueling cycle: 12-24 months

Approach to safety systems: Fully passive

Design life: 60 years

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  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)

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  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

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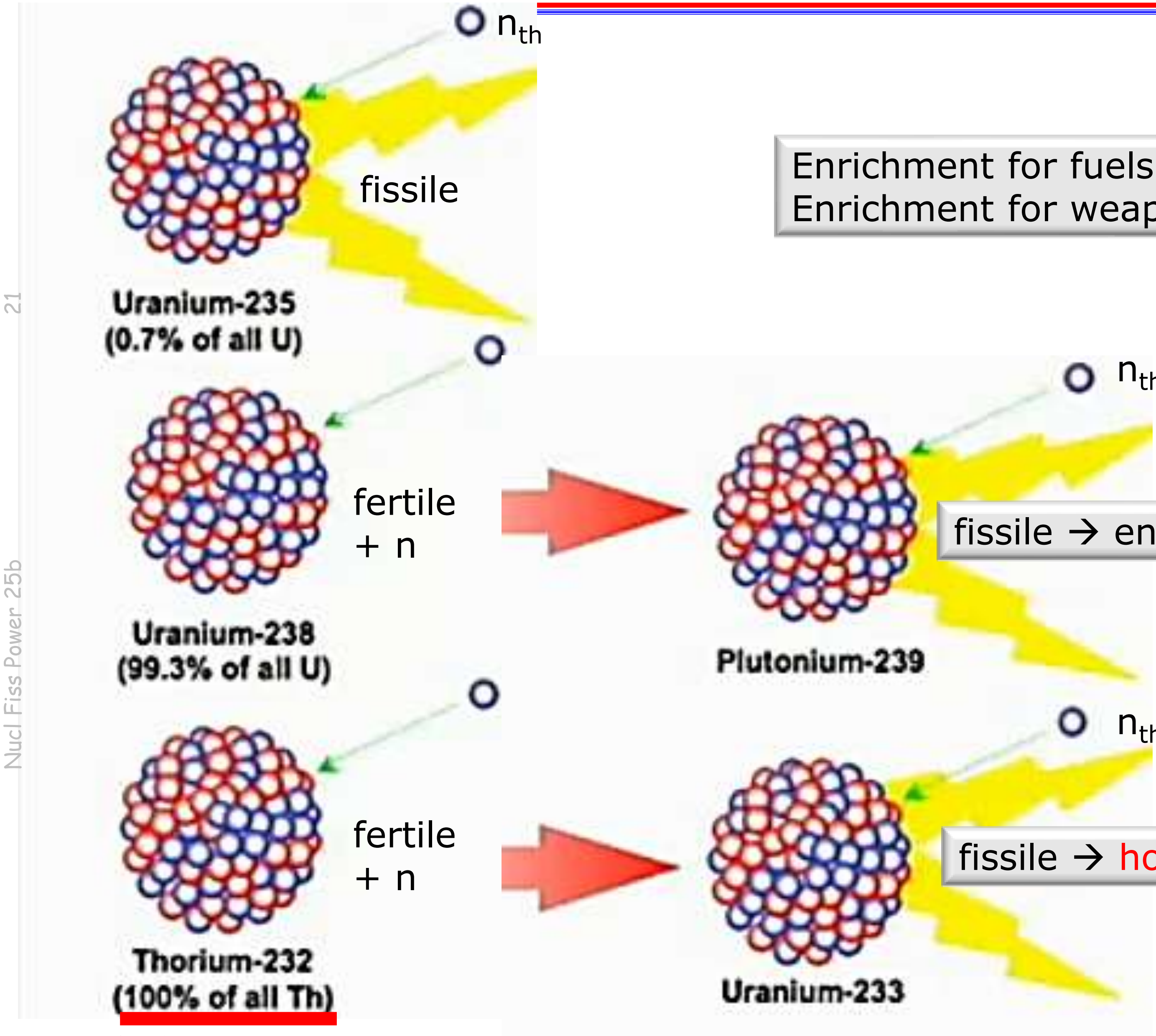
Reading Assignments

A&J; Ch. 9-10
LN 4.3

Fissile and Fertile Nuclear Fuels



Enrichment for fuels → 3-4 % fissile
Enrichment for weapons → >90 % fissile

fissile → enrichment→ weapons

fissile → hot enrichm.→weapons

U and Th Nuclear Fuel Resources

World (US, 2023)
440 (92) reactors
400 (100) GW

U use: 2 kt/a
World reserves: 5 Mt known (15 est.)
Once-through cycle:200 years

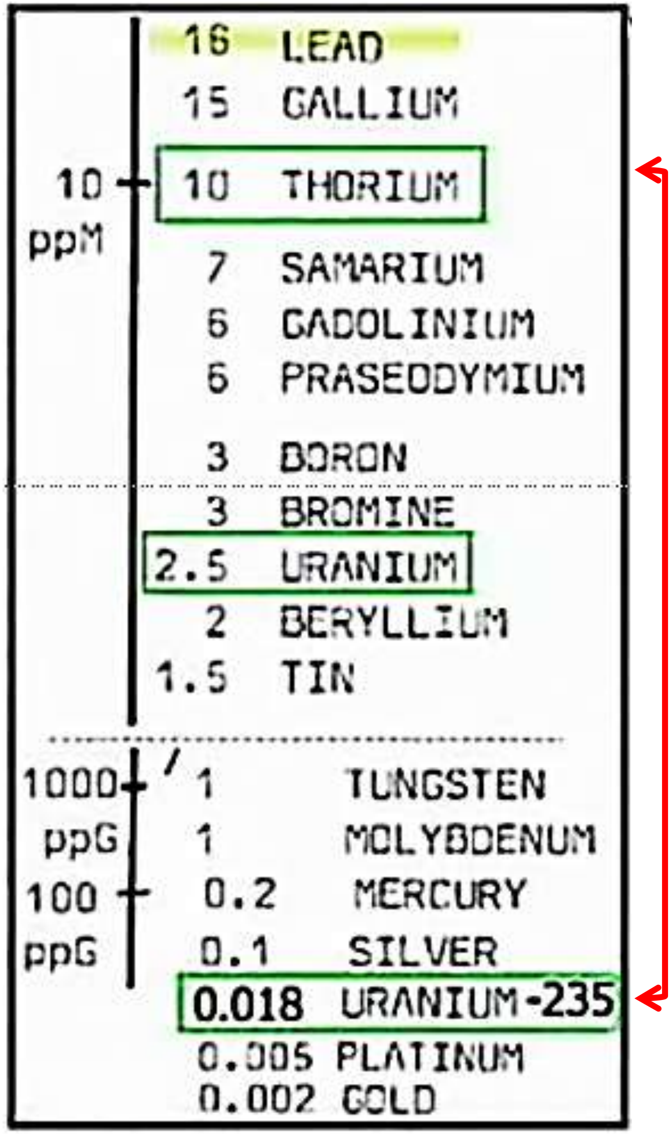
Reprocessing: ~10^3 years
US:174 t weapons grade U +20t/a Pu for fuel mix (→ 0.2 Mt fuel)

Th use: low (India ramping up)
World reserves >15 Mt ~10^3 a with reprocessing.

→ essentially sustainable energy source

Gen IV breeder (^{238}U, ^{232}Th) reactors, molten salt reactors

Reserves in Earth Crust



	16	LEAD
	15	GALLIUM
10 ppM	10	THORIUM
	7	SAMARIUM
	6	GADOLINIUM
	6	PRASEODYMIUM
	3	BORON
	3	BROMINE
	2.5	URANIUM
	2	BERYLLIUM
	1.5	TIN
1000 ppG	1	TUNGSTEN
	1	MOLYBDENUM
100 ppG	0.2	MERCURY
	0.1	SILVER
	0.018	URANIUM-235
	0.005	PLATINUM
	0.002	GOLD

Fuel Breeding ^{239}Pu/^{233}U Breeding

Technologically understood, several working research/test reactors

Fast (neutron spectrum) U reactor: *n*-capture without fission

Additional n capture

$+n\uparrow \qquad\qquad +n\uparrow$

U – Pu Cycle

$$^{238}U + n \rightarrow {}^{239}_{92}U \xrightarrow[t_{1/2}=23\,min]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.4d]{\beta^-} {}^{239}_{94}Pu\left(2.4\cdot 10^4\,a\right)$$

Continued n capture/β decay

$$\begin{array}{r} {}^{239}_{94}Pu + n \rightarrow {}^{240}_{94}Pu \,\Big|\, {}^{240}_{94}Pu + n \rightarrow {}^{241}_{94}Pu \\ \Downarrow \\ {}^{241}_{95}Am \end{array}$$

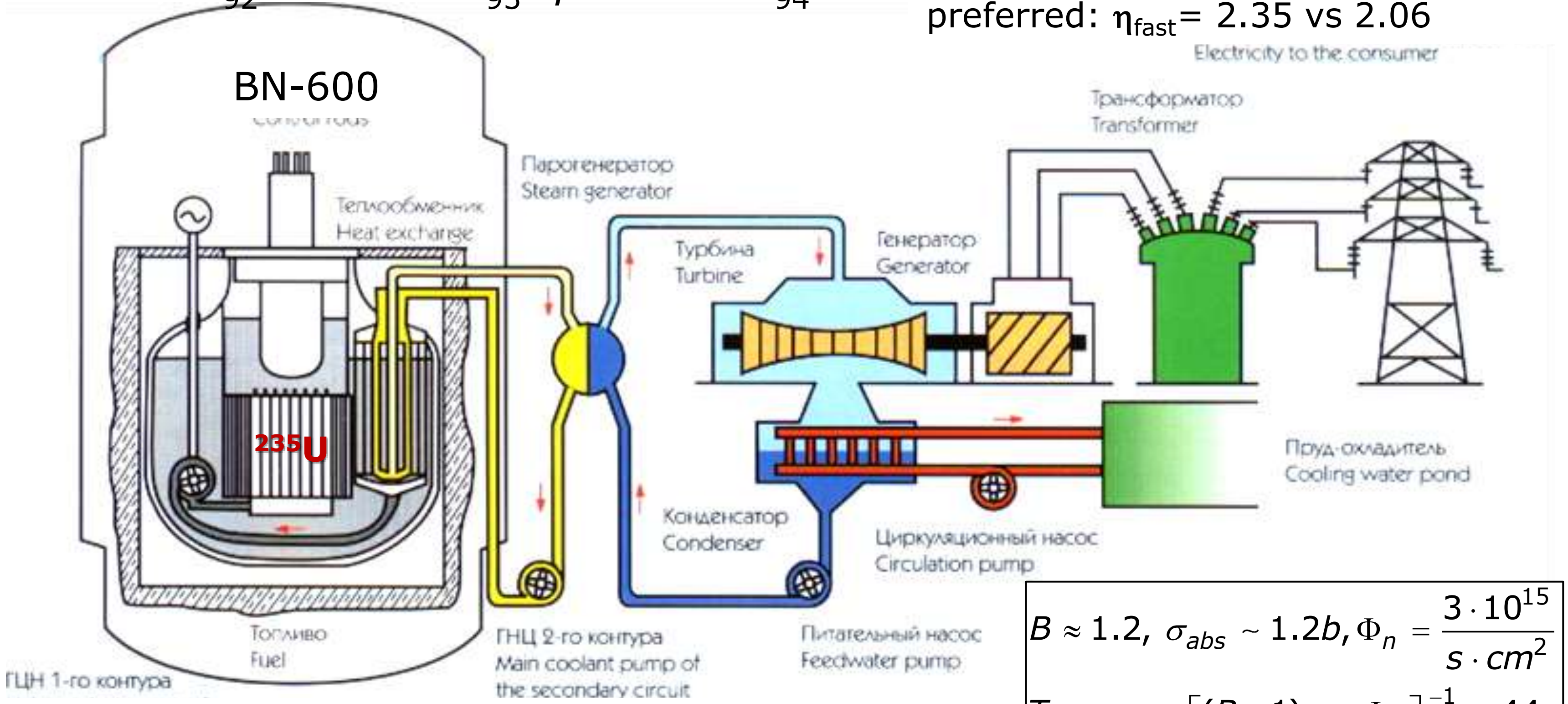
Isotope mix: Not useful for nuclear fuel/weapons → extensive isotope separation

Need many neutrons: source is unimportant !
Could use nuclear spent fuel waste (=incineration) or heavy materials like Pb, Bi,…. as spallation targets/neutron source)

Metal-Cooled Fast Breeder Reactor (1981-...)

$$^{238}U + n \rightarrow {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu$$

Fast (E_n>0.5 MeV) neutrons preferred: η_{fast}= 2.35 vs 2.06



$$B \approx 1.2,\ \sigma_{abs} \sim 1.2b, \Phi_n = \frac{3\cdot 10^{15}}{s\cdot cm^2}$$

$$T_{doubling} = \left[(B-1)\sigma_{abs}\Phi_n\right]^{-1} \approx 44a$$

Doubling time depends on flux Φ_n, σ_{abs} , geometry.

Core: 45.5% ^{235}U; **Blanket**: 20 t nat UO_2
cooling/mod.: liquid ***Na***, ***K***, magnetic pumps.

Na-23: little moderation, good heat transfer
T_{melt}=98^{0}C, T_{boil} = 883^{0}C
Na-23+n → Na-24 is β-active ($t_{1/2}$= 15 h) !

Studies/tests for Gen IV: modern alternatives to liquid-Na, e.g., Pb/Bi alloys

^{232}Th/^{233}U Fuel Breeding

Technologically understood, several working research/test reactors

Fast=un-moderated (neutron spectrum) U reactor:

→ *n*-capture without spontaneous fission

Isotope mix: Not useful for nuclear fuel/weapons → extensive isotope separation

Additional n capture

$$^{234}_{91}Pa \xrightarrow[6h]{\beta^-} {}^{234}_{92}U\left(2.5\cdot 10^5 a\right)$$

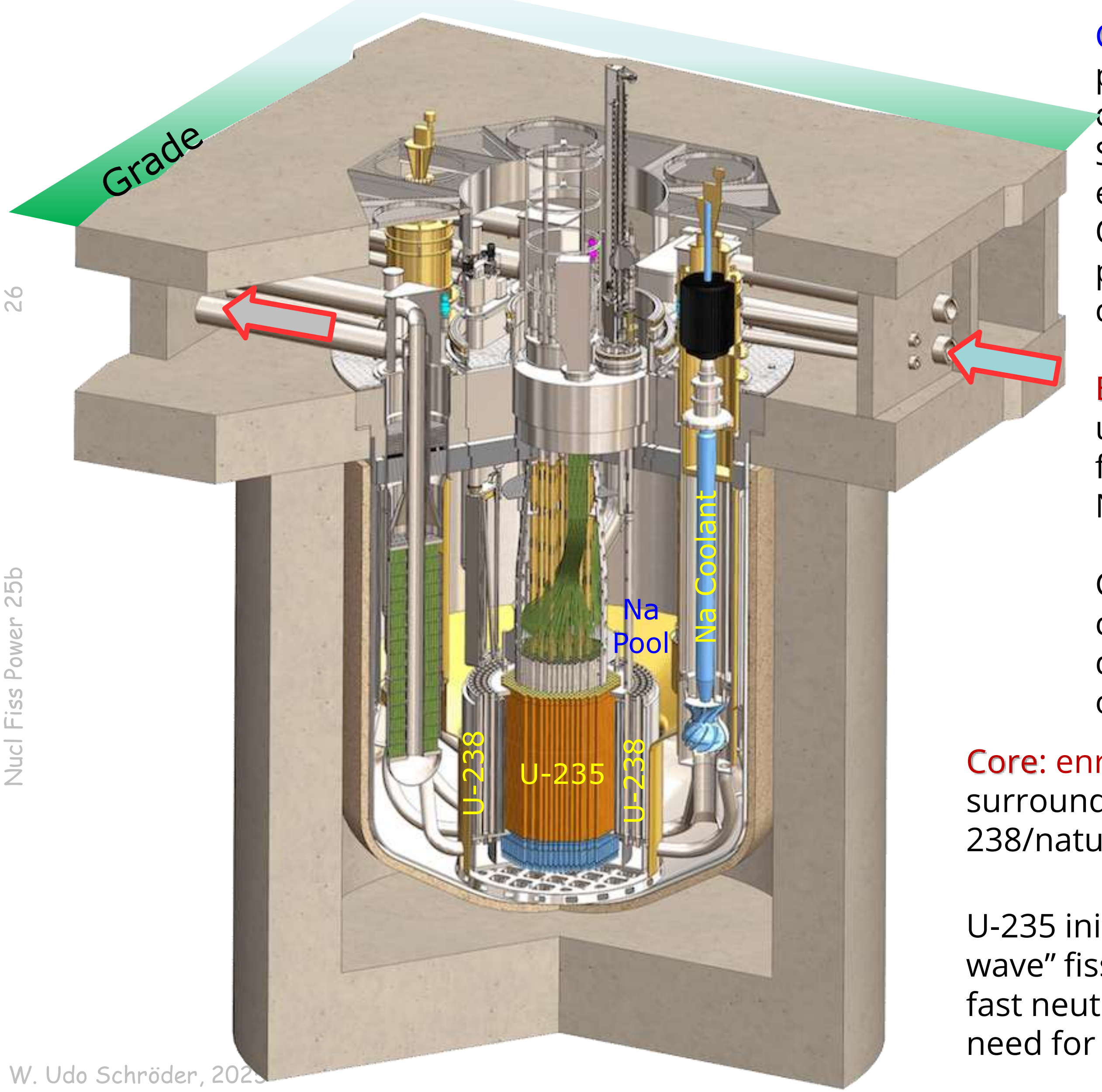
$$+n\uparrow \qquad\qquad +n\uparrow$$

Th – U Cycle

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow[t_{1/2}=22\,\mathrm{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27d]{\beta^-} {}^{233}_{92}U\left(1.6\cdot 10^5 a\right)$$

India builds Th reactor fleet → large Th resources, small waste problem. (Mumbay test reactor). Also France, Russia

TerraPower Traveling-Wave Fast-Neutron U Breeder



Coolant: liquid sodium primary pool surrounding core. Natural circulation. Secondary Na loop heat exchanger.
Operates at atmospheric pressure. Gravity activated control rods.

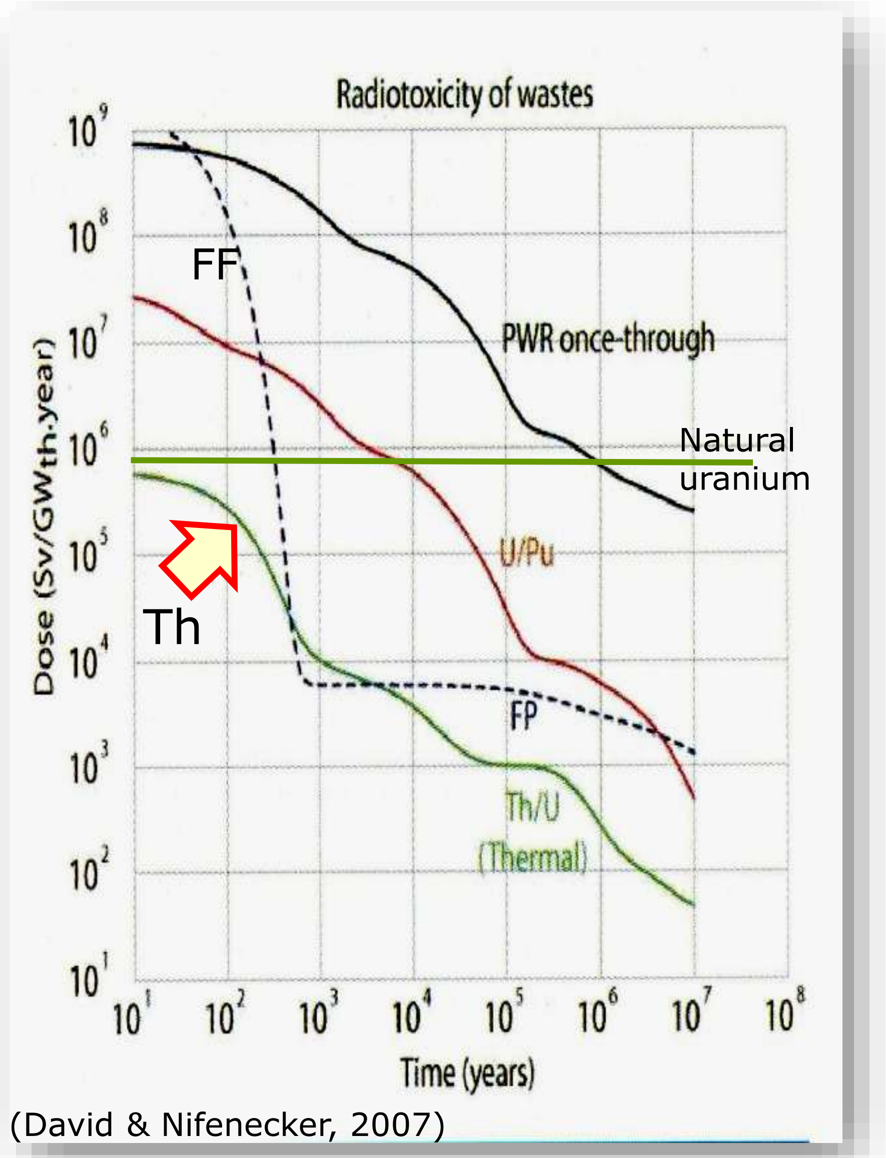
Blanket: depleted or natural uranium → gradually breed fissionable material in situ = Non-proliferation attribute.

Generates heat by Rankine cycle and electricity over decades of continuous operation.

Core: enriched uranium U-235 rods surrounded by blanket of depleted U-238/natural uranium rods.

U-235 initiates a slow-moving “traveling wave” fission chain reaction delivering fast neutrons for U→Pu breeding. No need for reprocessing.

Radiotoxicity of Spent Nuclear Fuel: Th vs. U



(David & Nifenecker, 2007)

Radio toxicity vs. time after shutdown, of spent fuel from

•pressurized water uranium reactor (PWR),

- U/Pu breeder, and
- Th/U fuel cycle.

FP fast decay of fission products.

Multiple reprocessing, less residual waste.

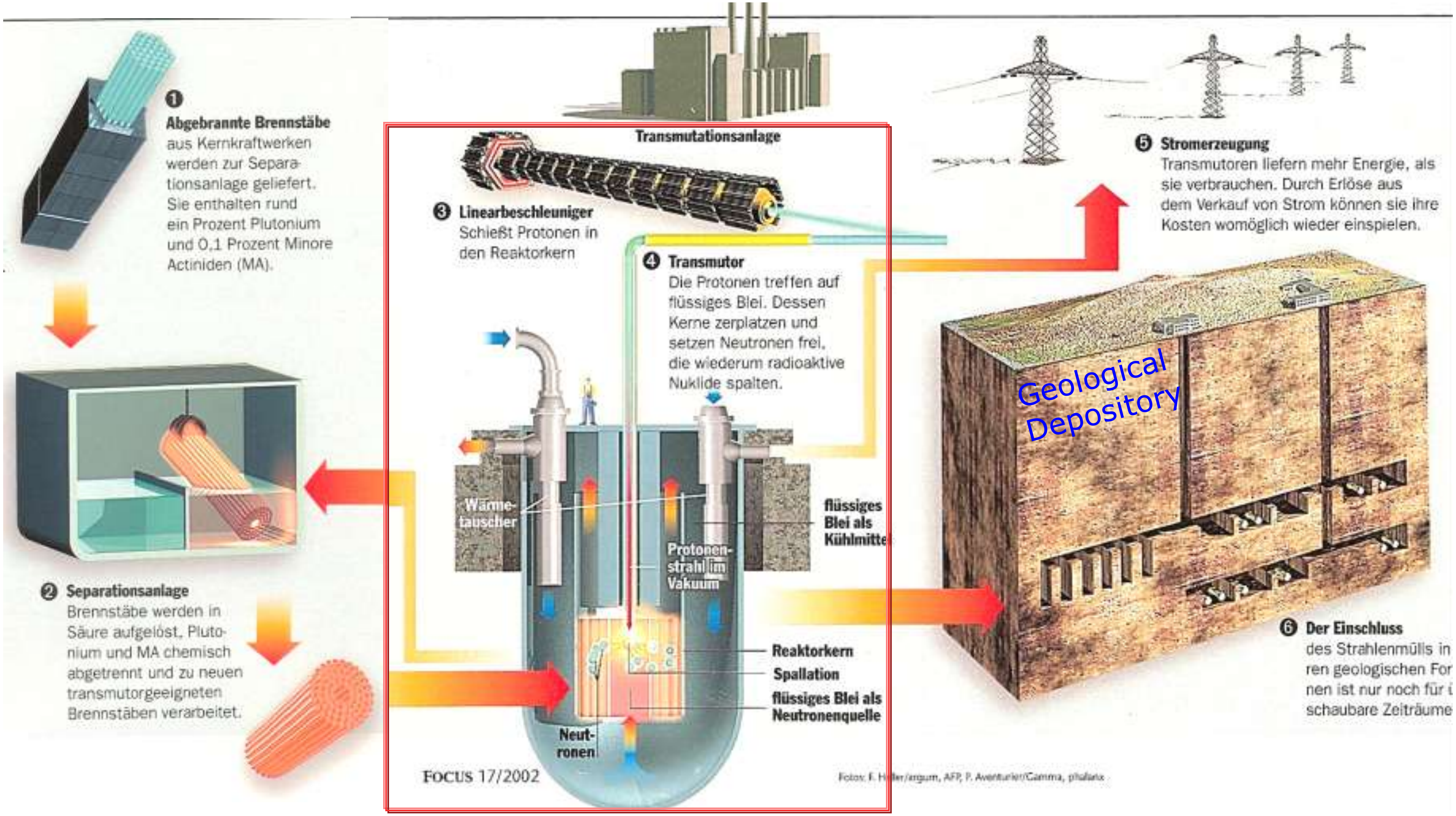
Transmute/incinerate transactinides and FF solves waste issue

Store small amounts of HL waste for ~100 years (use for decay-α's ?) Needs small geological depository.

Subcritical Accelerator Driven

Transmutation/Breeding in **ADS**

Spallation: n multiplication → incineration of waste generates E
Advanced (ADS) reactor development under GNEP program



① **Abgebrannte Brennstäbe** aus Kernkraftwerken werden zur Separationsanlage geliefert. Sie enthalten rund ein Prozent Plutonium und 0,1 Prozent Minore Actiniden (MA).

② **Separationsanlage** Brennstäbe werden in Säure aufgelöst, Plutonium und MA chemisch abgetrennt und zu neuen transmutorgeeigneten Brennstäben verarbeitet.

③ **Linearbeschleuniger** Schießt Protonen in den Reaktorkern

④ **Transmutor** Die Protonen treffen auf flüssiges Blei. Dessen Kerne zerplatzen und setzen Neutronen frei, die wiederum radioaktive Nuklide spalten.

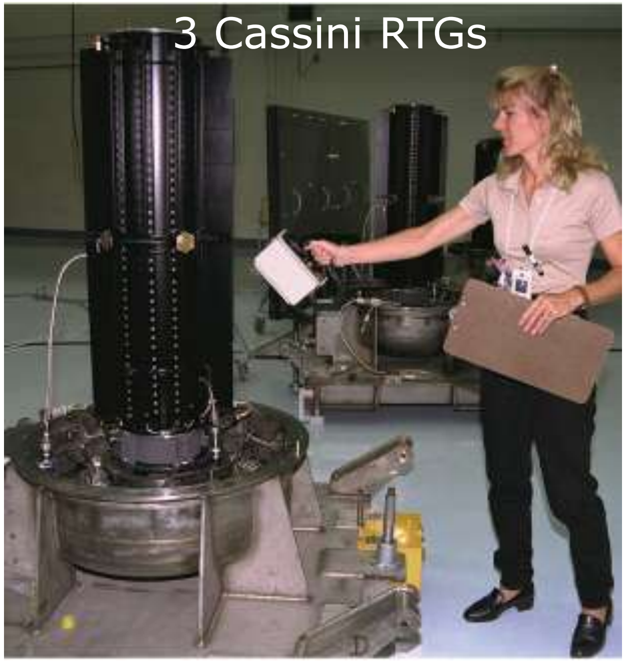
⑤ **Stromerzeugung** Transmutoren liefern mehr Energie, als sie verbrauchen. Durch Erlöse aus dem Verkauf von Strom können sie ihre Kosten womöglich wieder einspielen.

⑥ **Der Einschluss** des Strahlenmülls in
ren geologischen For
nen ist nur noch für i
schaubare Zeiträume

FOCUS 17/2002

Fotos: F. Heller/argum, AFP, P. Aventurier/Gamma, phalanx

Radioisotope Thermoelectric Generators



Pu-238 ($t_{1/2} = 87.7a$) RTG in many NASA space applications, also for remote terrestrial instrumentation (Arctic scientific or military outposts).

Heat → Thermocouple → Electricity

General Purpose Heat Source

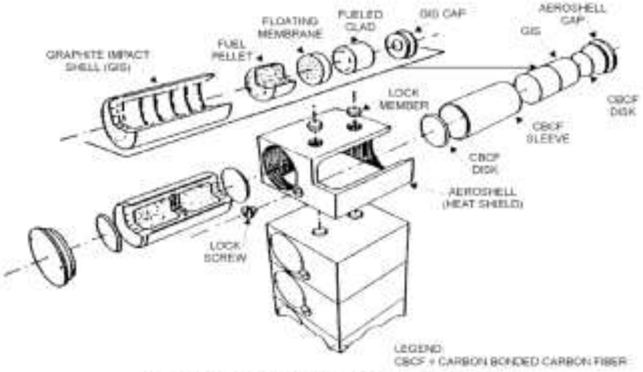
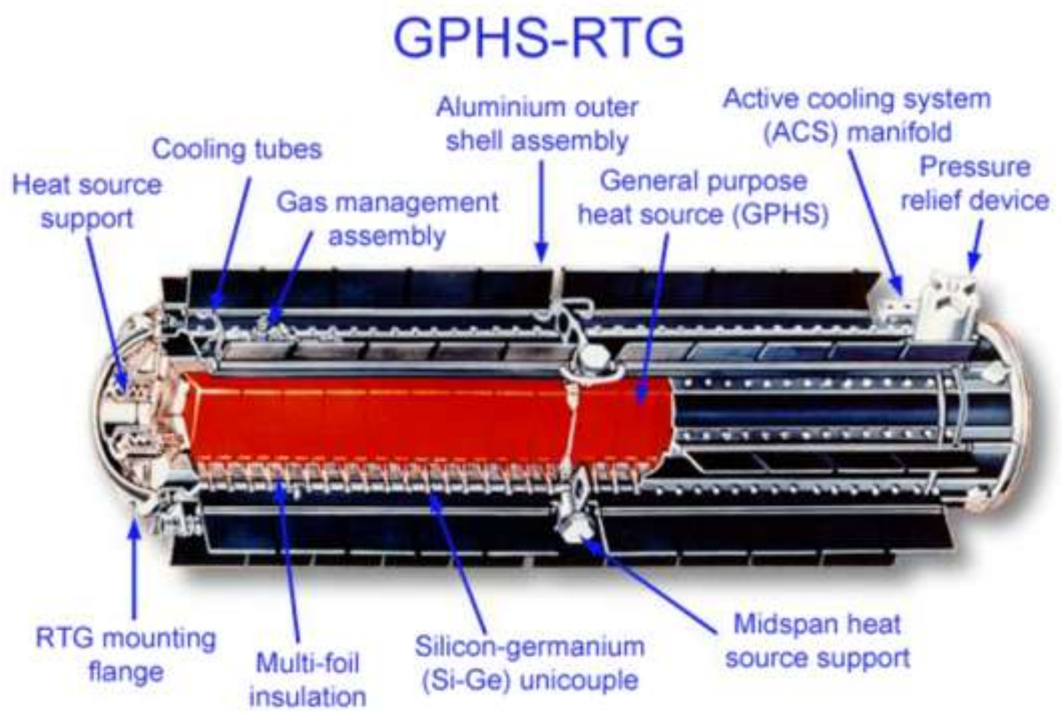


FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE



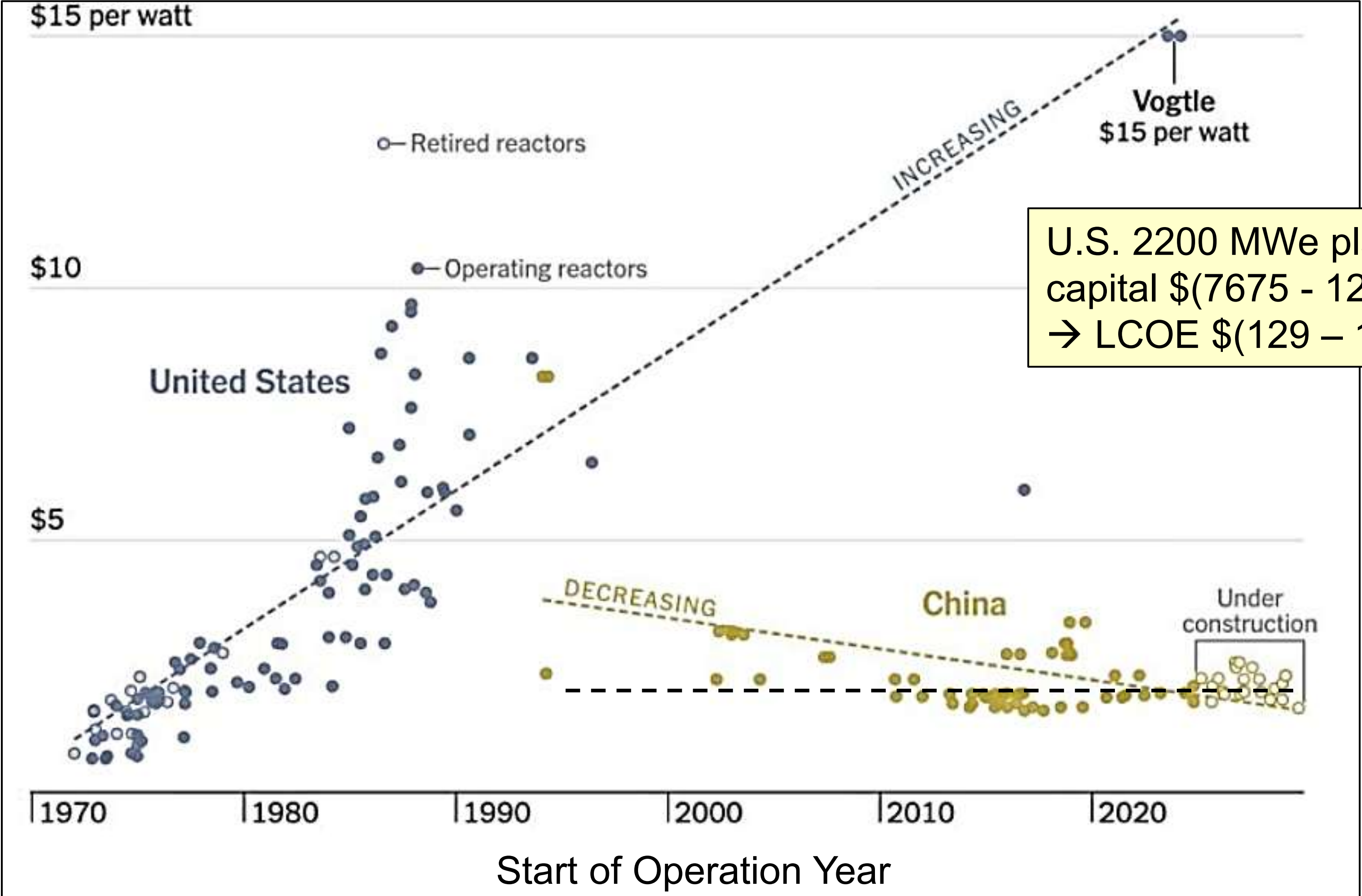
NASA Space Probe

A NASA Pu-238 Radioisotope Thermoelectric Generator has been in use to power space probes for many decades.

Efficient combination with Stirling engine.

Voyager I and II, Cassini probe.

Nuclear Fission Reactors: Construction Cost

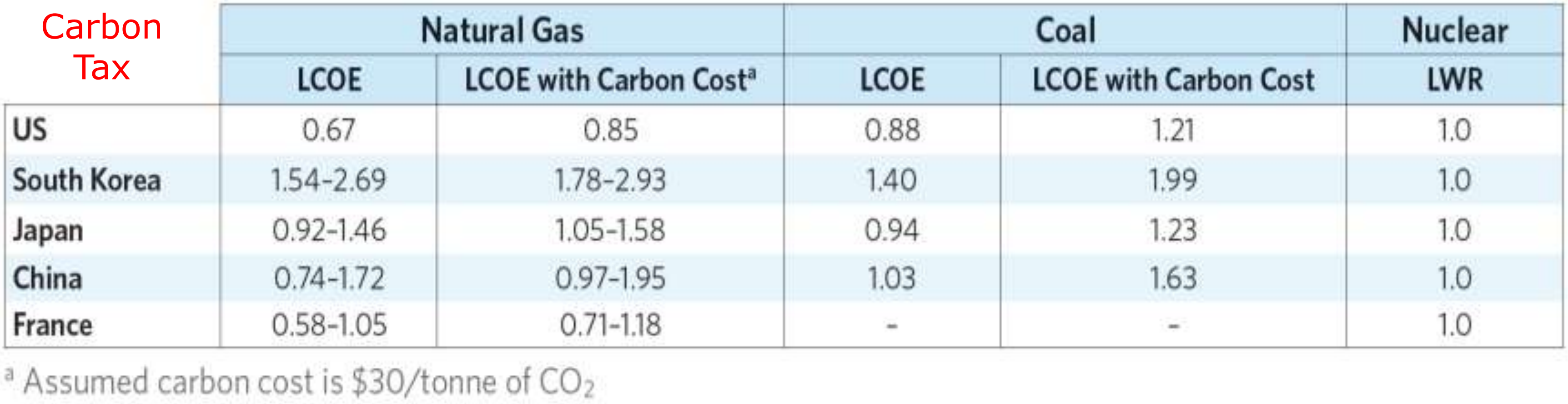


U.S. 2200 MWe plant:
capital $(7675 - 12,500)/kW
→ LCOE $(129 – 198)/MWh.

Note: Reactors are placed according to the date they entered or are expected to enter commercial operation. Chart shows inflation-adjusted overnight costs, which exclude interest payments. Trend lines show linear regression slope. · Source: Liu et al. 2025

LCOE Nuclear vs. Fossil-Fuel Power in US/EU

Carbon Tax



	Natural Gas		Coal		Nuclear
	LCOE	LCOE with Carbon Cost[a]	LCOE	LCOE with Carbon Cost	LWR
US	0.67	0.85	0.88	1.21	1.0
South Korea	1.54-2.69	1.78-2.93	1.40	1.99	1.0
Japan	0.92-1.46	1.05-1.58	0.94	1.23	1.0
China	0.74-1.72	0.97-1.95	1.03	1.63	1.0
France	0.58-1.05	0.71-1.18	-	-	1.0

[a] Assumed carbon cost is \$30/tonne of CO_2

- Currently: New NPP not profitable investment in US and EU.
  - Capital on-site construction costs too high (➔modern modular, factory).

- Cost not dominated by reactor and turbine islands but by
  - civil works, structures and buildings, electrical installation; associated indirect costs for this work on site.

- Cost reductions and/or revenue enhancement accomplished by
  - standardizing design, modus of reactor construction (prefab, modular), reduced commodity use, incorporating modern fabrication/construction technologies from other fields applicable to nuclear power.

MIT Report: The future of Nuclear Power in a Carbon-Constrained World

Conclusion: Nuclear Power in a Sustainable Future (?)

Western Gen III plants have good safety record (safest dispatchable energy).
But 3 *preventable* accidents with core damage ("melt down"), 1 accident fatal, temporary evacuation.
Gen III, III+ proven/mature technologies (PWR, U based), breeder reactors

To develop and employ advanced nuclear power in the U.S.:

- Continue to improve the safety of nuclear reactors and processing plants.
- Test/construct advanced modular nuclear reactors @ sites of existing plants.
- Test/construct advanced burner/transmuter → reduce radiotoxic waste.
- Import/develop closed nuclear fuel cycle technologies.
- Develop/test proliferation-safe reprocessing methods (e.g., UREX+).
- Further test/develop a closed Th/U breeder fuel cycle.
- Develop ADS systems, high current accelerator technology.
- Develop the material chemistry of molten salt mixtures, molten salt reactor.
- Expand the radio-chemistry of actinides, transactinides and fission products.
- Operating a semi-permanent nuclear waste depository, flexible strategy.
- Train personnel in nuclear and radiation technologies !