Power from Nuclear Fission b

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

- Principles of Energy Generation from Nuclear Fission
    - Basic energetics
    - Fission chain reaction and reactor control
    - Reactor types
    - Nuclear fuels, fuel cycle

- New Nukes: Advanced Nuclear Fission Energy Technologies
    - Advanced/modular (Gen IV) reactors
    - Closed fuel cycle, U/Th breeder reactors
    - Radioisotope thermoelectric generators (RTG).

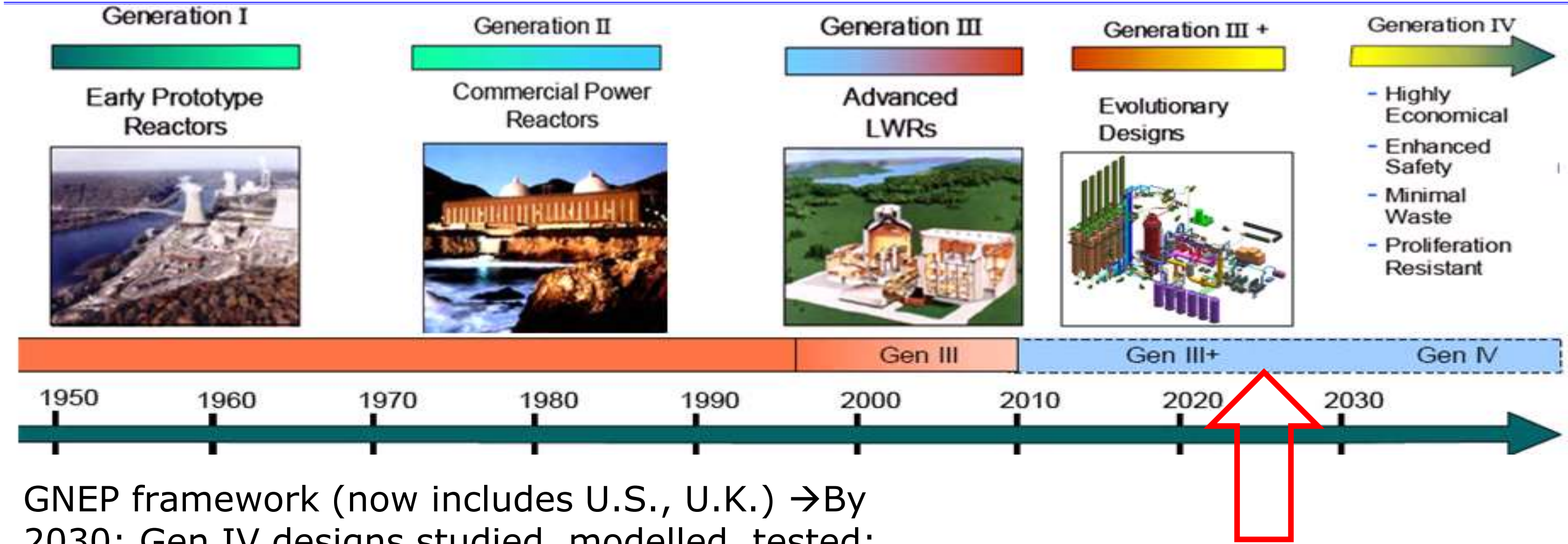
- Strategic Issues for Nuclear fission Power
    - Sustainability, reliability, safety, eco-footprint, cost, scalability
    - Proliferation safety

- Energy from future nuclear fusion reactors
    - Fusion energetics, critical
    - Principles of magnetic and inertial confinement technologies

Reading Assignments

A&J; Ch. 9-10
LN 4.3

Timeline of Reactors/Fuel Cycles



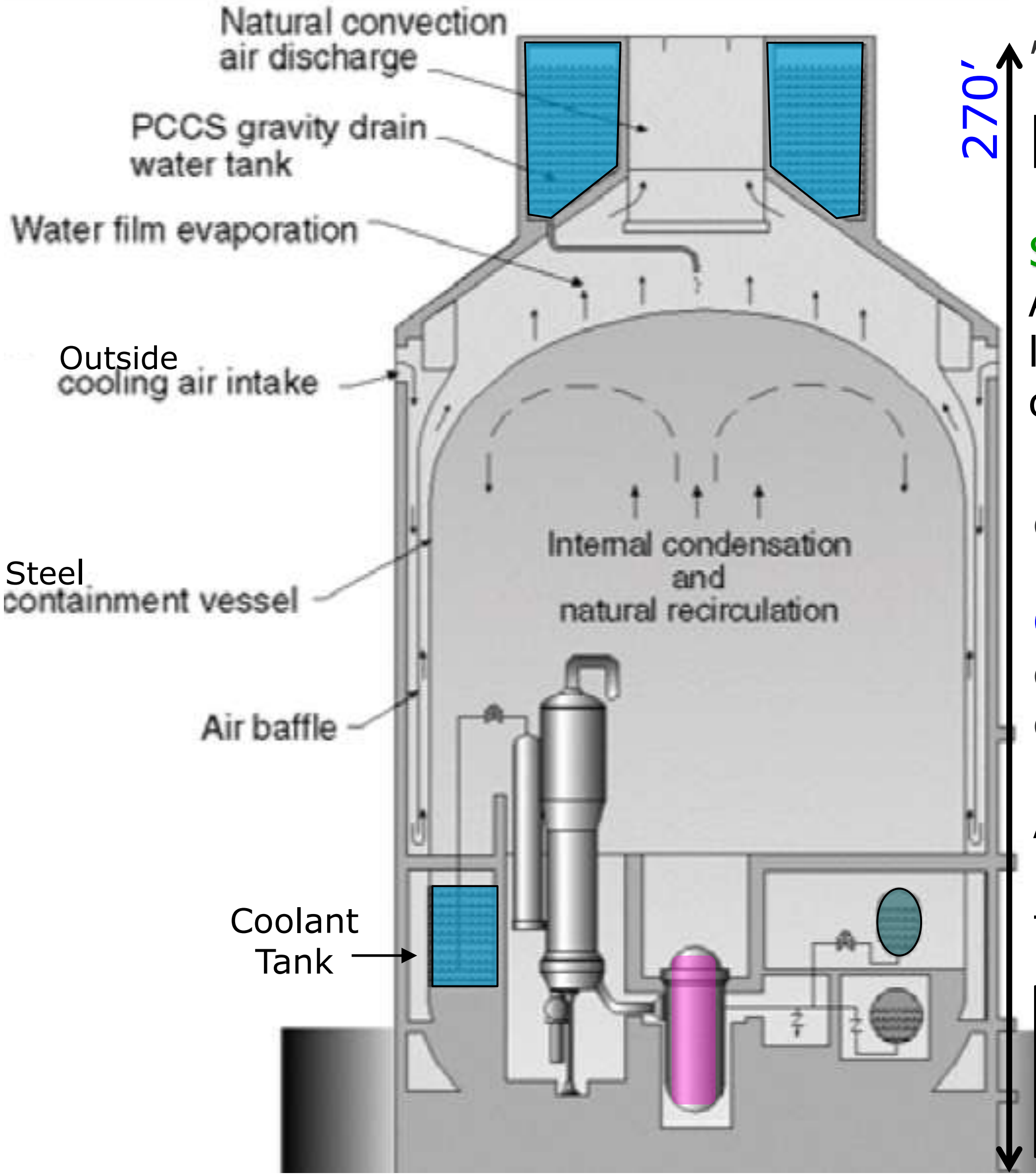
GNEP framework (now includes U.S., U.K.) →By 2030: Gen IV designs studied, modelled, tested:

- 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 ADS
- 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-Africa, 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 airflow cools large-surface shield & steel containment buildings.

Damage-resistant pressure vessel contains all primary components

Core cooling by gravity feed → cannot suffer major loss of coolant even if pipe breaks.

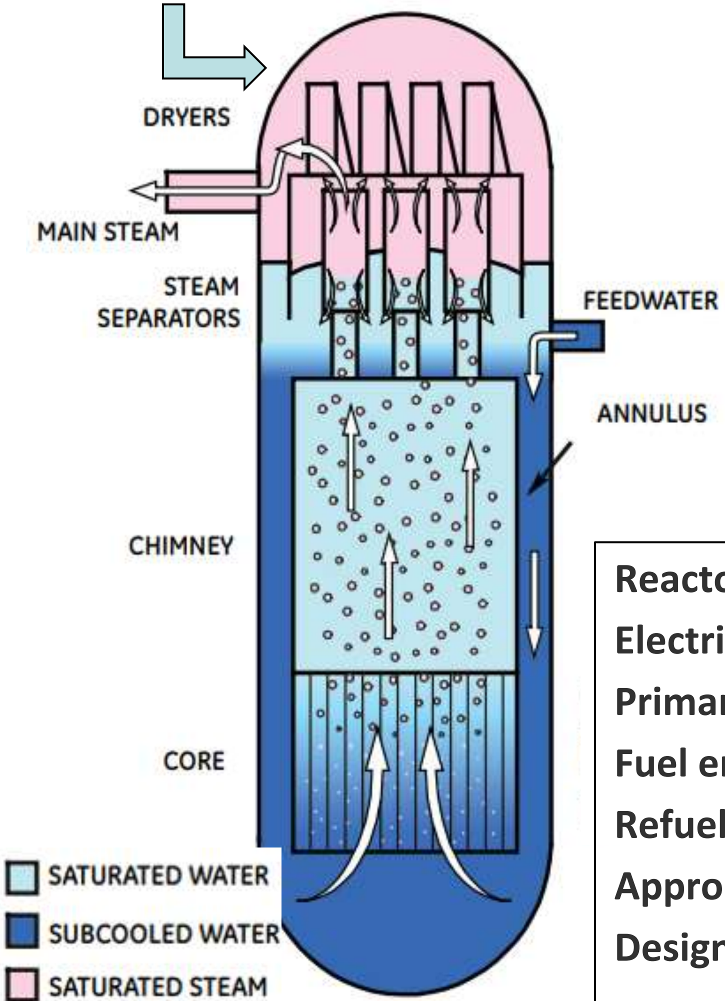
Ancillary water tanks on top release water to cool containment for up to 3 days.

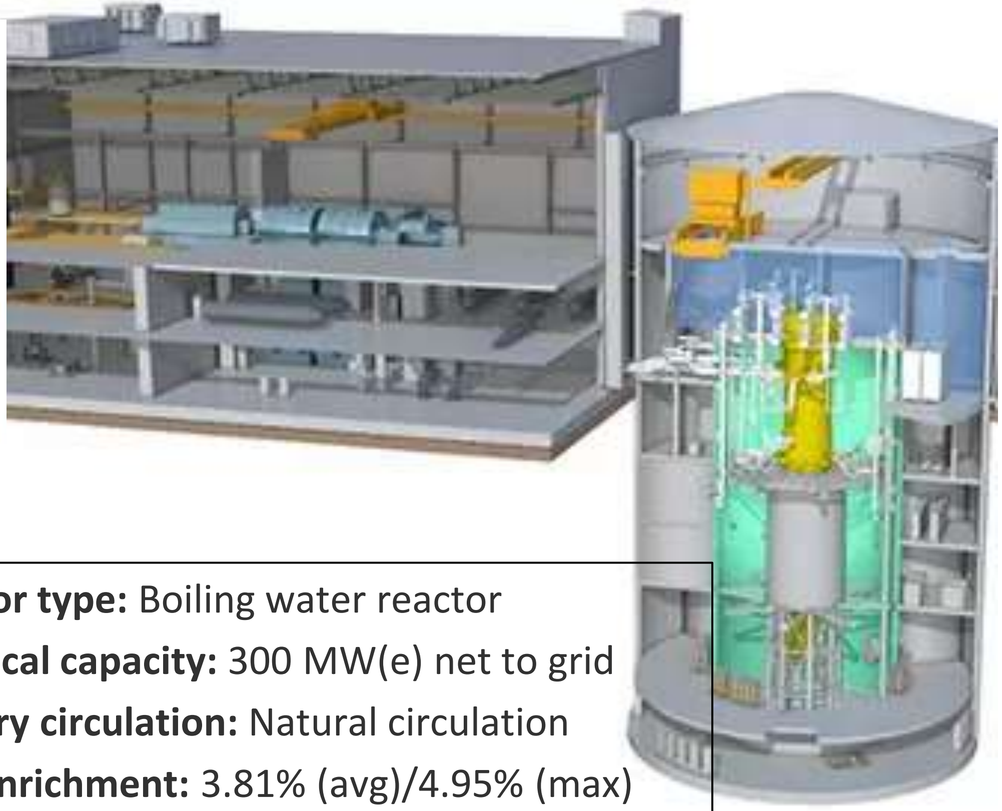
Westinghouse FOAK default
China: 2 builds + take over development/license APC1000

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

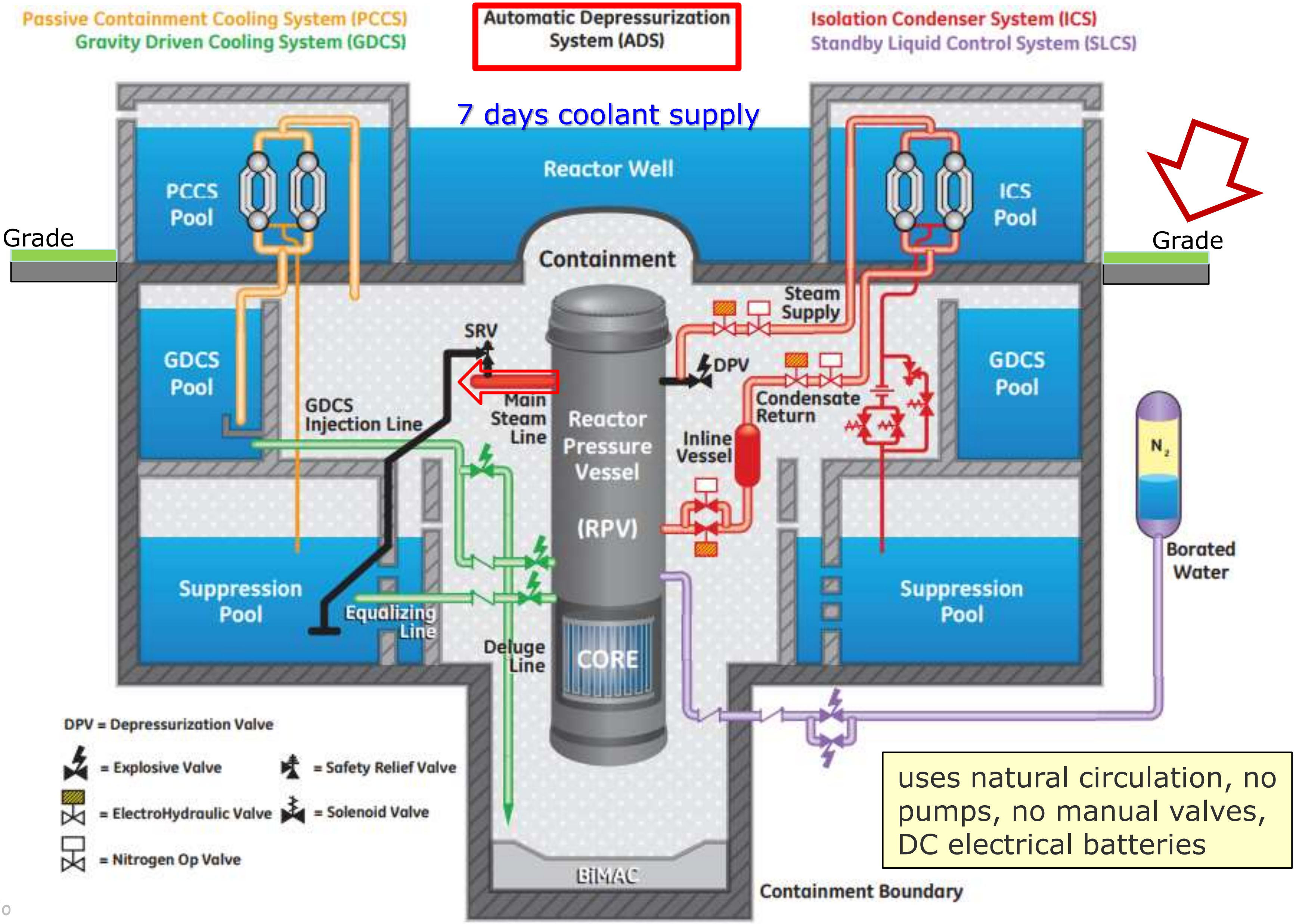
Fuel enrichment: 3.81% (avg)/4.95% (max)

Refueling cycle: 12-24 months

Approach to safety systems: Fully passive

Design life: 60 years

ESBWR passive safety systems



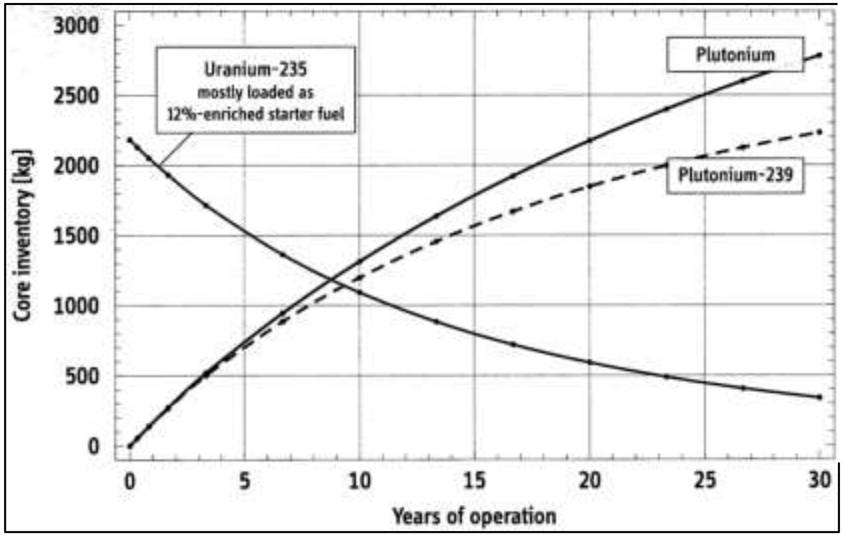
uses natural circulation, no pumps, no manual valves, DC electrical batteries

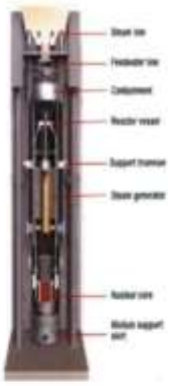
Small Modular Reactors: Current Development

Lifetime cores

Design	Company	Power	Status
mPower	Babock & Wilcox	2 x 180 MWe	Detailed design
NuScale	NuScale Power	12 x 45 MWe	Detailed design
W-SMR*	Westinghouse	225 MWe	Basic design
HI-SMUR (SMR-160)	Holtec	145 MWe	Basic design
SMART	KAERI,S-Korea	100 MWe	Licensed
KLT-40S	OKBM, Russia	2 x 32 MWe	Under construction

*Project currently suspended

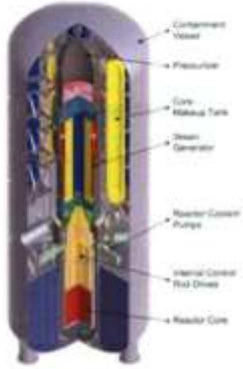




NuScale

mPower

Holtec SMR-160



Westinghouse SMR

Small Modular NPPT (RF 2019)

Nuclear Ships America's Nuclear Navy presently has 86 nuclear powered submarines and aircraft ... [+] UNITED STATES NAVY

Since 1955 nuclear powered USS Nautilus, now 26 (→+30?) submarines,
1960: aircraft carrier *USS Enterprise* has 8 NPPT., etc. All PWR types.

Russian nuclear-powered submarines operate with lead coolant.

Spacecraft (Voyagers, Cassini,…, Rover,…) have Pu-238 nuclear thermal generators

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

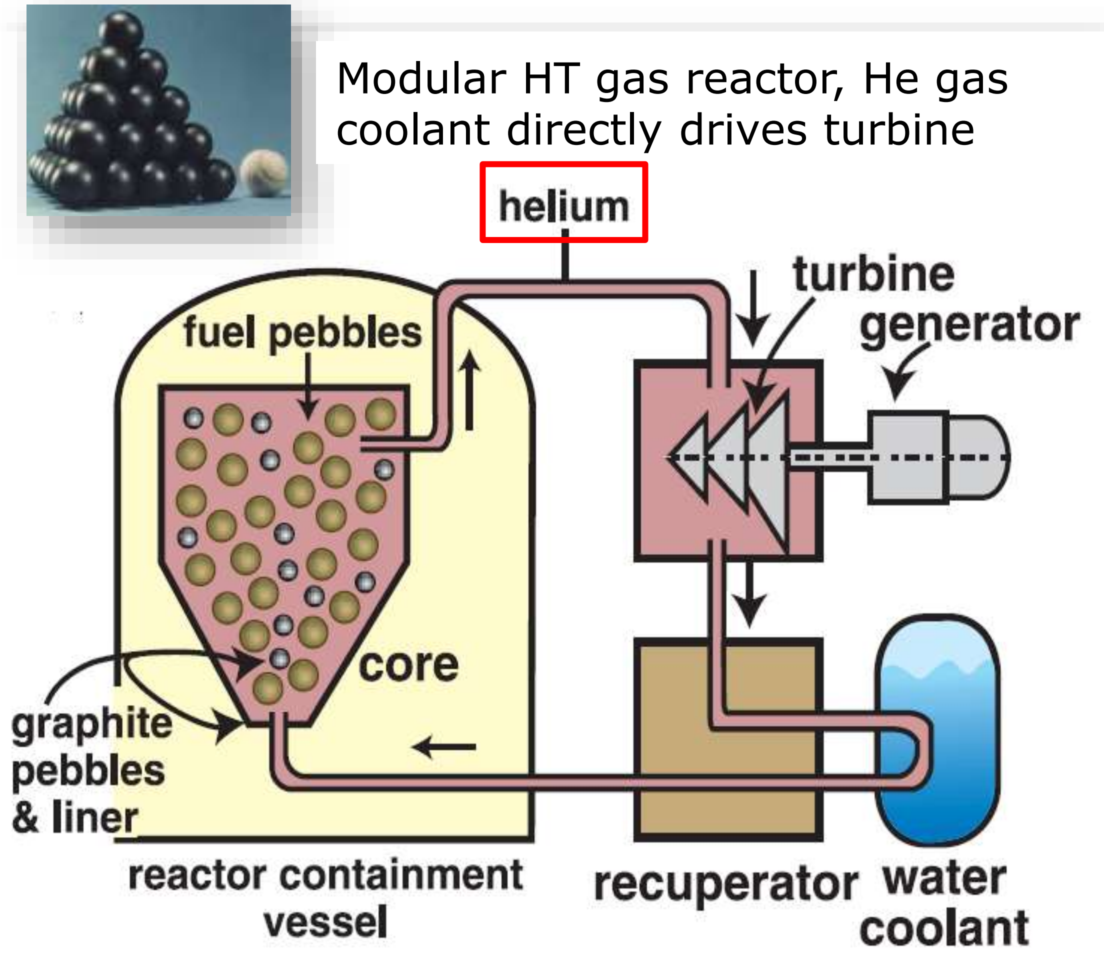
Heat 50 Gcal/h (210 GJ/h)

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.

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

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

Continuous throughput replacement of "pebble" fuel elements

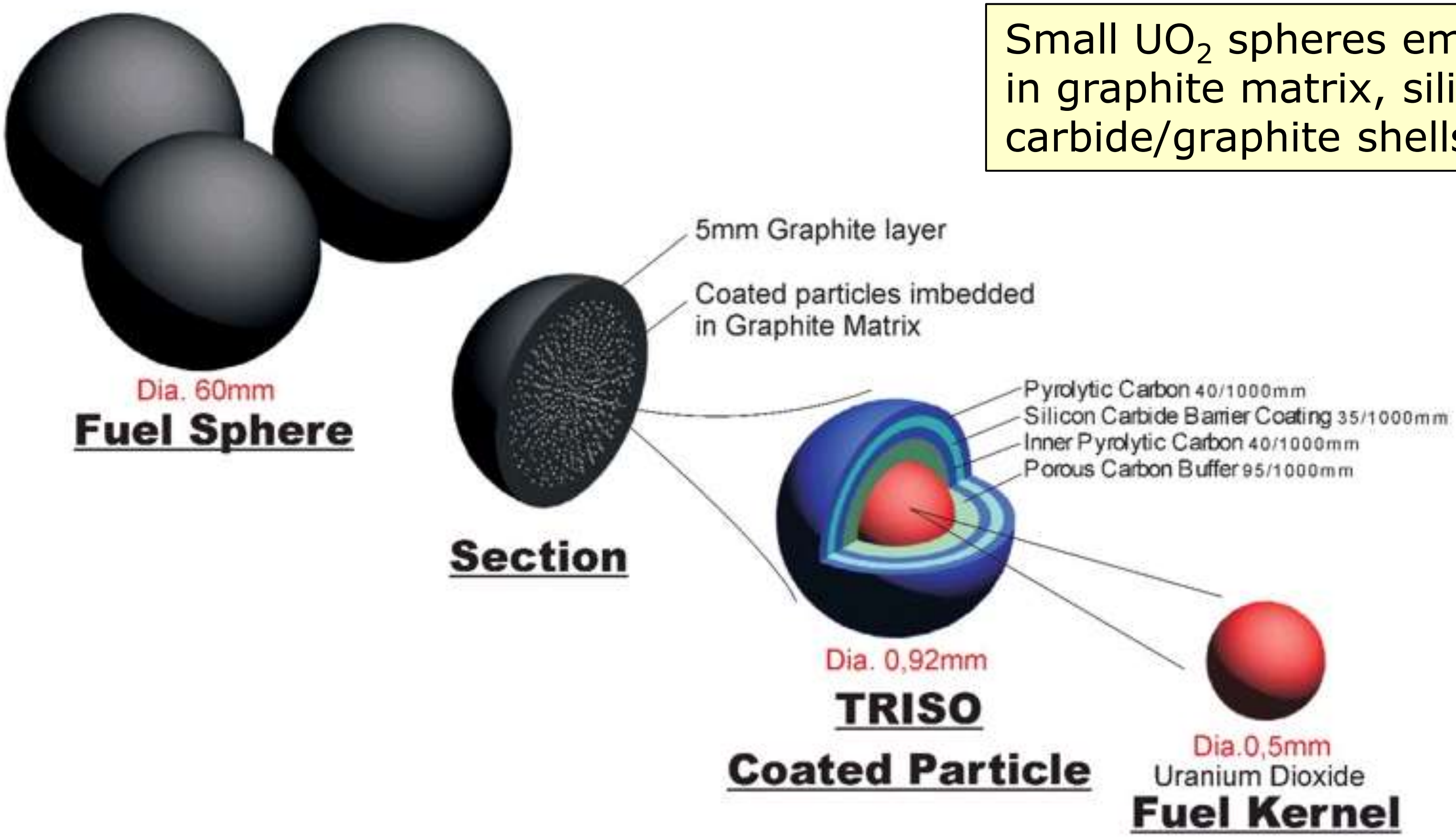
→Strongly negative reactivity

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

→Fail-safe operation.

Modular Pebble Bed Reactor 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.

SS-Small Modular

Agenda

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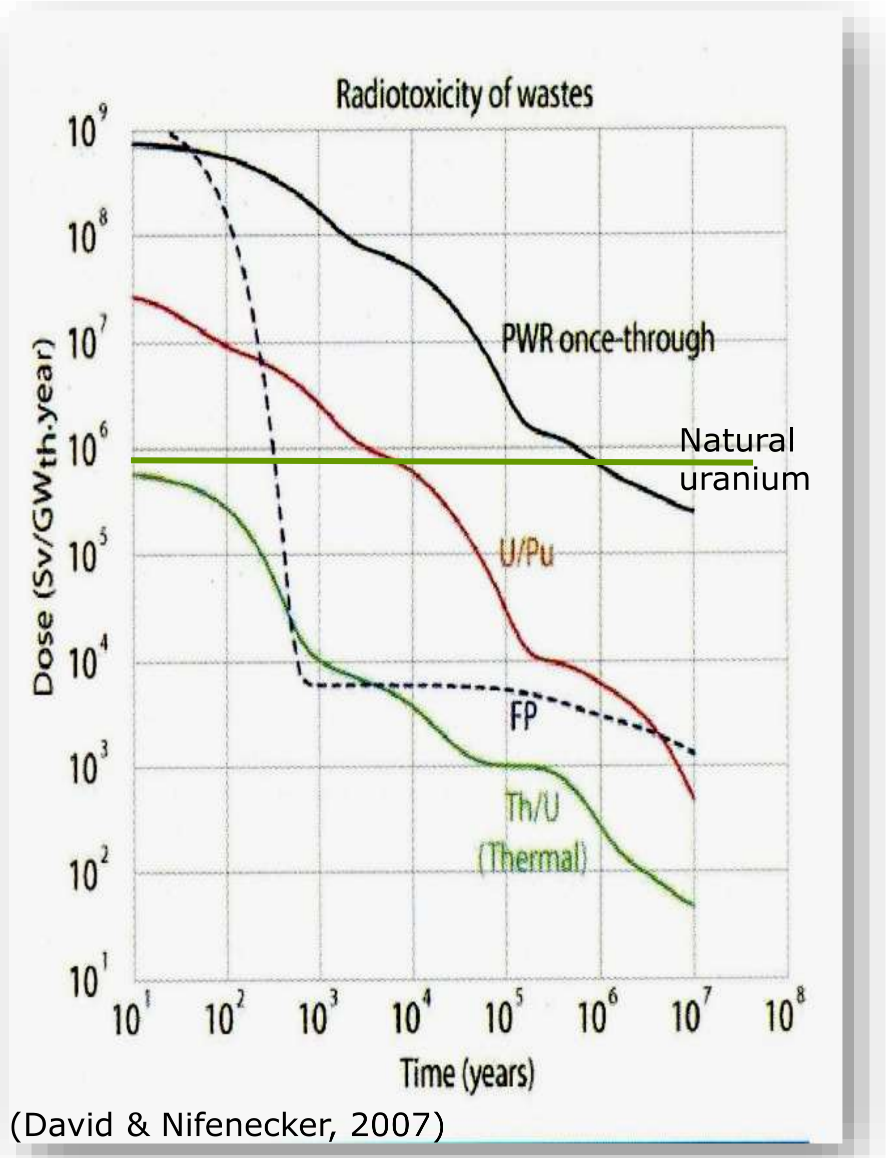
LN 4.3

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.

Gen III+

U and Th Nuclear Fuel Resources

World (US)
443 (103) reactors
365 (100) GW

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

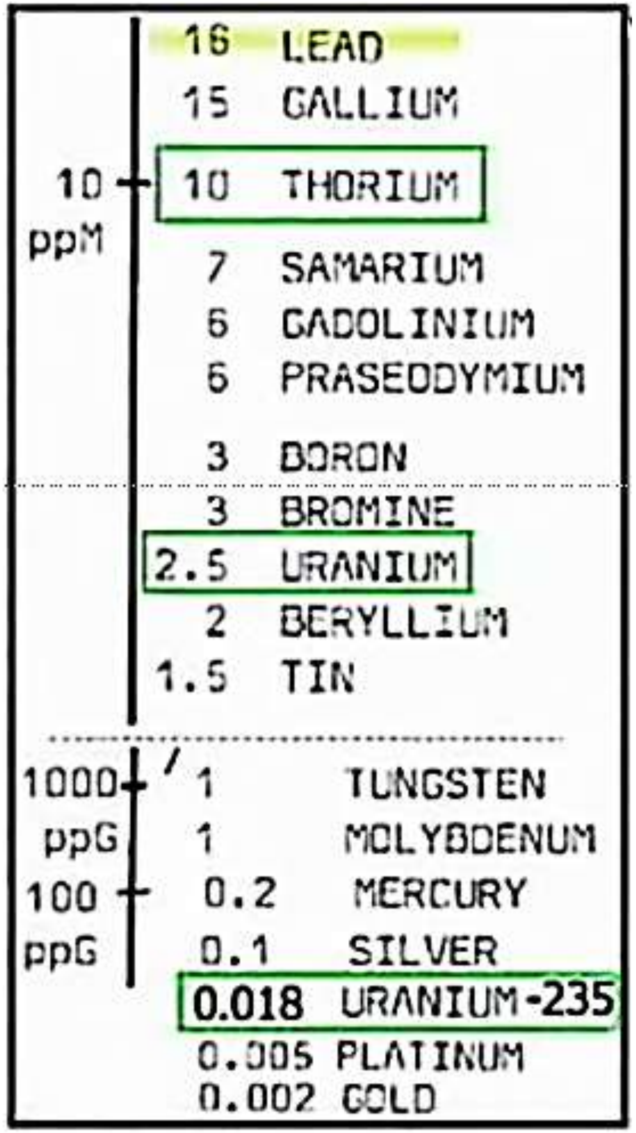
Reprocessing: $\sim 10^3$ years
US:174 t weapons grade U +20t/a Pu for fuel mix (→ 0.2 Mt fuel)

Th use: little yet (India ramping up)
World reserves >15 Mt $\sim 10^3$ a with reprocessing.

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

→ **essentially sustainable energy source**

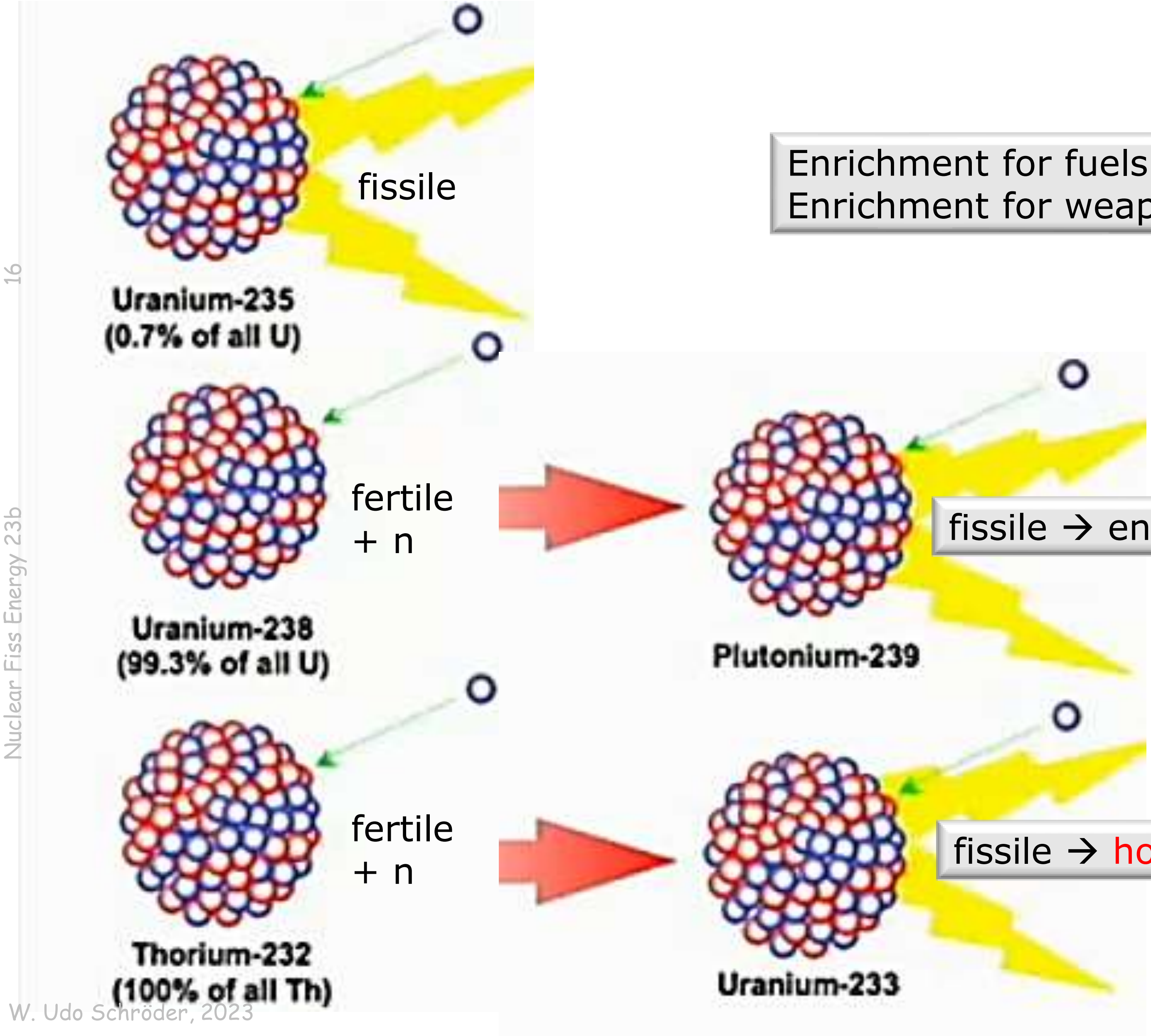
Reserves in Earth crust



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

Fissile and Fertile Nuclear Fuels

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



fissile

fertile
+ n

fertile
+ n

fissile → enrichment→ weapons

fissile → hot enrichm.→weapons

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

Technologically understood, several working research/test reactors

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

Prevent additional n capture

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

U – Pu Cycle

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

Continued n capture/β decay

$${}^{239}_{94}Pu + n \rightarrow {}^{240}_{94}Pu \,|\, {}^{240}_{94}Pu + n \rightarrow {}^{241}_{94}Pu$$

$$\downarrow$$

$${}^{241}_{95}Am$$

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

Need many neutrons: source is unimportant !

(Use waste or heavy materials like Pb, Bi,….)

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

Technologically understood, several working research/test reactors

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

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

Prevent additional n capture

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

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

Th – U Cycle

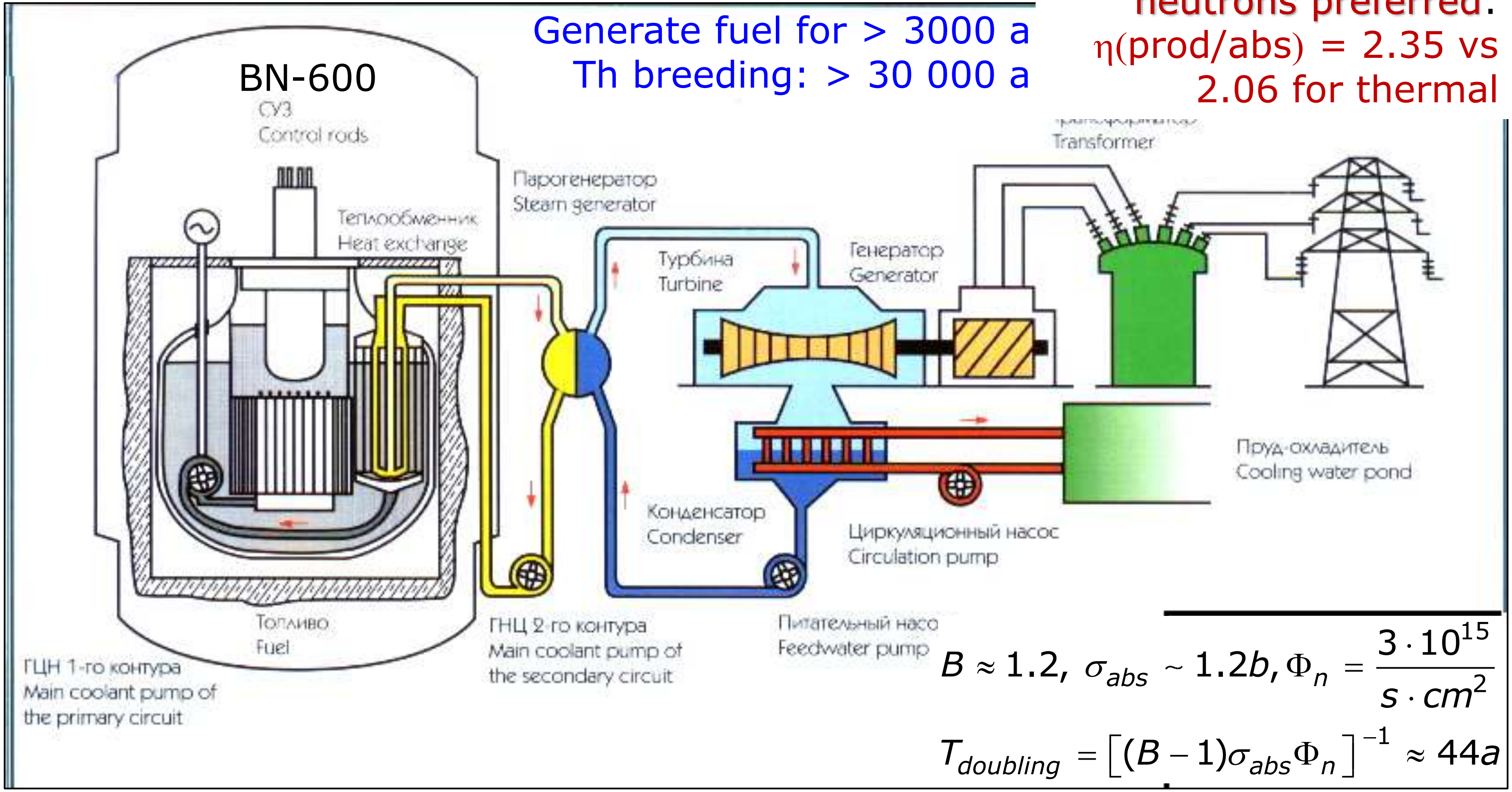
$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow[t_{1/2}=22\,\text{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27d]{\beta^-} {}^{233}_{92}U\left(1.6\cdot 10^5 a\right)$$

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

Metal-Cooled Breeder Reactor

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

Fast (>0.5 MeV) neutrons preferred: η(prod/abs) = 2.35 vs 2.06 for thermal



BN-600

Generate fuel for > 3000 a

Th breeding: > 30 000 a

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

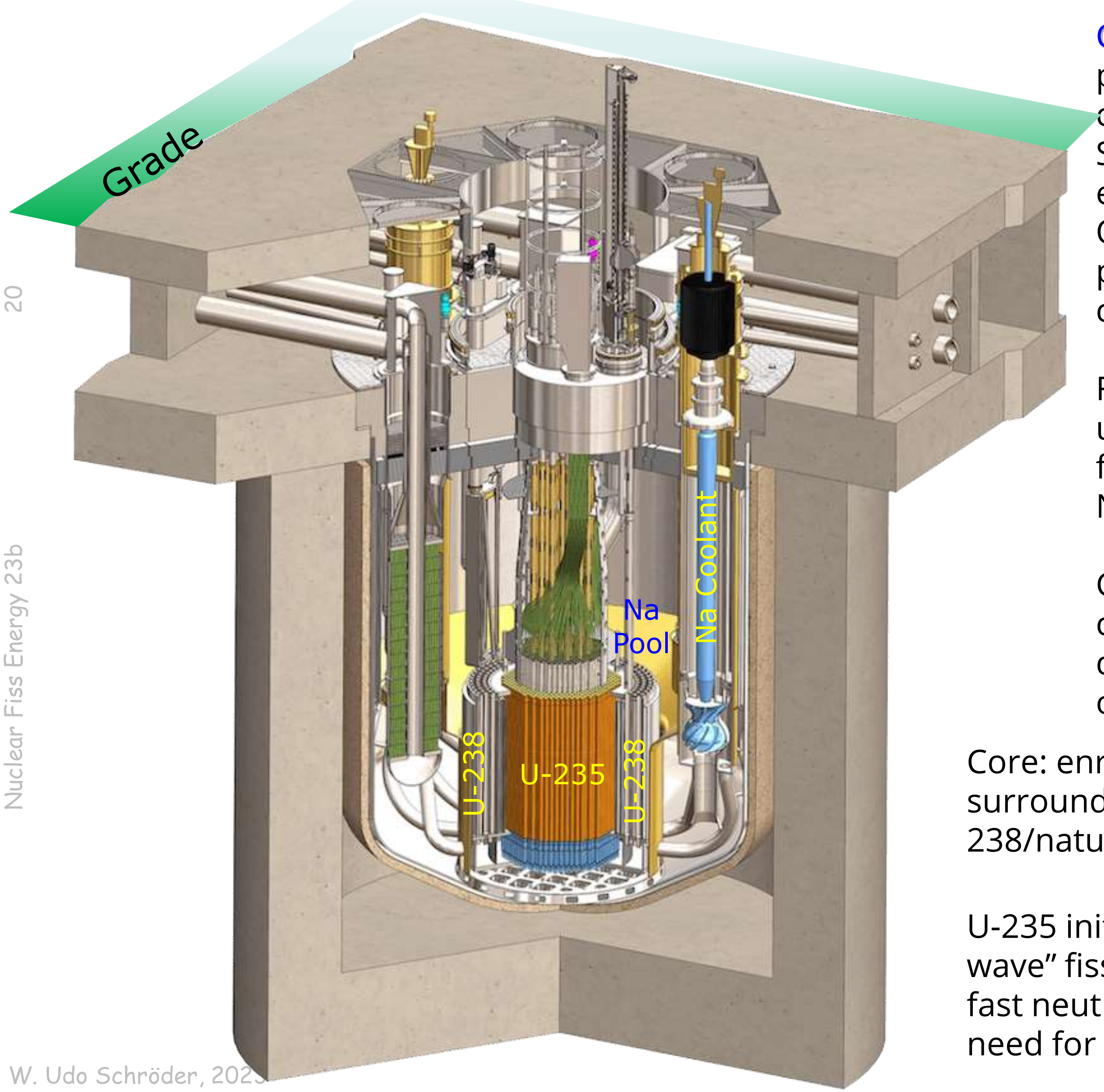
$$T_{doubling} = \left[(B-1)\sigma_{abs}\Phi_n\right]^{-1} \approx 44a$$

core:45.5% ^{235}U blanket: 20 t UO_2

cooling molten Na, K magnetic pumps

long doubling time!

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.

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

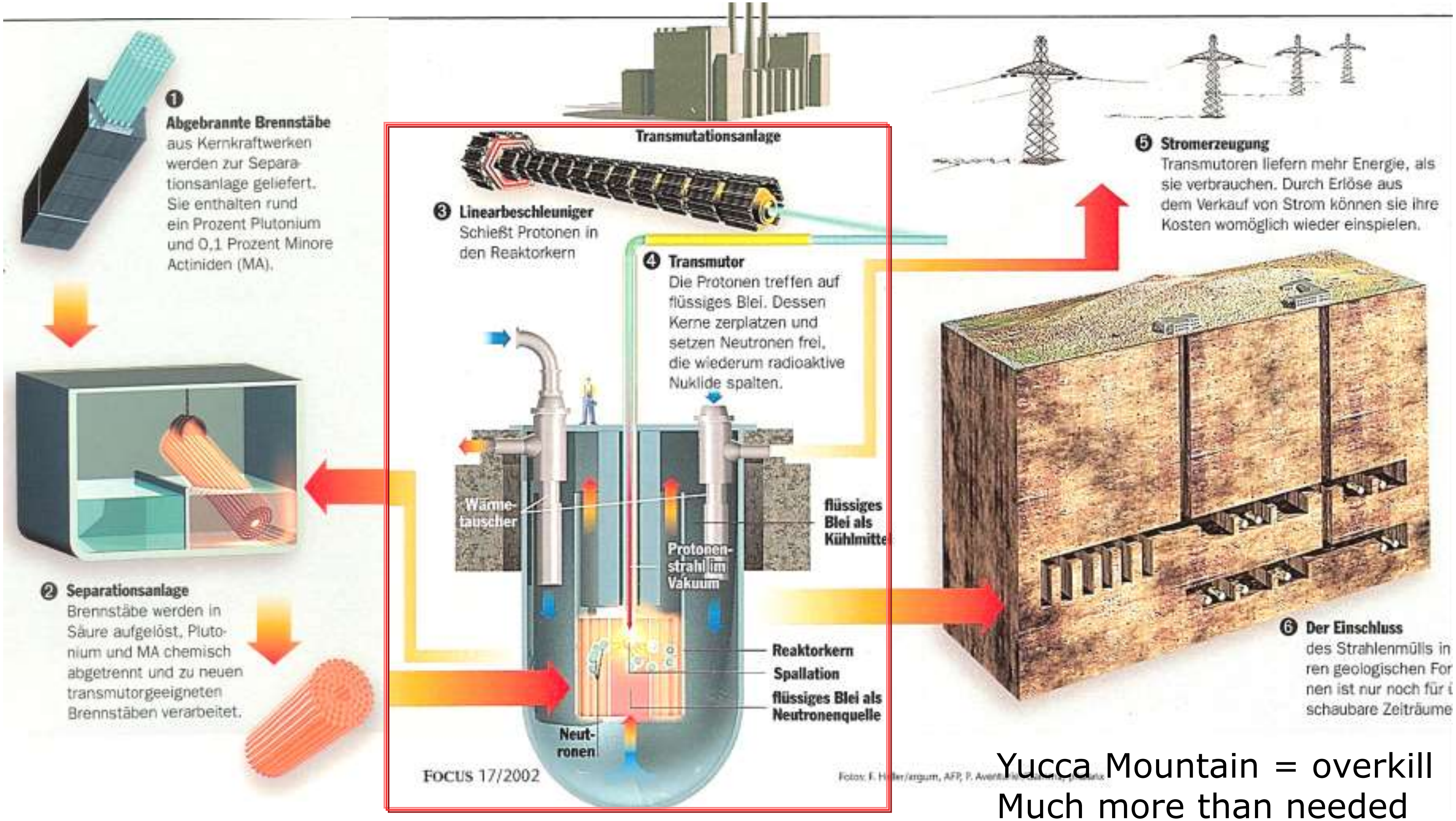
Generates heat by Rankine cycle and electricity over decades of continuous operation.

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 Th breeding. No need for reprocessing.

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.

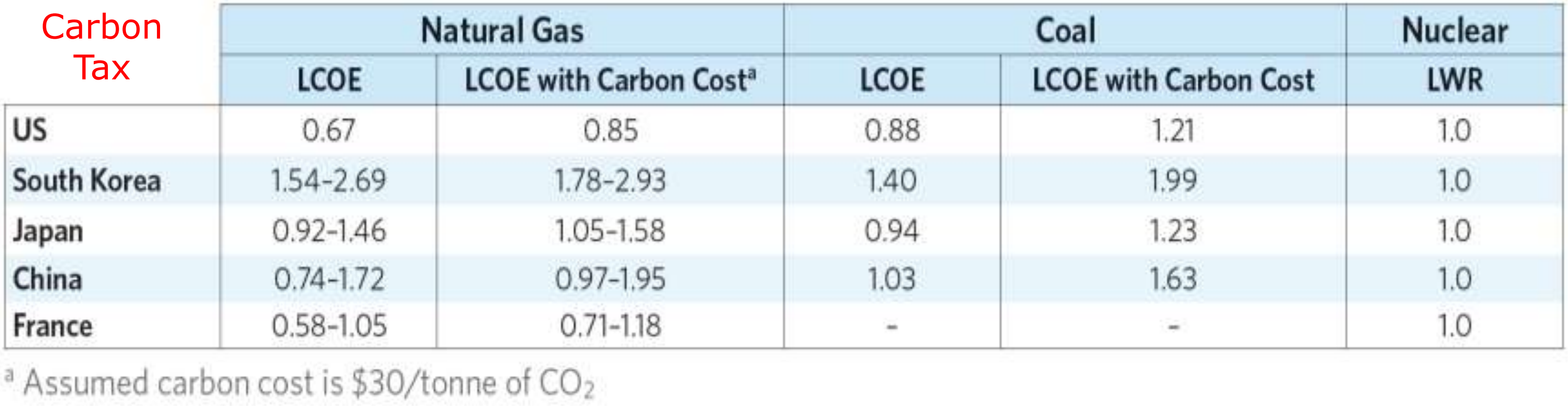
⑥ **Der Einschluss** des Strahlenmülls in
ren geologischen For
nen ist nur noch für i
schaubare Zeiträume

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

Yucca Mountain = overkill
Much more than needed
with reprocessing

Outlook: LCOE Nuclear 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 !

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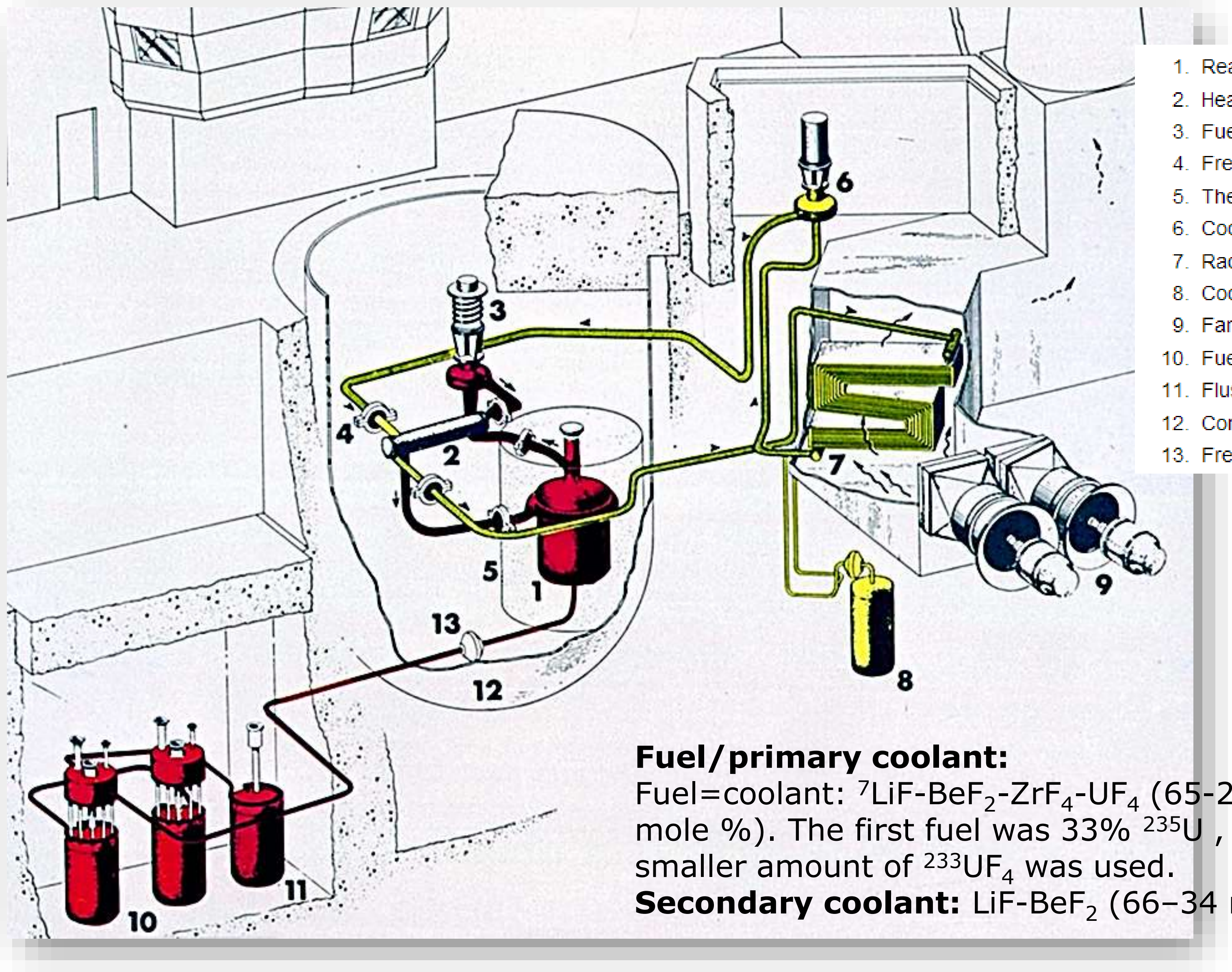
LN 4.3

Molten Salt Th Reactor

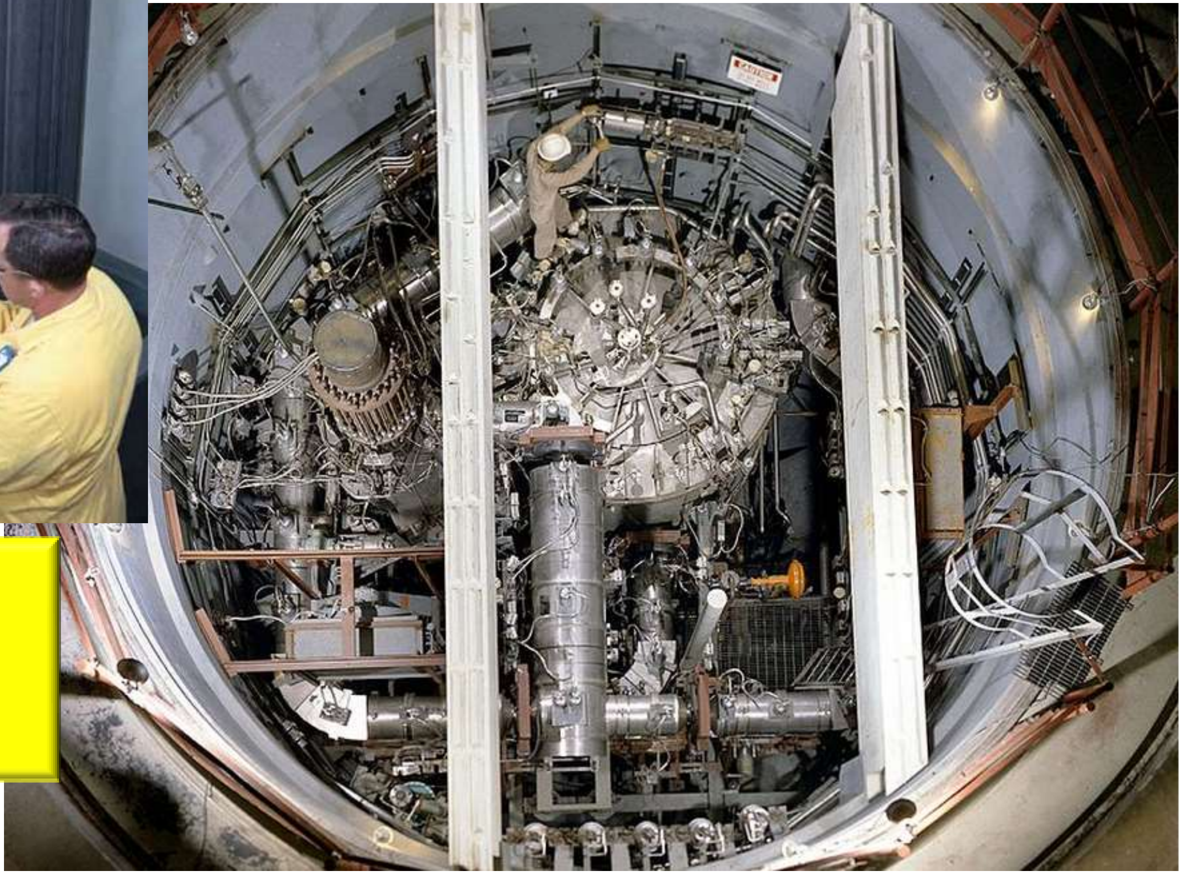


1. Reactor Vessel
2. Heat Exchanger
3. Fuel Pump
4. Freeze Flange
5. Thermal Shield
6. Coolant Pump
7. Radiator
8. Coolant Drain Tank
9. Fans
10. Fuel Drain Tanks
11. Flush Tank
12. Containment Vessel
13. Freeze Valve

Fuel/primary coolant:
Fuel=coolant: $^{7}LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ (65-29.1-5-0.9 mole %). The first fuel was 33% ^{235}U , later a smaller amount of $^{233}UF_4$ was used.
Secondary coolant: $LiF\text{-}BeF_2$ (66–34 mole %)

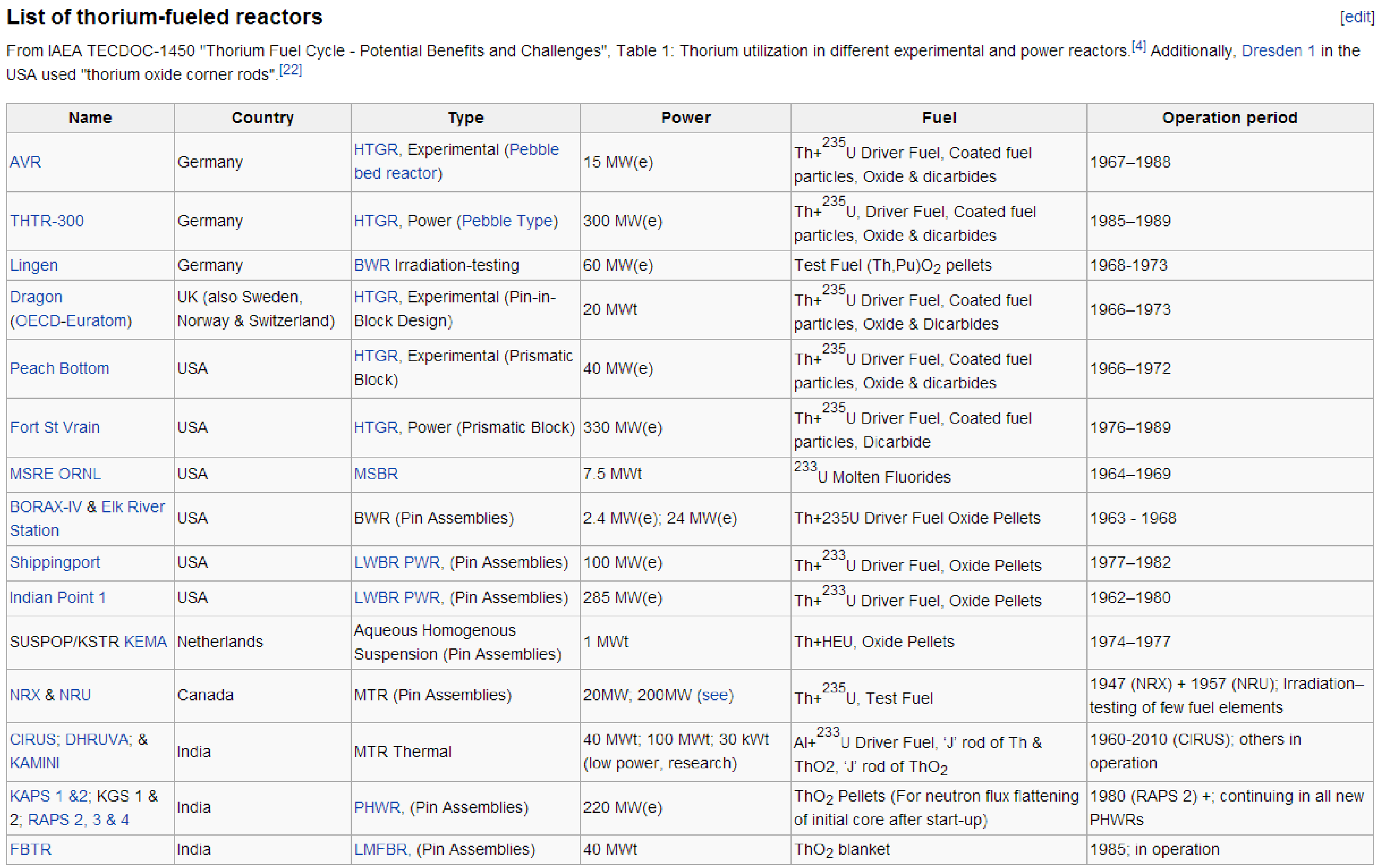
US Molten Salt Th Reactor Experiment

In pipes/containers of salt, low chromium, nickel–molybdenum alloy, Hastelloy-N, was used in the MSRE and proved compatible with the fluoride salts FLiBe and FLiNaK. All metal parts contacting salt were made of Hastelloy-N.



The MSRE operated for 5 years: 1964 - 1969. Objectives of experiment were achieved: viable reactor technology.

Thorium Test Reactors



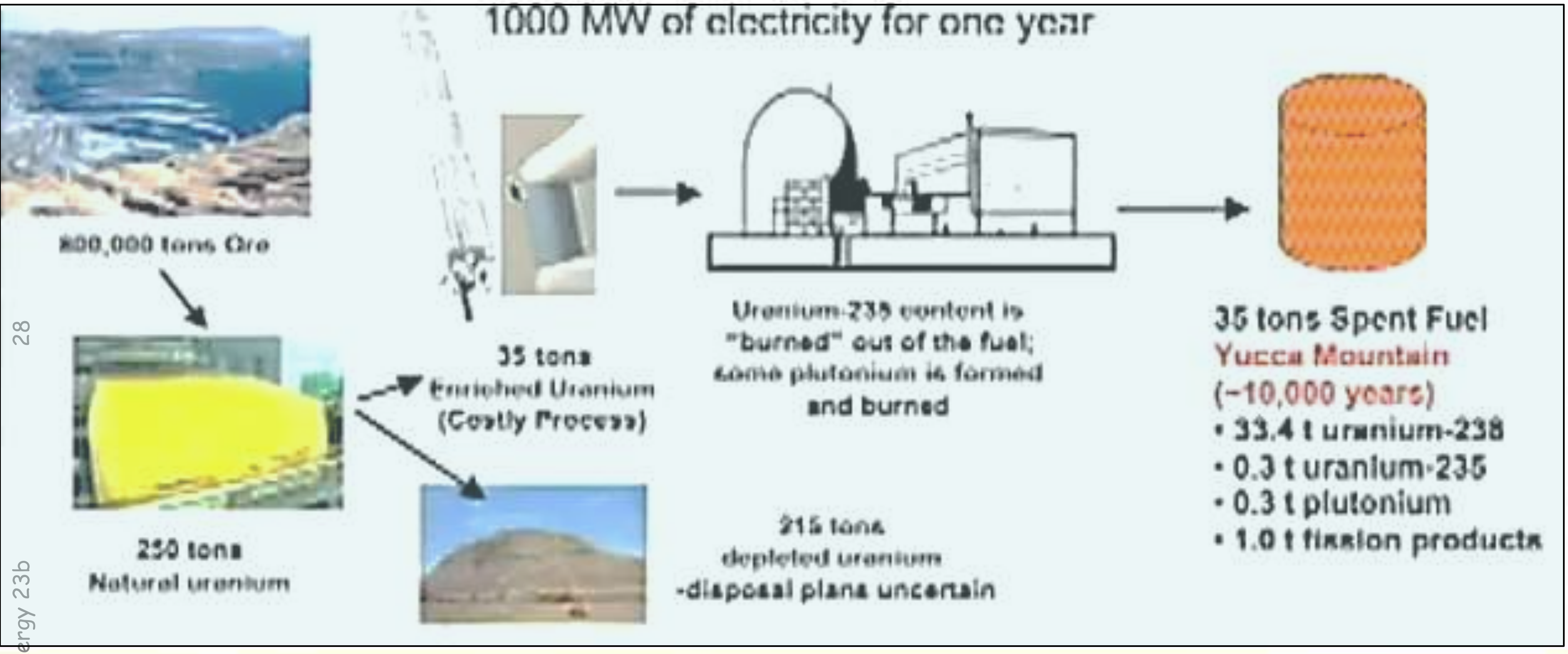
List of thorium-fueled reactors

[edit]

From IAEA TECDOC-1450 "Thorium Fuel Cycle - Potential Benefits and Challenges", Table 1: Thorium utilization in different experimental and power reactors.[4] Additionally, Dresden 1 in the USA used "thorium oxide corner rods".[22]

Name	Country	Type	Power	Fuel	Operation period
AVR	Germany	HTGR, Experimental (Pebble bed reactor)	15 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles, Oxide & dicarbides	1967–1988
THTR-300	Germany	HTGR, Power (Pebble Type)	300 MW(e)	Th+^{235}U, Driver Fuel, Coated fuel particles, Oxide & dicarbides	1985–1989
Lingen	Germany	BWR Irradiation-testing	60 MW(e)	Test Fuel $(Th,Pu)O_2$ pellets	1968-1973
Dragon (OECD-Euratom)	UK (also Sweden, Norway & Switzerland)	HTGR, Experimental (Pin-in-Block Design)	20 MWt	Th+^{235}U Driver Fuel, Coated fuel particles, Oxide & Dicarbides	1966–1973
Peach Bottom	USA	HTGR, Experimental (Prismatic Block)	40 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles, Oxide & dicarbides	1966–1972
Fort St Vrain	USA	HTGR, Power (Prismatic Block)	330 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles, Dicarbide	1976–1989
MSRE ORNL	USA	MSBR	7.5 MWt	^{233}U Molten Fluorides	1964–1969
BORAX-IV & Elk River Station	USA	BWR (Pin Assemblies)	2.4 MW(e); 24 MW(e)	Th+235U Driver Fuel Oxide Pellets	1963 - 1968
Shippingport	USA	LWBR PWR, (Pin Assemblies)	100 MW(e)	Th+^{233}U Driver Fuel, Oxide Pellets	1977–1982
Indian Point 1	USA	LWBR PWR, (Pin Assemblies)	285 MW(e)	Th+^{233}U Driver Fuel, Oxide Pellets	1962–1980
SUSPOP/KSTR KEMA	Netherlands	Aqueous Homogenous Suspension (Pin Assemblies)	1 MWt	Th+HEU, Oxide Pellets	1974–1977
NRX & NRU	Canada	MTR (Pin Assemblies)	20MW; 200MW (see)	Th+^{235}U, Test Fuel	1947 (NRX) + 1957 (NRU); Irradiation–testing of few fuel elements
CIRUS; DHRUVA; & KAMINI	India	MTR Thermal	40 MWt; 100 MWt; 30 kWt (low power, research)	Al+^{233}U Driver Fuel, 'J' rod of Th & ThO2, 'J' rod of ThO_2	1960-2010 (CIRUS); others in operation
KAPS 1 &2; KGS 1 & 2; RAPS 2, 3 & 4	India	PHWR, (Pin Assemblies)	220 MW(e)	ThO_2 Pellets (For neutron flux flattening of initial core after start-up)	1980 (RAPS 2) +; continuing in all new PHWRs
FBTR	India	LMFBR, (Pin Assemblies)	40 MWt	ThO_2 blanket	1985; in operation

Uranium Fuel Cycle vs. Thorium



1000 MW of electricity for one year

800,000 tons Ore

250 tons
Natural uranium

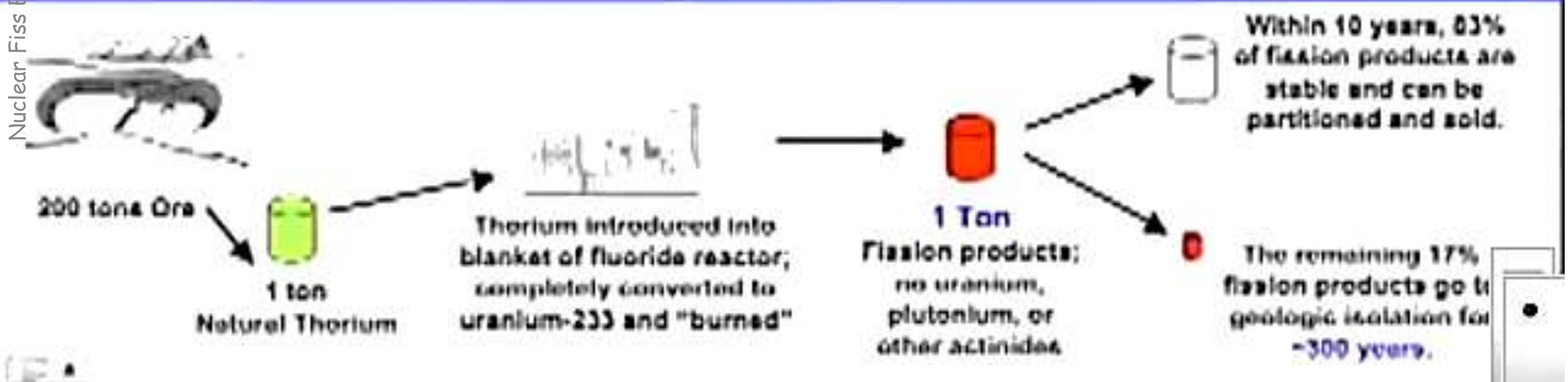
35 tons
Enriched Uranium
(Costly Process)

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

215 tons
depleted uranium
-disposal plans uncertain

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

- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products



200 tons Ore

1 ton
Natural Thorium

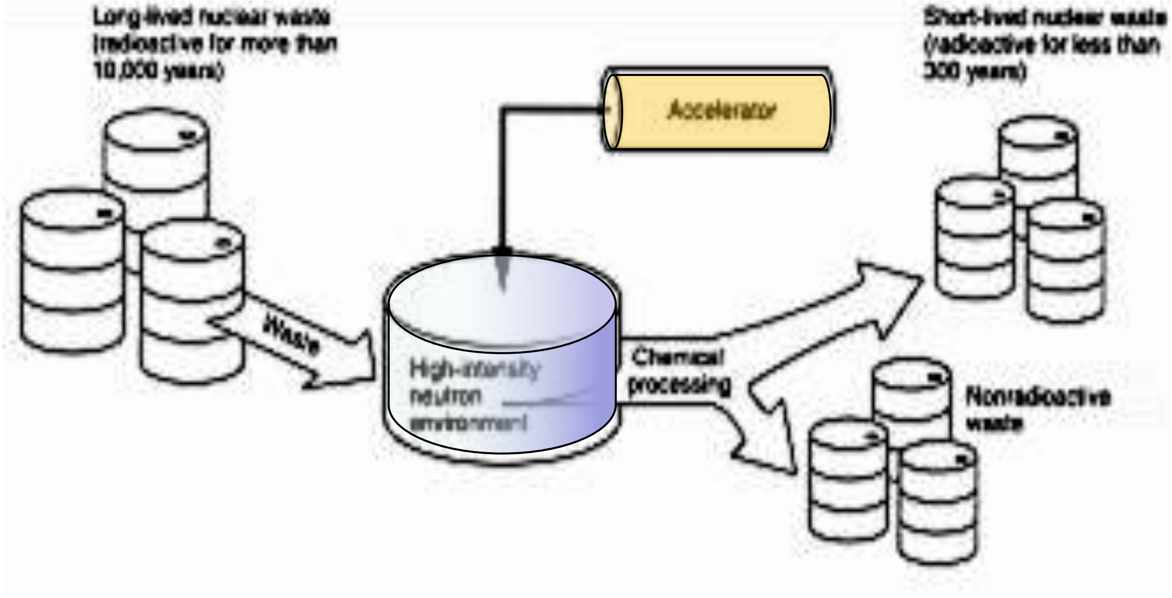
Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

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.

The remaining 17% fission products go t
geologic isolation fo
~300 years.

Nuclear Transmutation of Fission Products



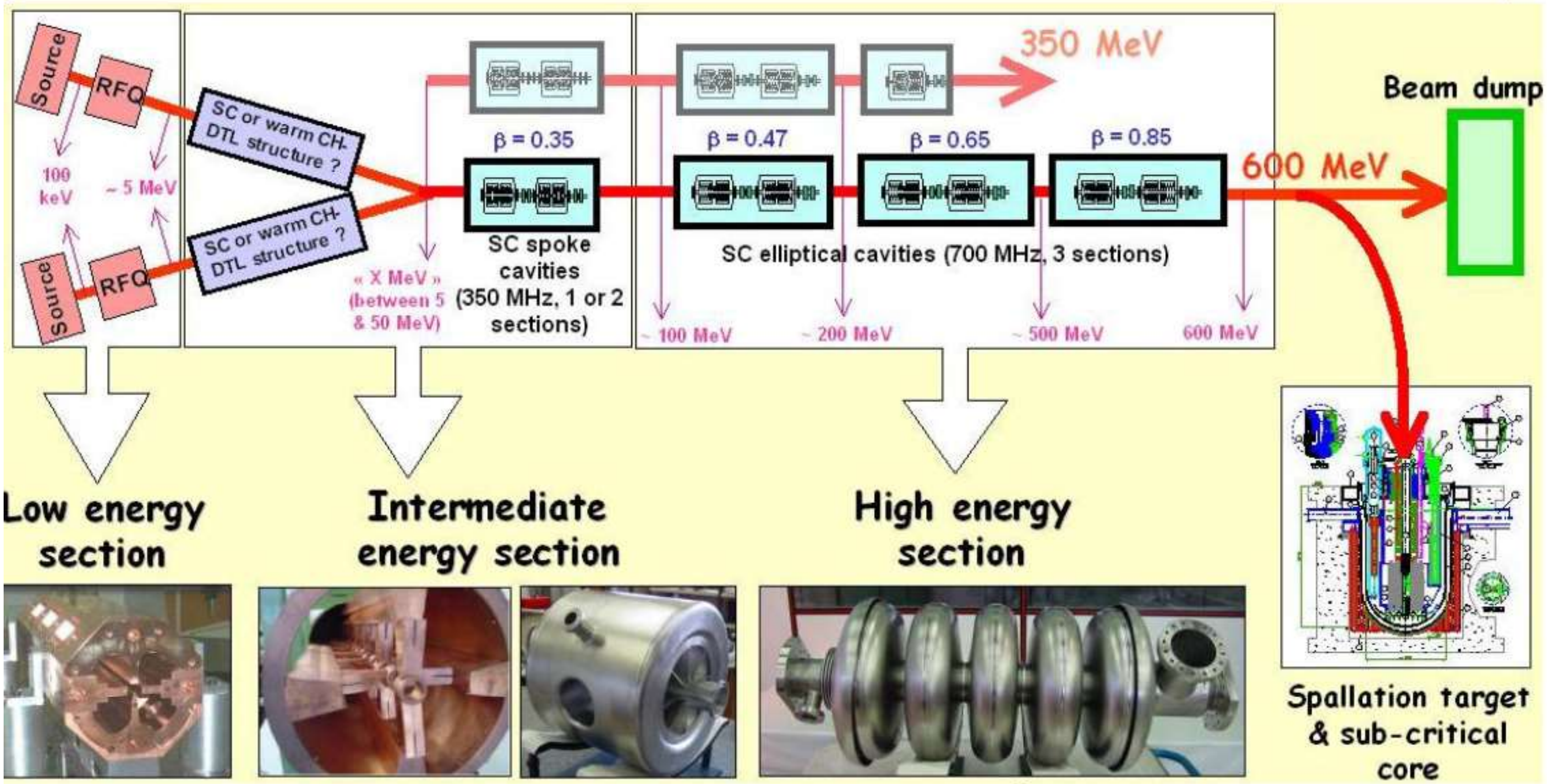
$$\left.\begin{array}{l} {}^{99}Tc + n \rightarrow {}^{100}Tc \xrightarrow[15.8s]{\beta^-} {}^{100}Ru \\ {}^{129}I + n \rightarrow {}^{130}I \xrightarrow[12.4h]{\beta^-} {}^{130}Xe \end{array}\right\} \text{stable isotopes}$$

Transmutation of fission products carried out by specific nuclear reactions induced by neutrons, protons, photons, light nuclei, e.g., resonant n-capture.
Need high n flux
$\Phi_n \sim 10^{16}/s\cdot cm^2$

C.D. Bowman et a., NIM A320, 336 (1992)
H. Nifenecker et al., *Accelerator Driven Subcritical Reactors*, IOP Bristol, 2003

Transmutation of actinides:
n-induced fission of Pu, Np, Am, Cm
→ radioactive and nonradioactive fission products (most with half-lives < 30 a).

Myrrha ADS Demonstration Facility (Belgium)



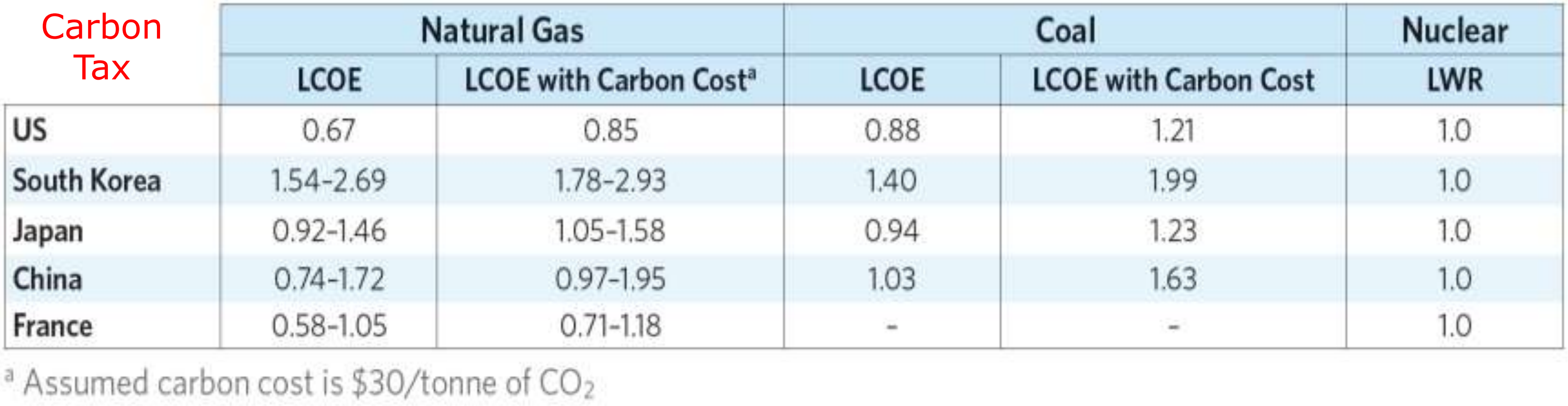
Strong R&D & construction programs for LINACs underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Alex Müller, NN2012, San Antonio/TX, 2012

Outlook: LCOE Nuclear Power in US/EU

Carbon Tax



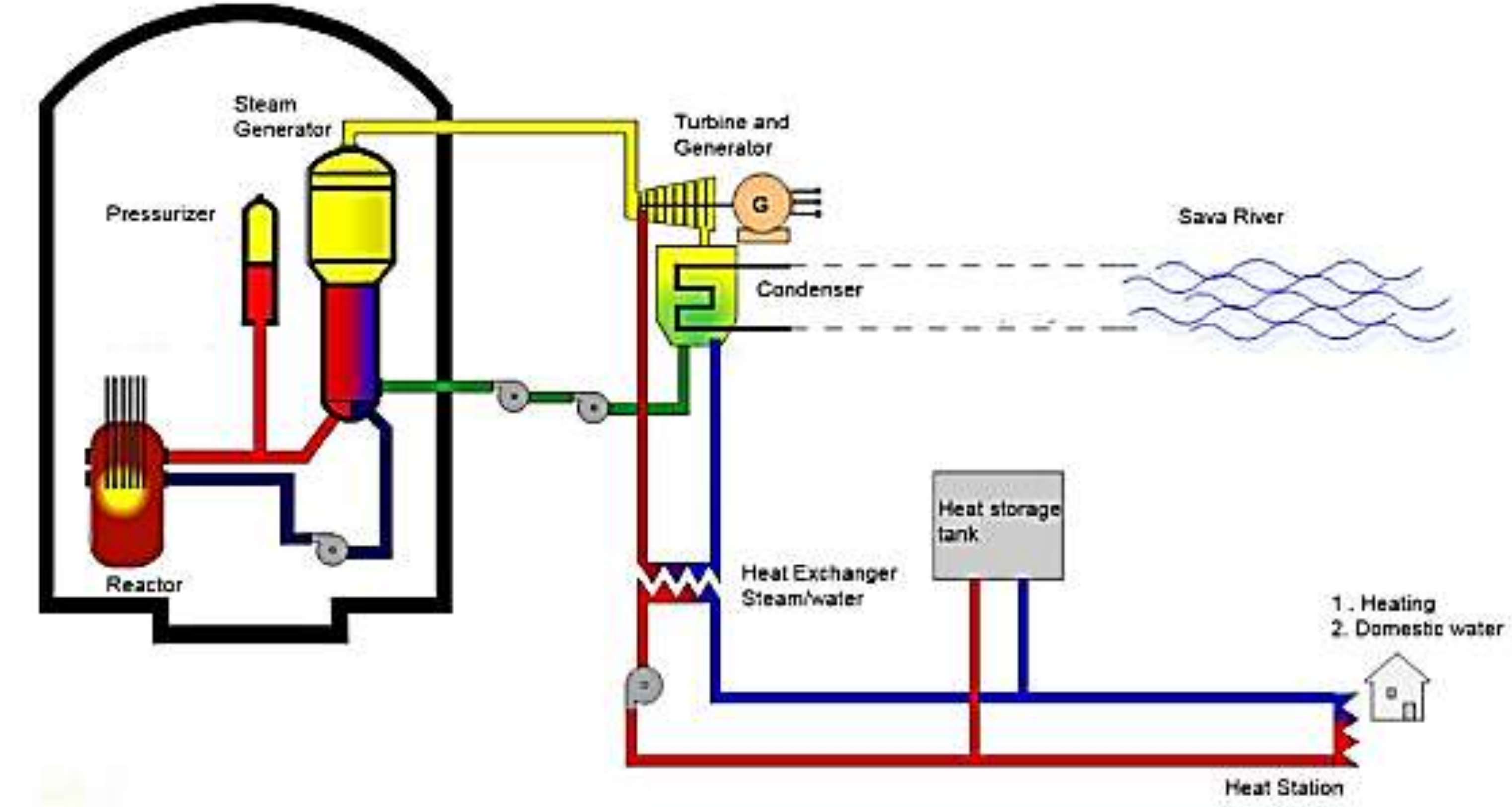
	Natural Gas		Coal		Nuclear
	LCOE	LCOE with Carbon Cost[a]	LCOE	LCOE with Carbon Cost	LWR
US	0.67	0.85	0.88	1.21	1.0
South Korea	1.54-2.69	1.78-2.93	1.40	1.99	1.0
Japan	0.92-1.46	1.05-1.58	0.94	1.23	1.0
China	0.74-1.72	0.97-1.95	1.03	1.63	1.0
France	0.58-1.05	0.71-1.18	-	-	1.0

[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

Cogeneration in the Krško Nuclear Power Plant in Slovenia



Source: GEN Energija (2013).

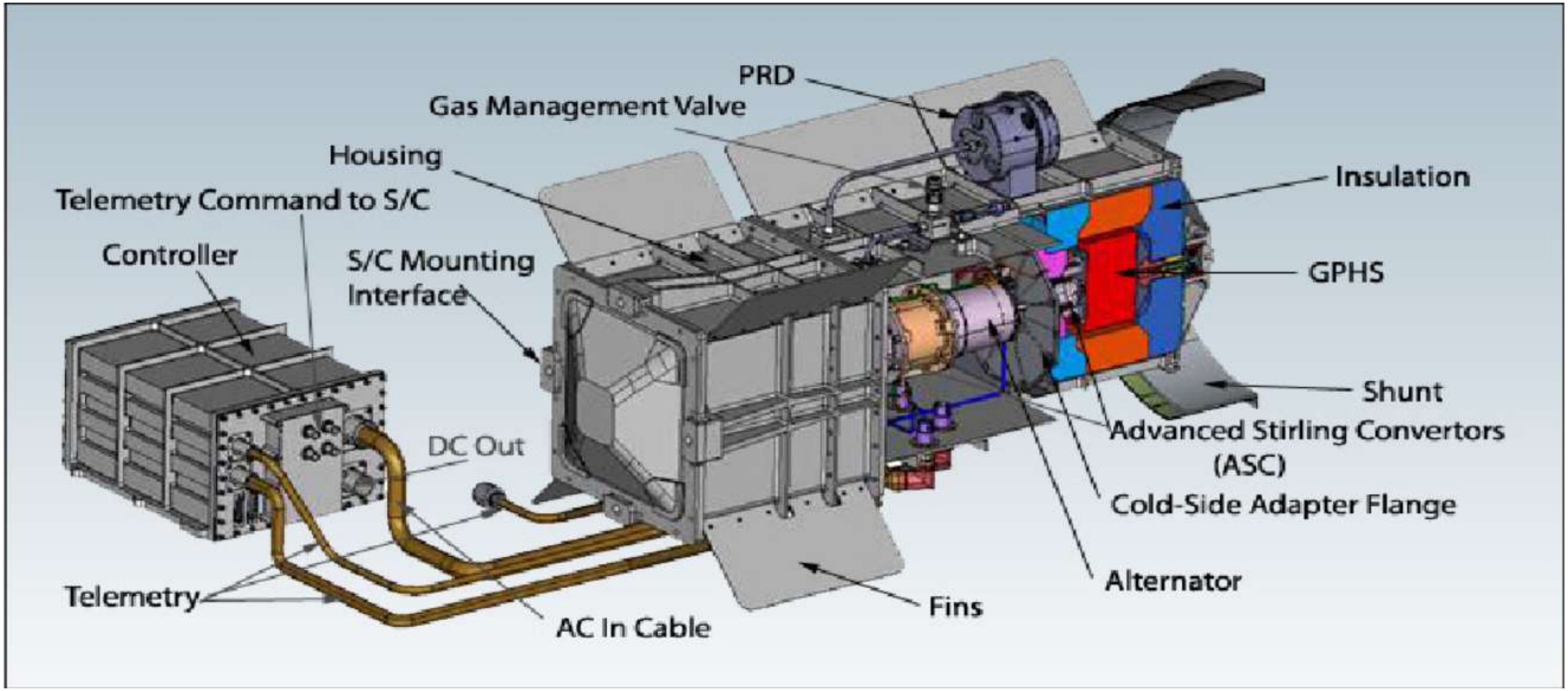
Cogeneration schemes used in Europe.

- heating;
- cooling;
- use of steam in industry;
- use of heat in agriculture.

Example in towns in Slovenia
Available steam capacities:

- steam of 12 bar (abs) pressure, 188°C temperature for Krka: 16 t/h;
- steam of 4.6 bar (abs) pressure, 190°C temperature for Vipap and Krka: 60 t/h.

Radioisotope thermoelectric generators (RTG)



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.

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 !

The End

AKW Krümmel

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

Technologically understood, several working research/test reactors

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

Pu breeding

Prevent additional n capture

U – Pu Cycle

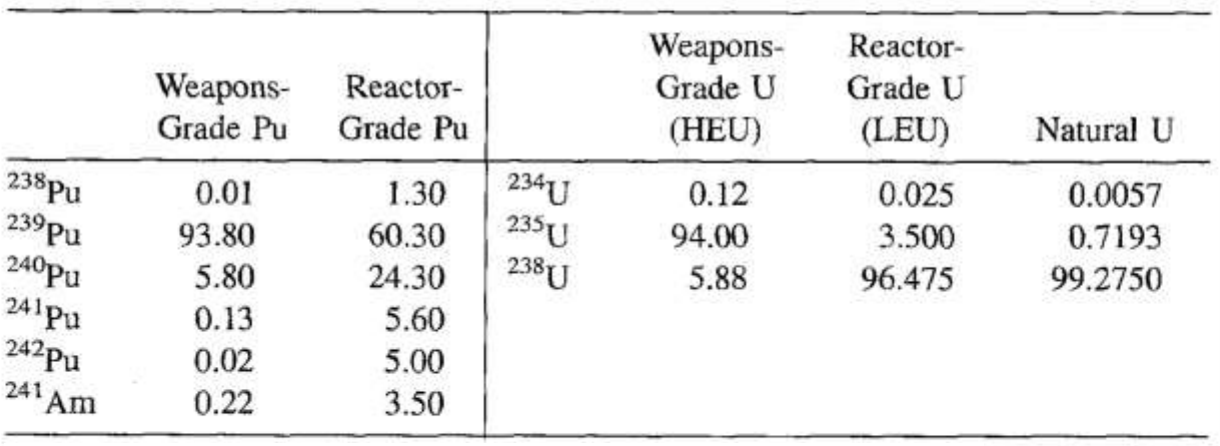
$$^{238}U + n \rightarrow {}^{239}_{92}U \xrightarrow[t_{1/2}=23\,\mathrm{min}]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.4d]{\beta^-} {}^{239}_{94}Pu\left(2.4\cdot 10^4\,a\right)$$

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

Continued n capture/β decay $^{239}_{94}Pu + n \rightarrow {}^{240}_{94}Pu \,|\, {}^{240}_{94}Pu + n \rightarrow {}^{241}_{94}Pu$

$$\Downarrow$$

$^{241}_{95}Am$

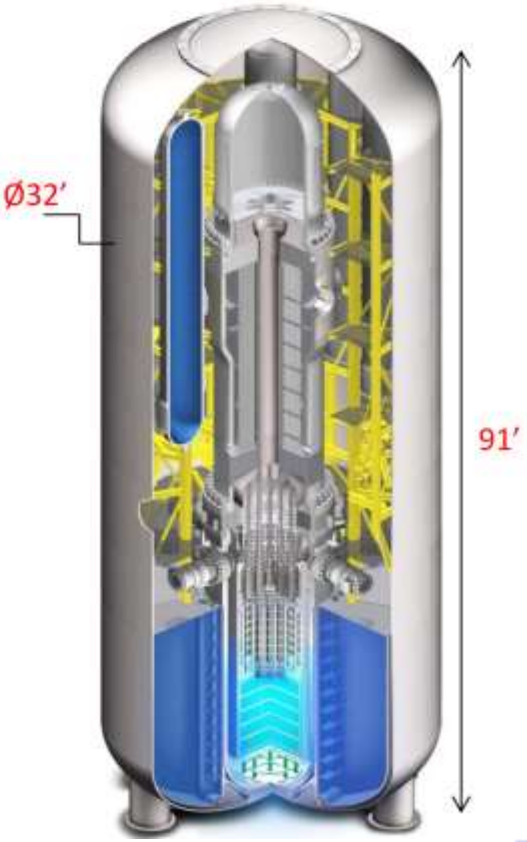


	Weapons-Grade Pu	Reactor-Grade Pu		Weapons-Grade U (HEU)	Reactor-Grade U (LEU)	Natural U
^{238}Pu	0.01	1.30	^{234}U	0.12	0.025	0.0057
^{239}Pu	93.80	60.30	^{235}U	94.00	3.500	0.7193
^{240}Pu	5.80	24.30	^{238}U	5.88	96.475	99.2750
^{241}Pu	0.13	5.60				
^{242}Pu	0.02	5.00				
^{241}Am	0.22	3.50				

W. M. Stacey, Nuclear Reactor Physics, Wiley Interscience., 2001

Above isotope mix: Not directly useful for nuclear fuel/weapons → extensive element/isotope separation needed

Westinghouse SMR Technology



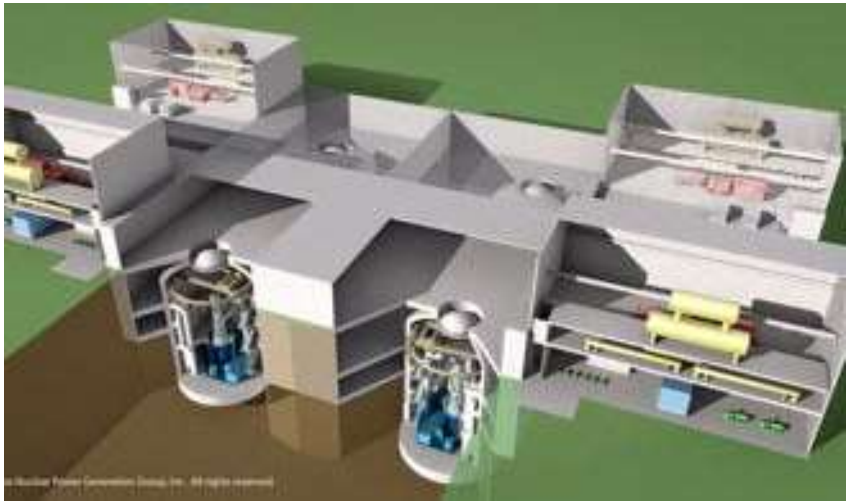
Thermal Output	800 MWt
Electrical Output	>225 Mwe
Passive Safety Systems	No operator intervention required for 7 days
Core Design	17x17 Robust Fuel Assembly 8.0 ft. Active Length < 5% Enriched U235 89 Assemblies Soluble Boron and 37 Internal CRDMs 24-Month Refueling Interval
Reactor Vessel Size	Outer Diameter: 12 ft. Height: 81 ft.
Upper Vessel Package	280 Tons
Containment Vessel Size	Outer Diameter: 32 ft. Height: 91 ft. Fully Modular Construction
Reactor Coolant Pumps	8 External, Horizontally-Mounted Pumps Sealless Configuration
Steam Generator	Recirculating, Once-Through, Straight-Tube
Pressurizer	Integral to Vessel
Instrumentation and Control	Ovation®-based Digital Control System

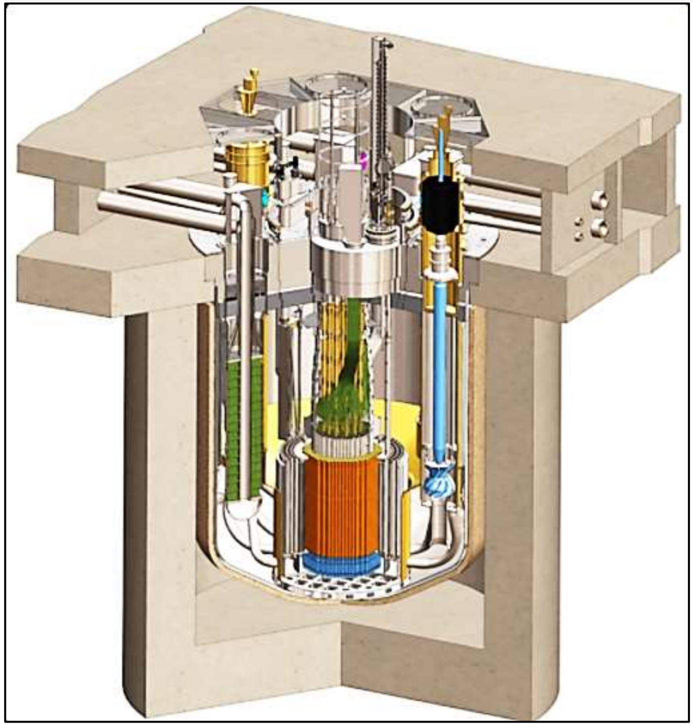
Developing: Super-Safe, Small, and Simple Modular Reactors

Prefabricated (GE A-1000 conventional PWR, comes in 300 prefab parts)
Only few standardized reactor designs.
Autonomous operation below grade without human interference,
→ self-fueling **breeder** (traveling wave) U/Th fuel

TerraPower Traveling-Wave

Additional companies: Hyperion 200 MW U/He
Babcock-Wilcox modular reactor





Core: enriched uranium U-235 rods surrounded by rods of depleted U-238/natural uranium. U-235 initiates a slow-moving “traveling wave” fission chain reaction delivering first neutrons for Th breeding.