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
  - Advanced (Gen II+, Gen IV) reactor designs,
  - U & Th breeder reactors, subcritical reactors,
  - Small modular reactors (SMR plants),
  - Closed fuel cycle,
  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)

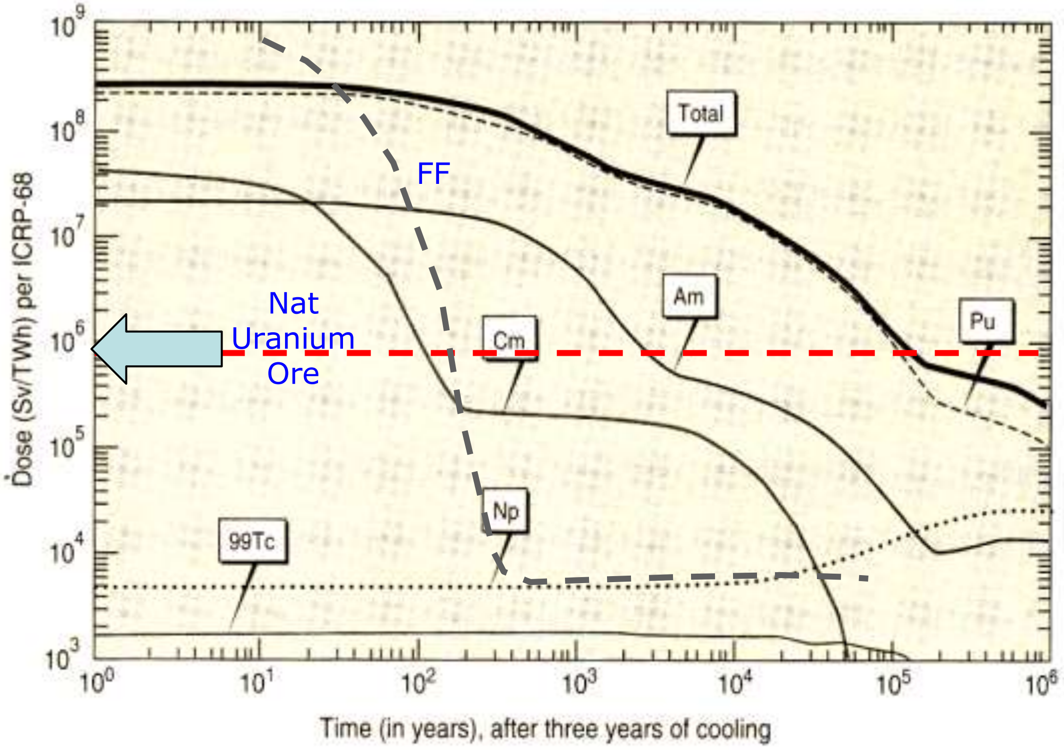
- Energy from nuclear fusion reactions
  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

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

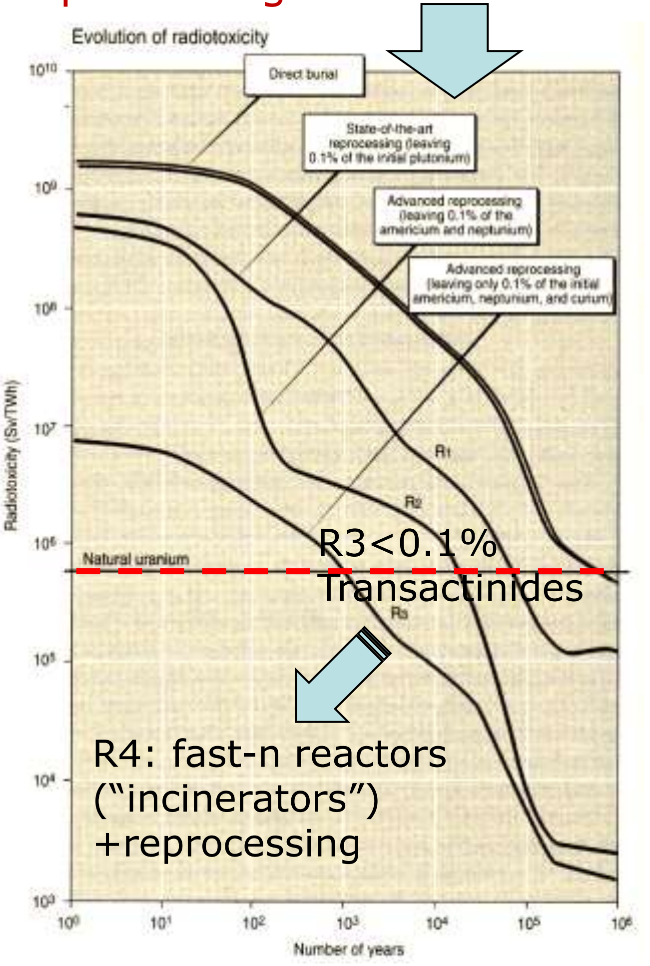
Reading Assignments

A&J; Ch. 9-10
LN 4.3

Radioactive Waste: Power Reactors/Weapons Stewardship



High-level waste depository for geological times → Yucca Mtns/NV ? Only radio-chem reprocessing of used fuel.



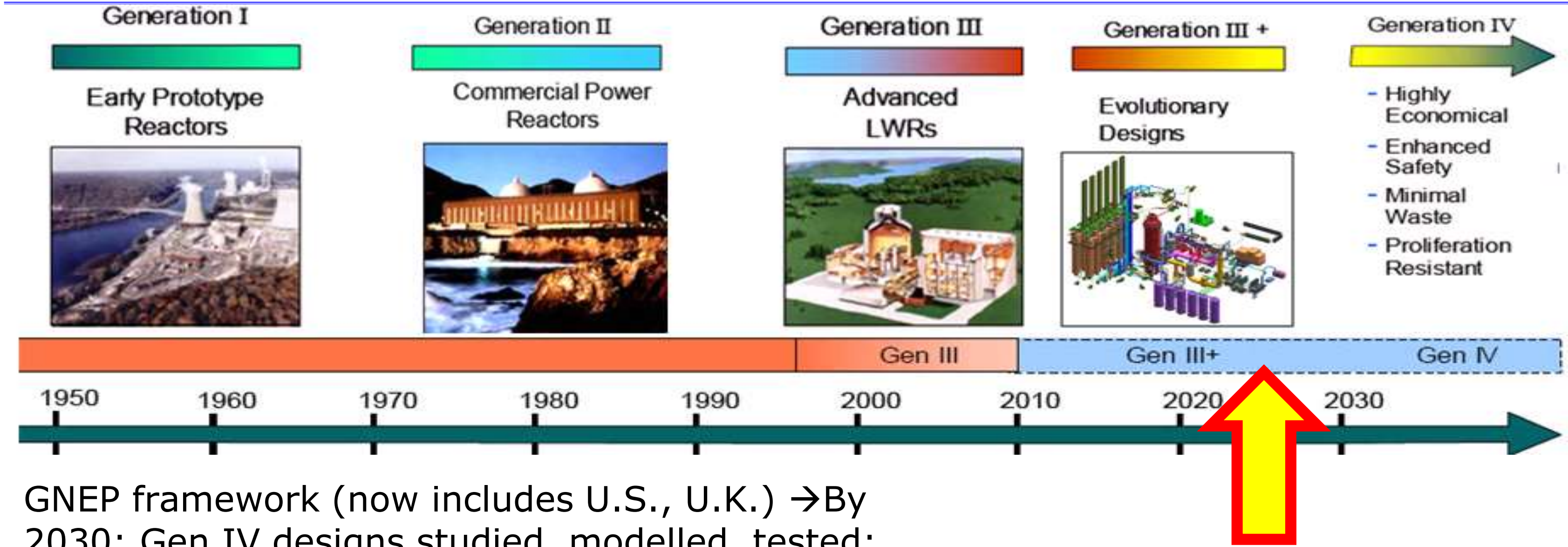
R4: fast-n reactors
("incinerators")
+reprocessing

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

Better: reprocessing eliminate Pu,Am,Np,Cu transmutation/incineration of ^{99}Tc, ^{129}I, Np

1 Sv (Sievert) = 100 rem, biolog. equivalent to 1J/kg X-rays
Radiotoxicity: R(Sv)=(Dose in Sv/decay), Activity/kg

Timeline of Reactor/Fuel Cycle Development



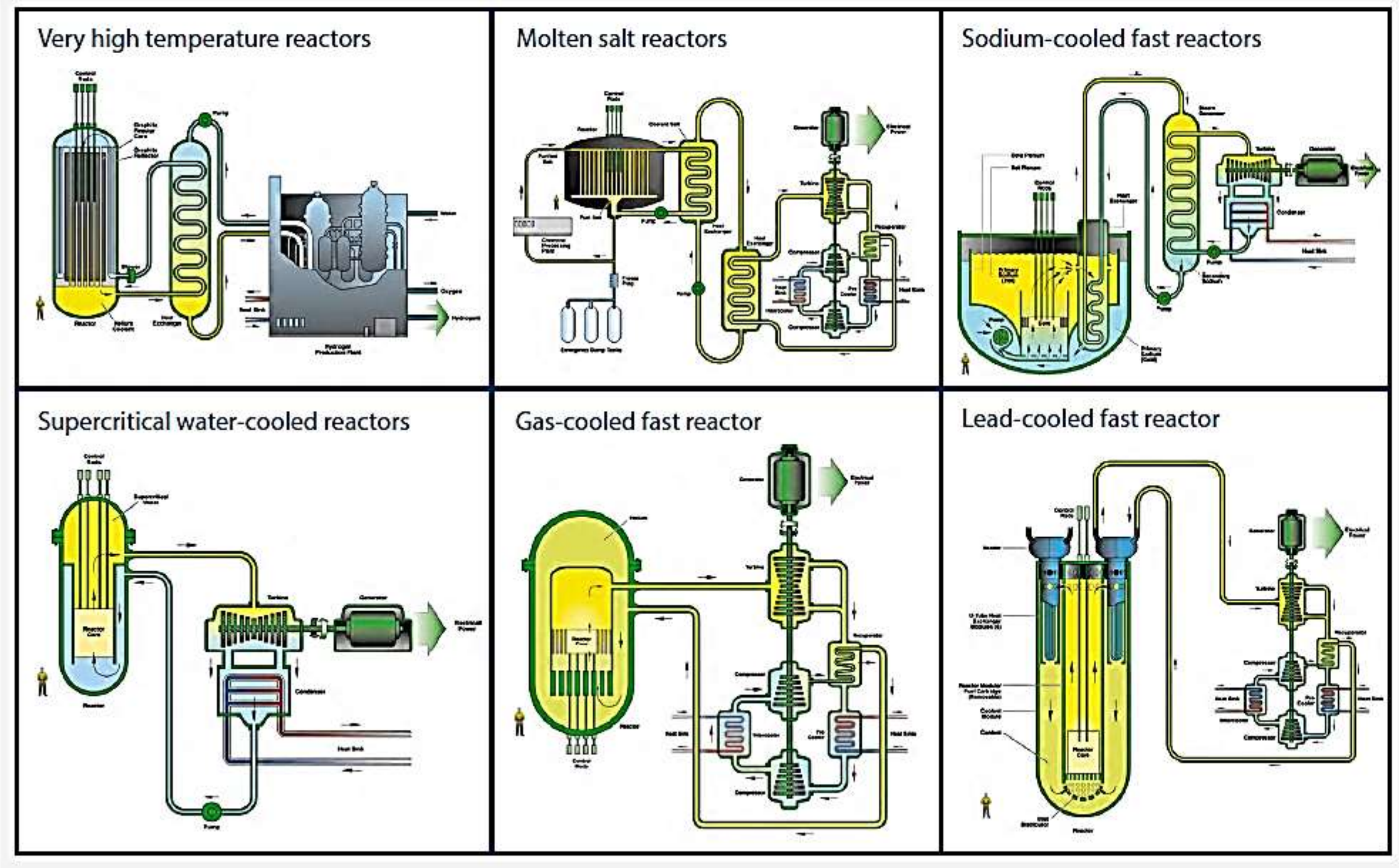
GNEP framework (now includes U.S., U.K.) →By 2030: Gen IV designs studied, modelled, tested:

- 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 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"

Nuclear Reactor Types Gen IV Systems



Very high temperature reactors

Molten salt reactors

Sodium-cooled fast reactors

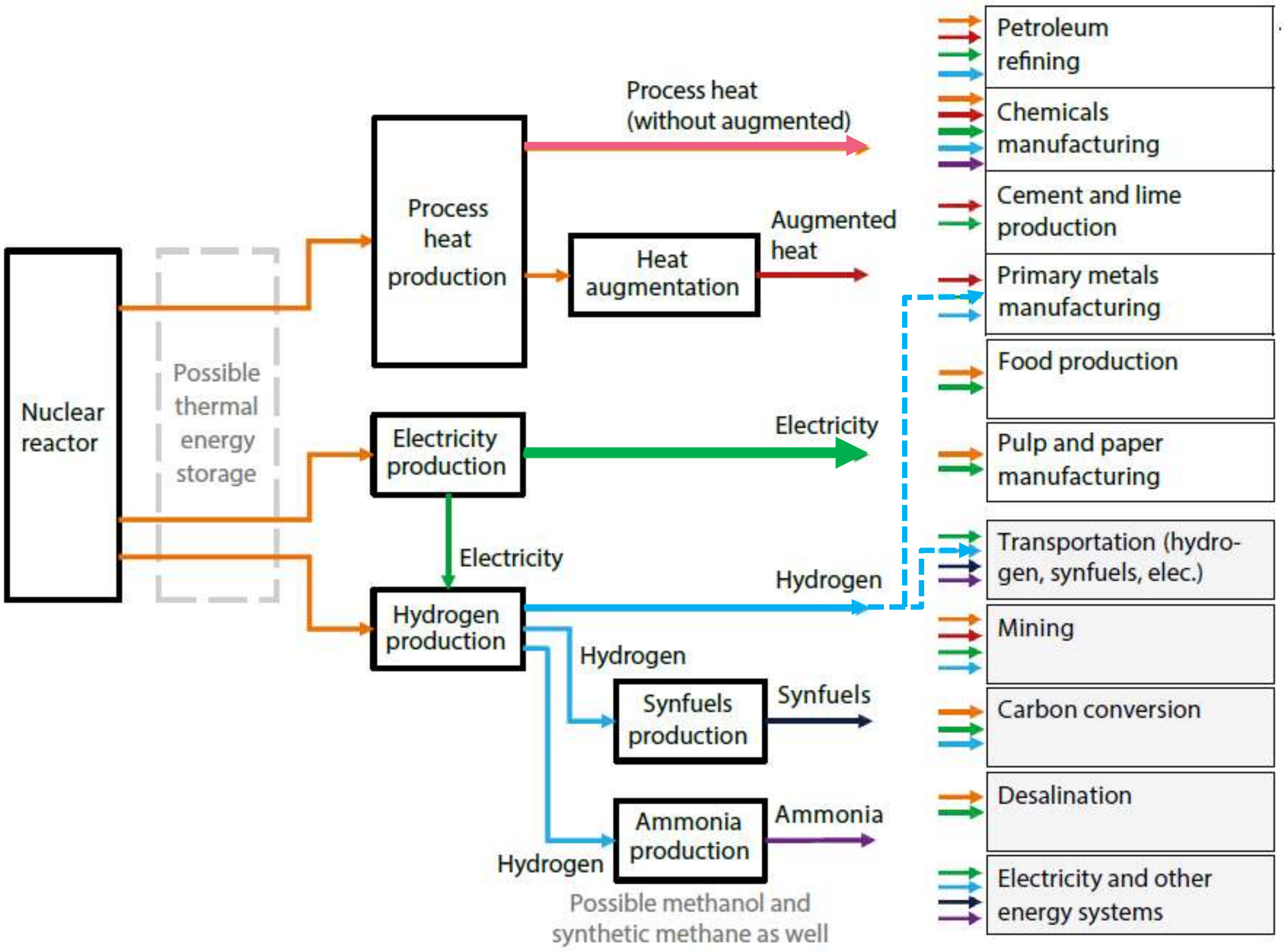
Supercritical water-cooled reactors

Gas-cooled fast reactor

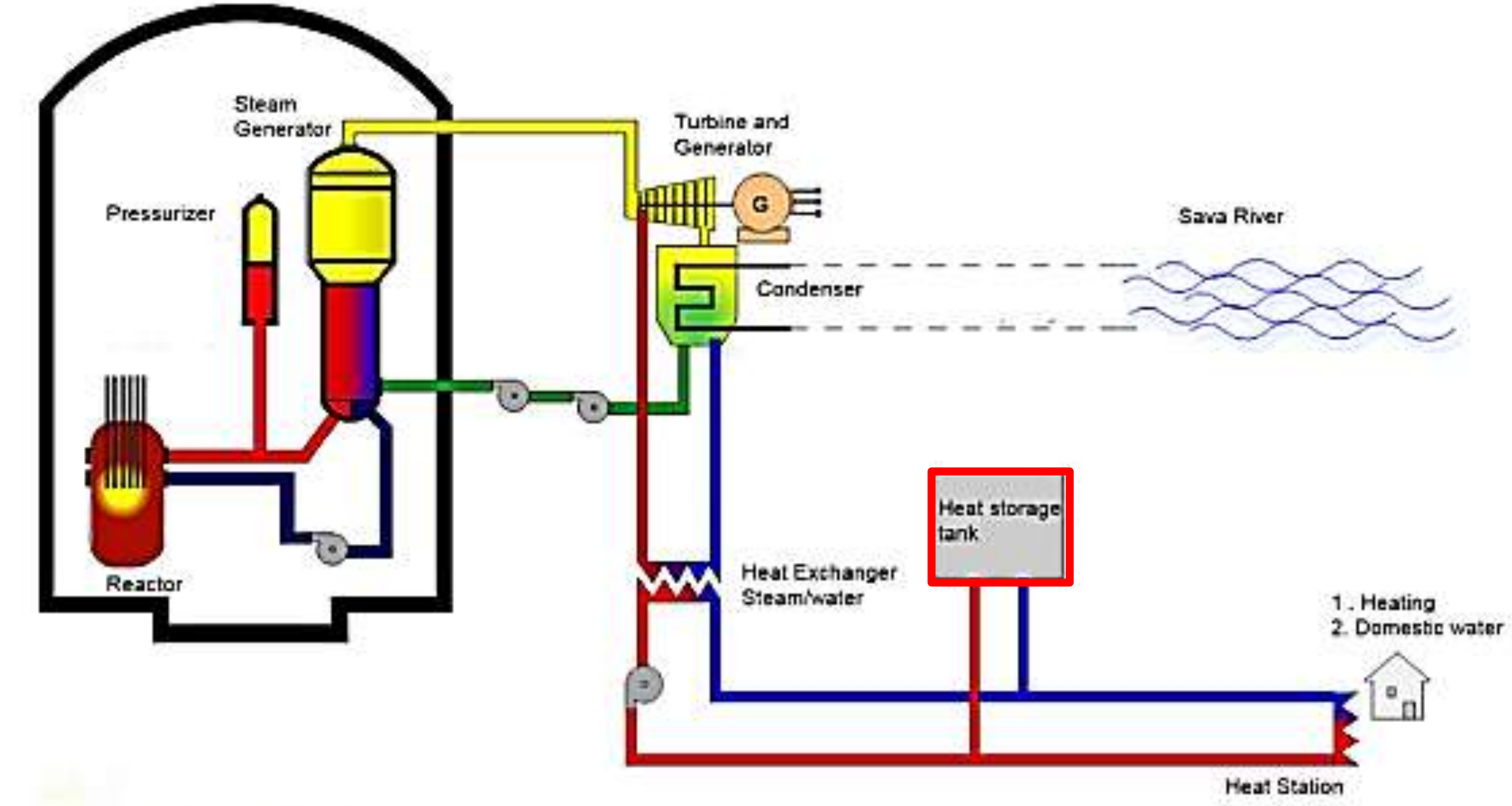
Lead-cooled fast reactor

Concepts: Gen III$^+$ Hybrid Energy Systems

Hybrid= electricity + co-production (of heat and new fuels)



Cogeneration in the Krško Nuclear Power Plant in Slovenia



Source: GEN Energija (2013).

Cogeneration schemes used in Europe.

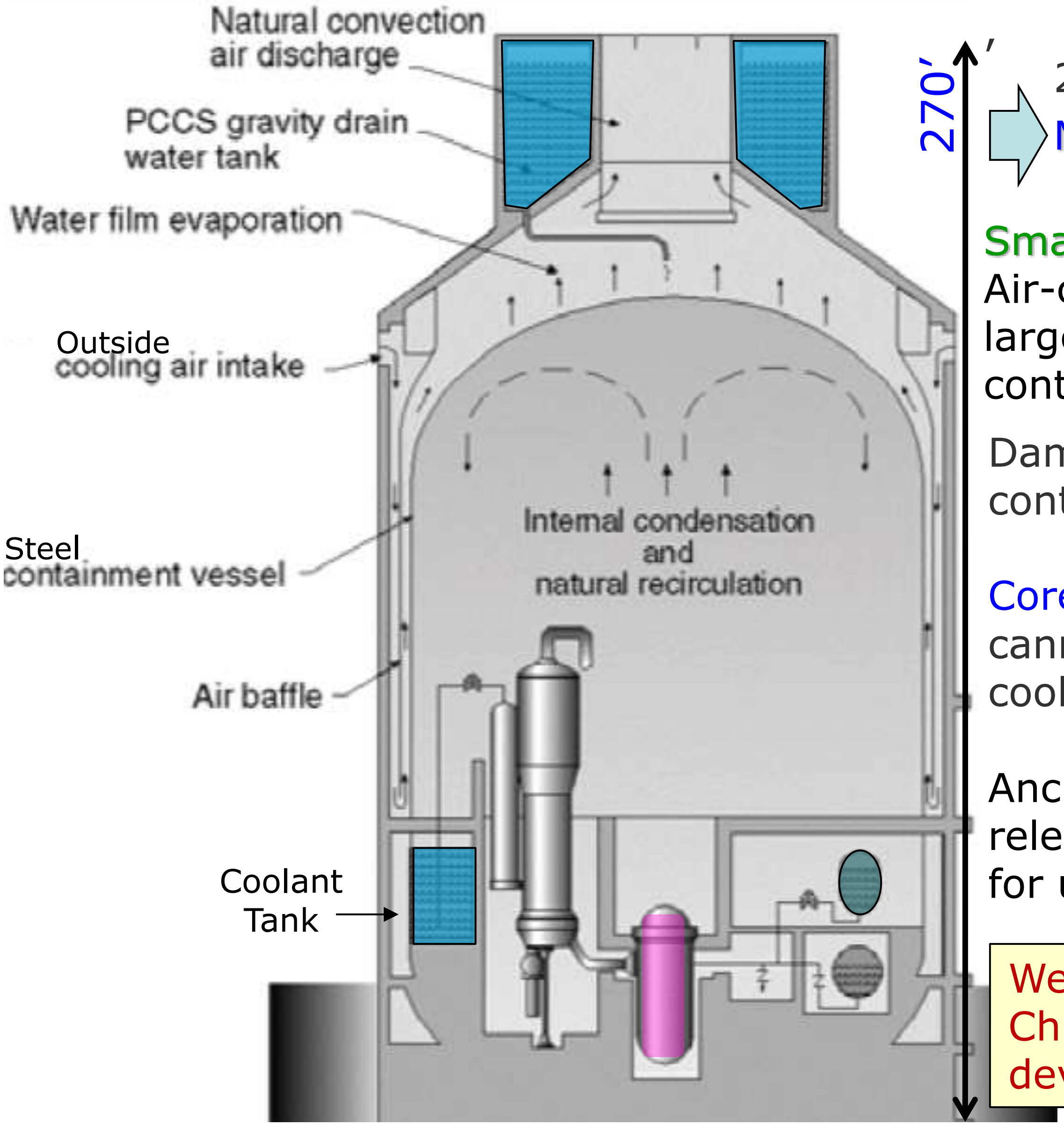
- heating;
- cooling;
- use of steam in industry;
- use of heat in agriculture.

Example in towns in Slovenia

Available steam capacities:

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

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.

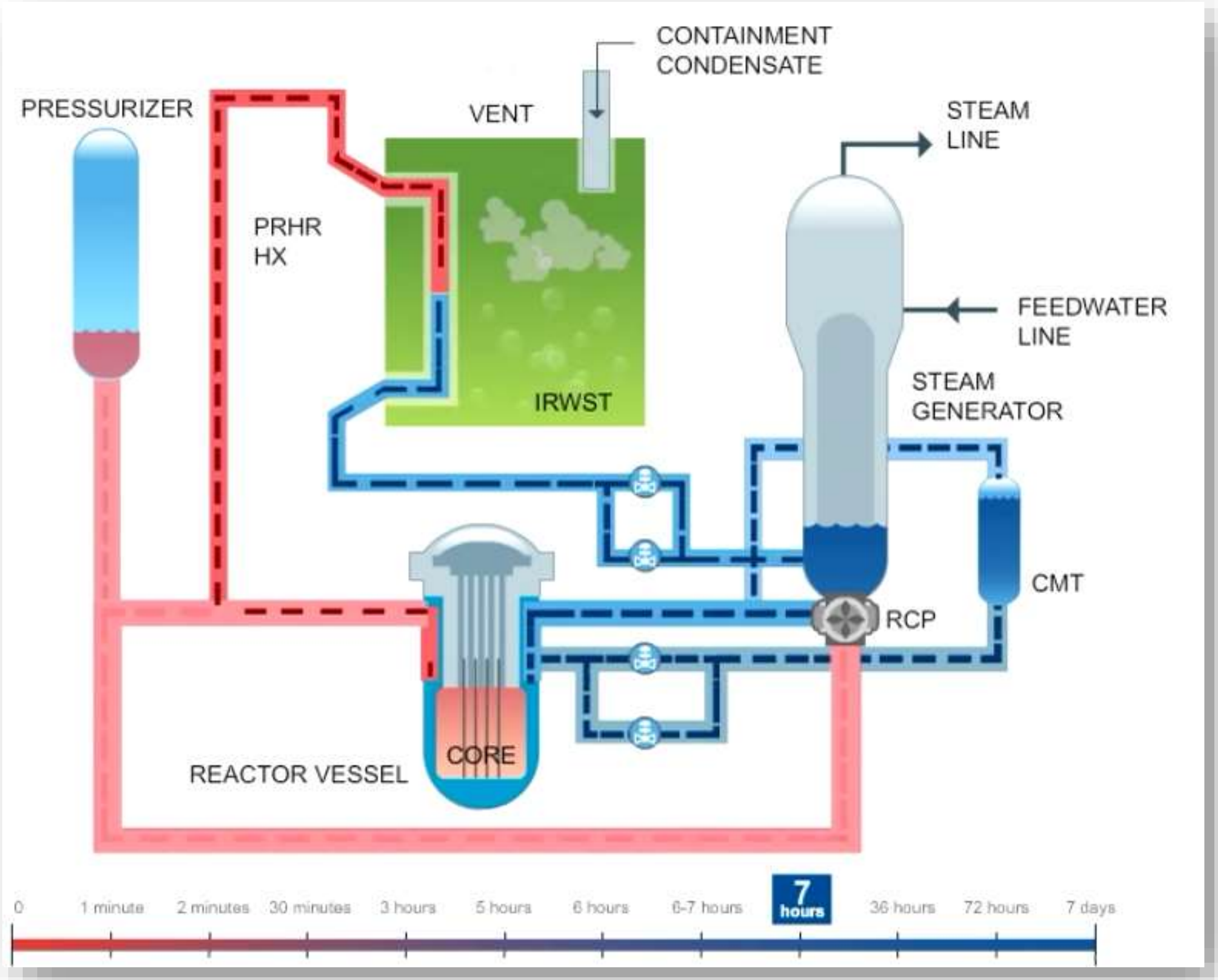
Damage-resistant pressure vessel contains all primary components

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

Passive Safety Features (Detail Westinghouse AP1000)



Station blackout → automatic shutdown:

Control rods drop into core → reactor shuts down.
Recirculation pump keeps running for hours on flywheel energy.

Core remains hot for a few days (decay heat).

Natural water circulation starts automatically (hot/cold density differences) transfers heat from reactor vessel to containment building.

Can go on "forever," autonomously=without operator intervention.

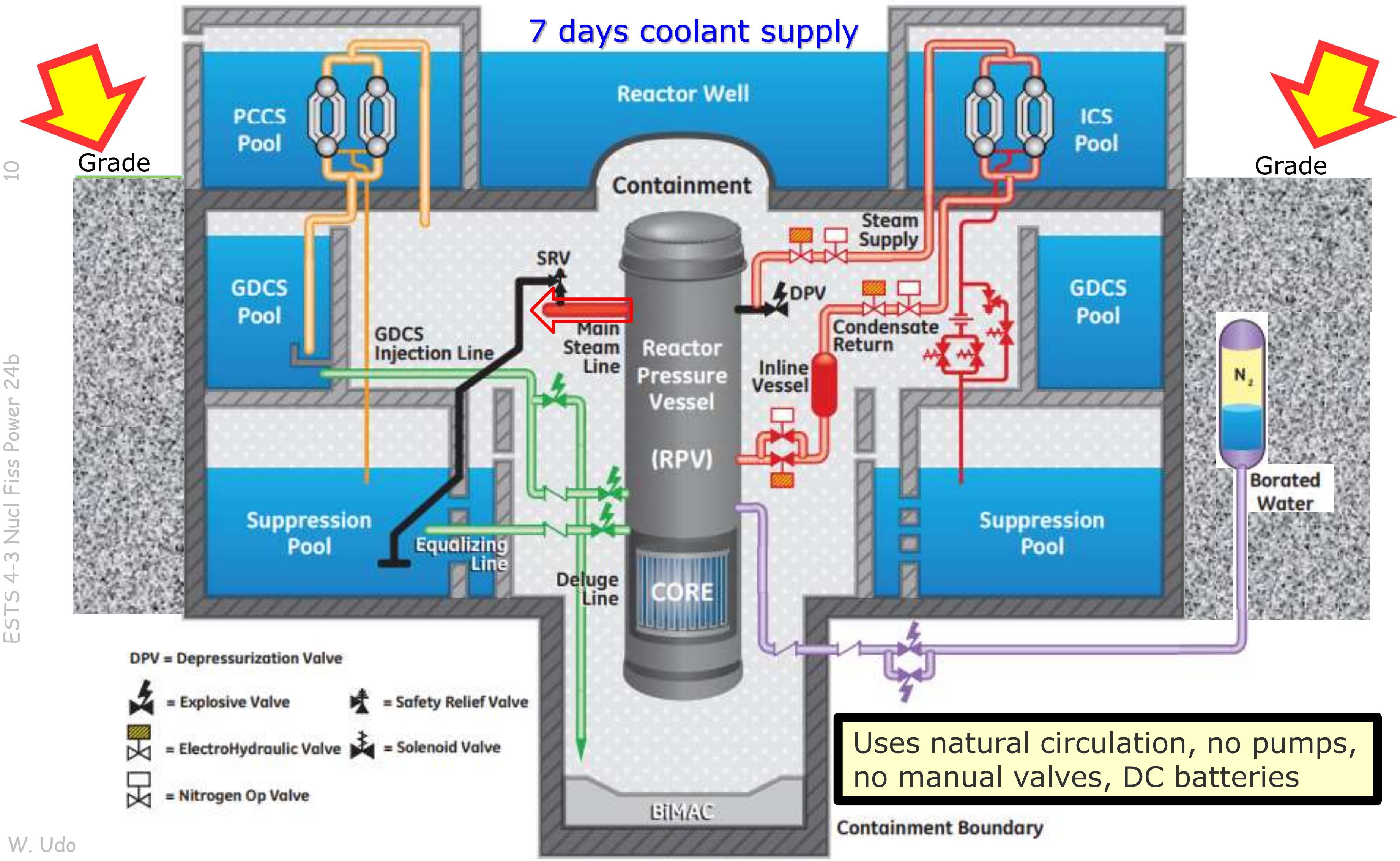
36 hrs: safe shutdown conditions are reached

ESBWR Passive Safety Systems (NRC Certified)

Passive Containment Cooling System (PCCS)
Gravity Driven Cooling System (GDCS)

Automatic Depressurization System (ADS)

Isolation Condenser System (ICS)
Standby Liquid Control System (SLCS)

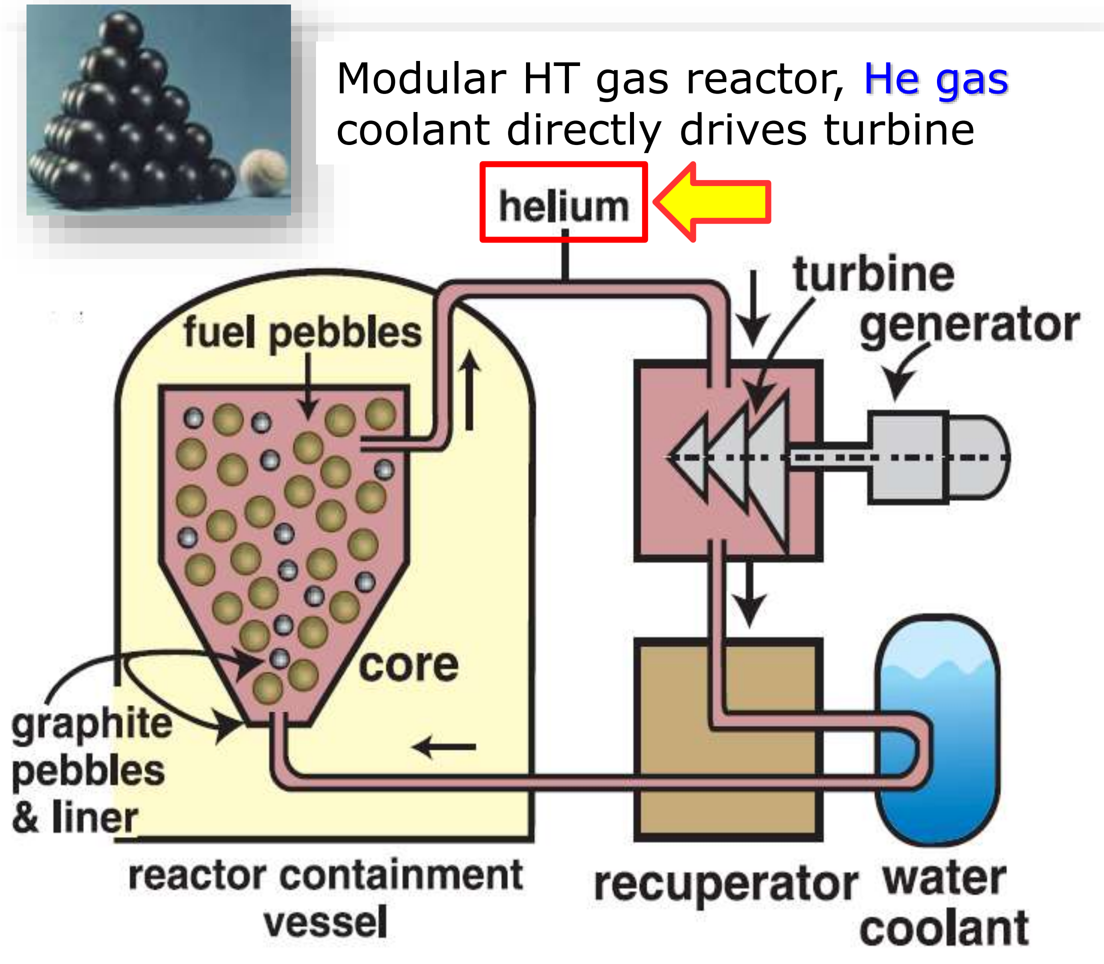


7 days coolant supply

Uses natural circulation, no pumps, no manual valves, DC batteries

Advanced Gen IV 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
$T \approx 950^0C$
C-moderator/reflector

Continuous throughput sorting & replacement of "pebble" fuel elements

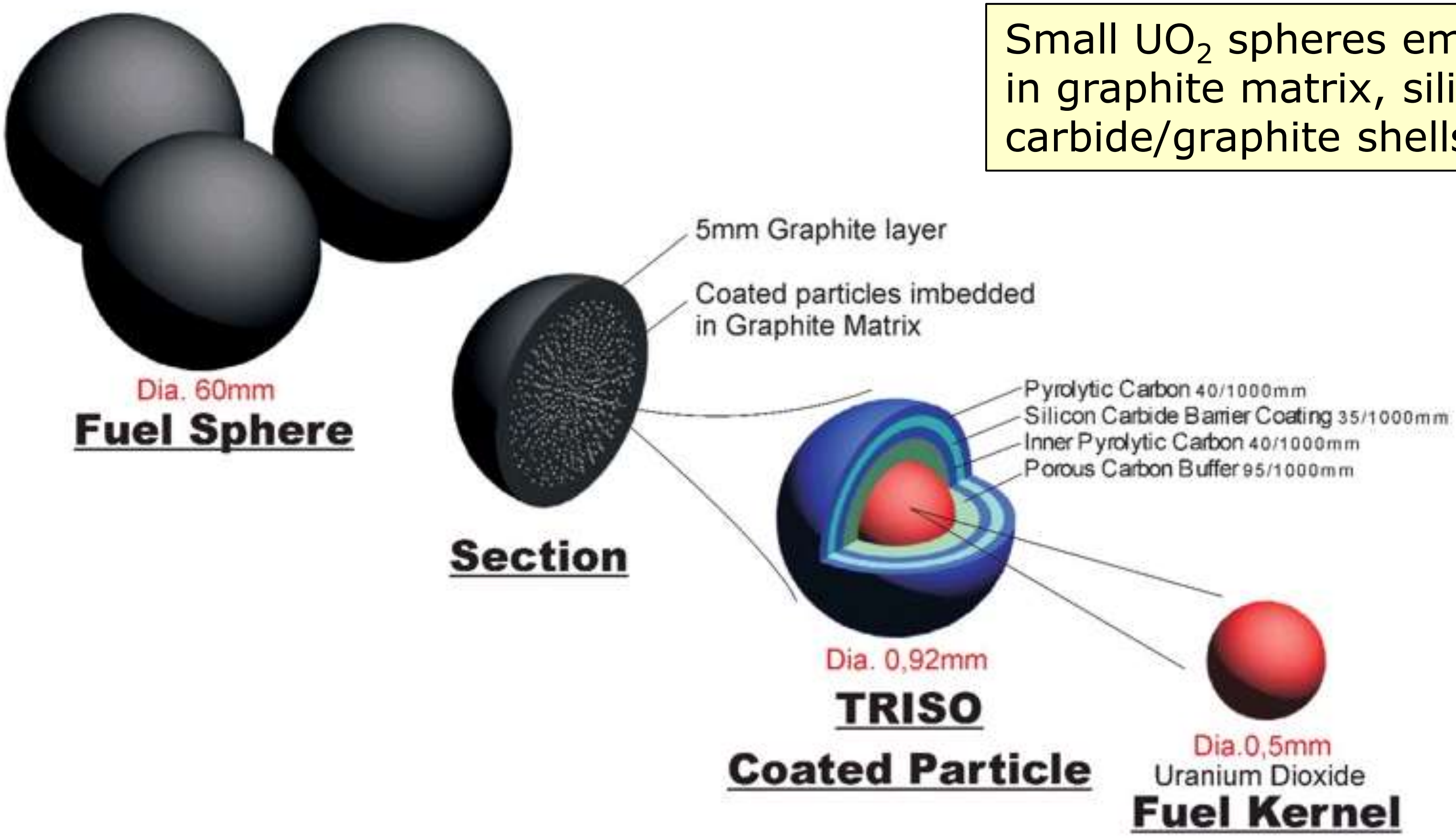
→Strongly negative reactivity

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

→Fail-safe operation.

Modular Pebble Bed Reactor TRISO Fuel Pebbles

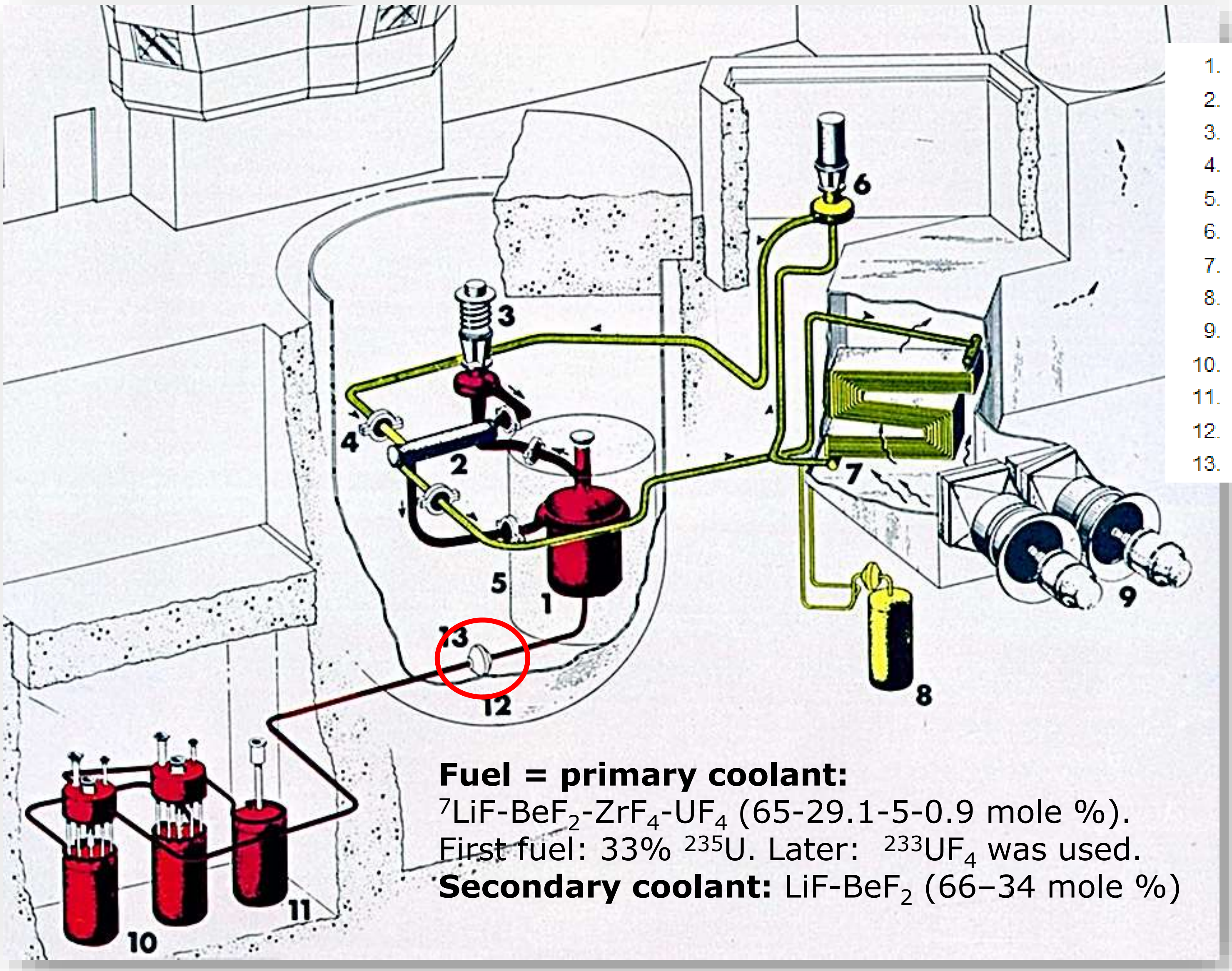
Small UO_2 spheres embedded in graphite matrix, silicon carbide/graphite shells



Proliferation resistant → difficult reprocessing, requires national facilities.

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

Gen IV Model: ORNL Molten Salt Reactor (Experiment 1964-69)



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

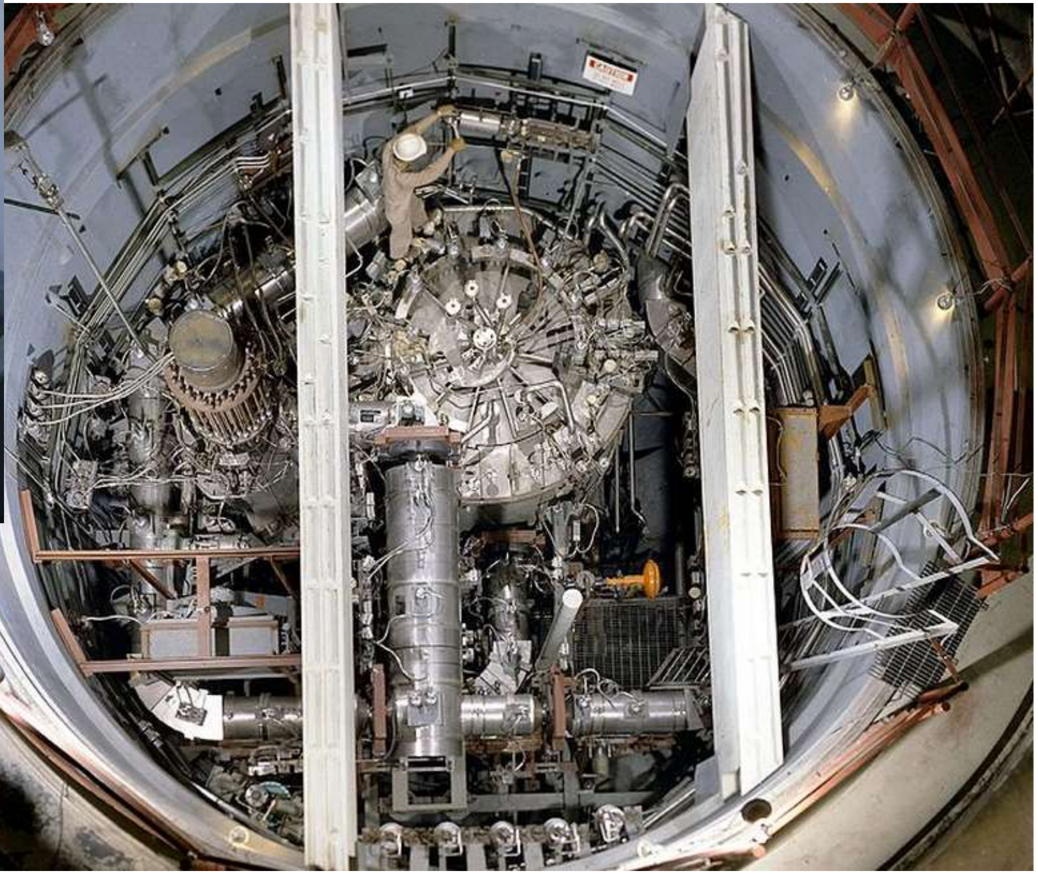
Fuel = primary coolant:
$^{7}LiF-BeF_2-ZrF_4-UF_4$ (65-29.1-5-0.9 mole %).
First fuel: 33% ^{235}U. Later: $^{233}UF_4$ was used.
Secondary coolant: $LiF-BeF_2$ (66–34 mole %)

US Molten Salt 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.

→ Can run as Th/U breeder→ ***LIFTR***

Development efforts in U.S. & several other nations.



The MSRE operated for 5 years: 1964 - 1969.
Objectives of experiment were achieved → viable reactor technology.
Lifetime of moderator 4-5 a.

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
  - Advanced (Gen II+, Gen IV) reactor designs,
  - U & Th breeder reactors, subcritical reactors,
  - Small modular reactors (SMR plants),
  - Closed fuel cycle,
  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)

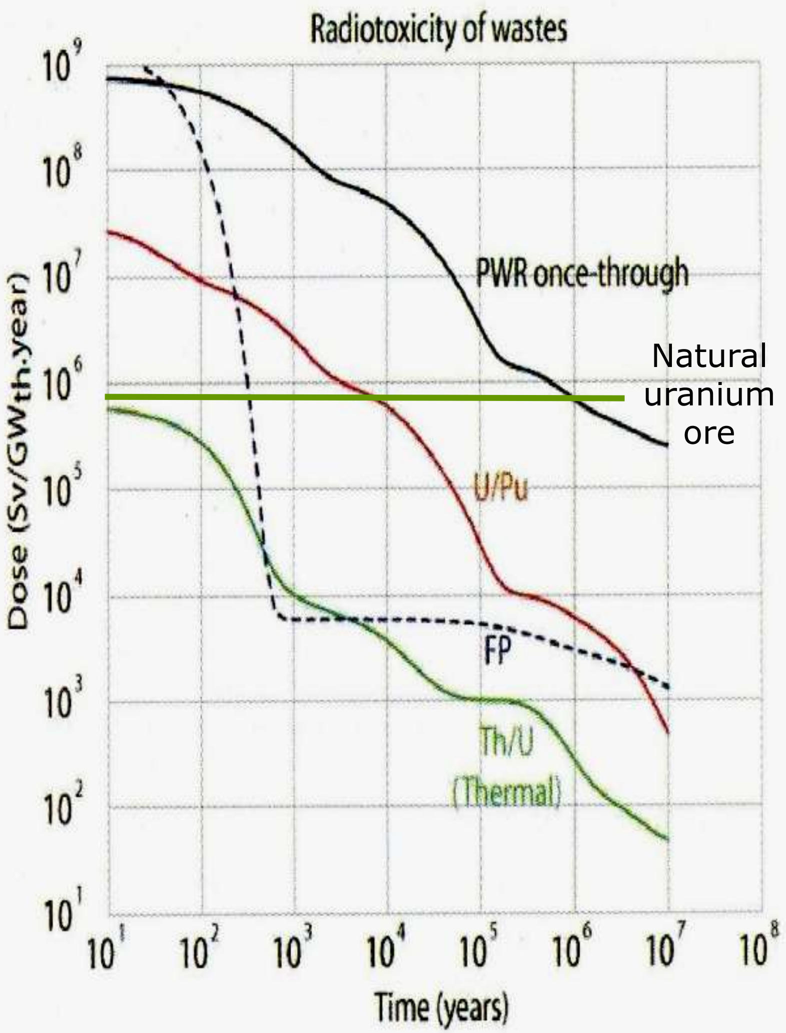
- Energy from nuclear fusion reactions
  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

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

Reading Assignments

A&J; Ch. 9-10
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, 2010)
443 (103) reactors
365 (100) GW

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

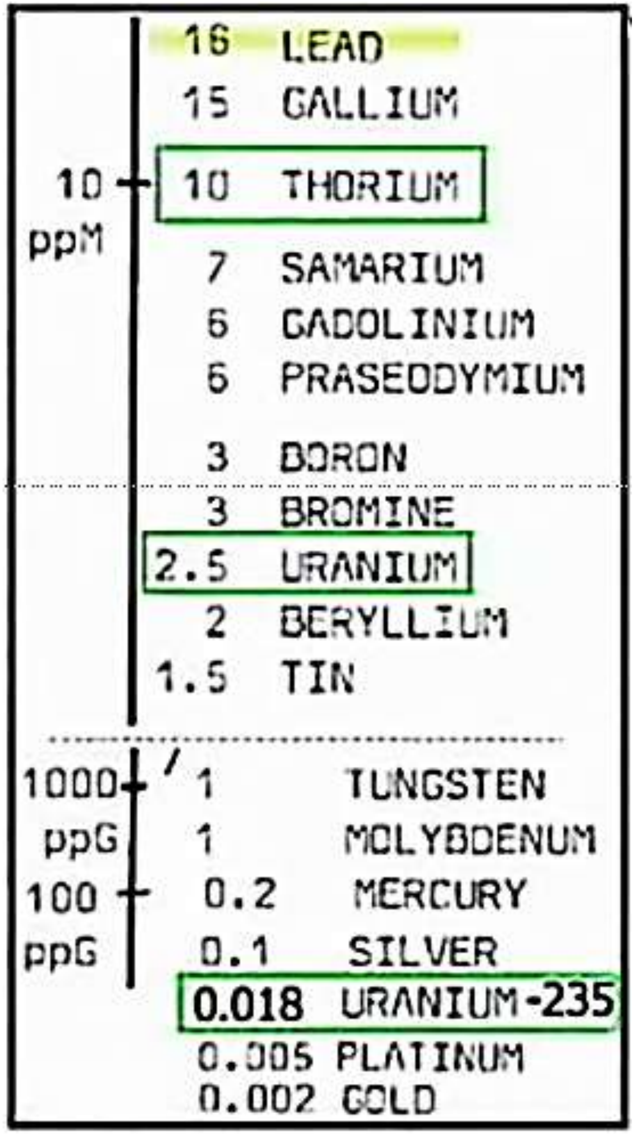
Reprocessing: ~10^3 years
US:174 t weapons grade U +20t/a Pu
for fuel mix (→ 0.2 Mt fuel)

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

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

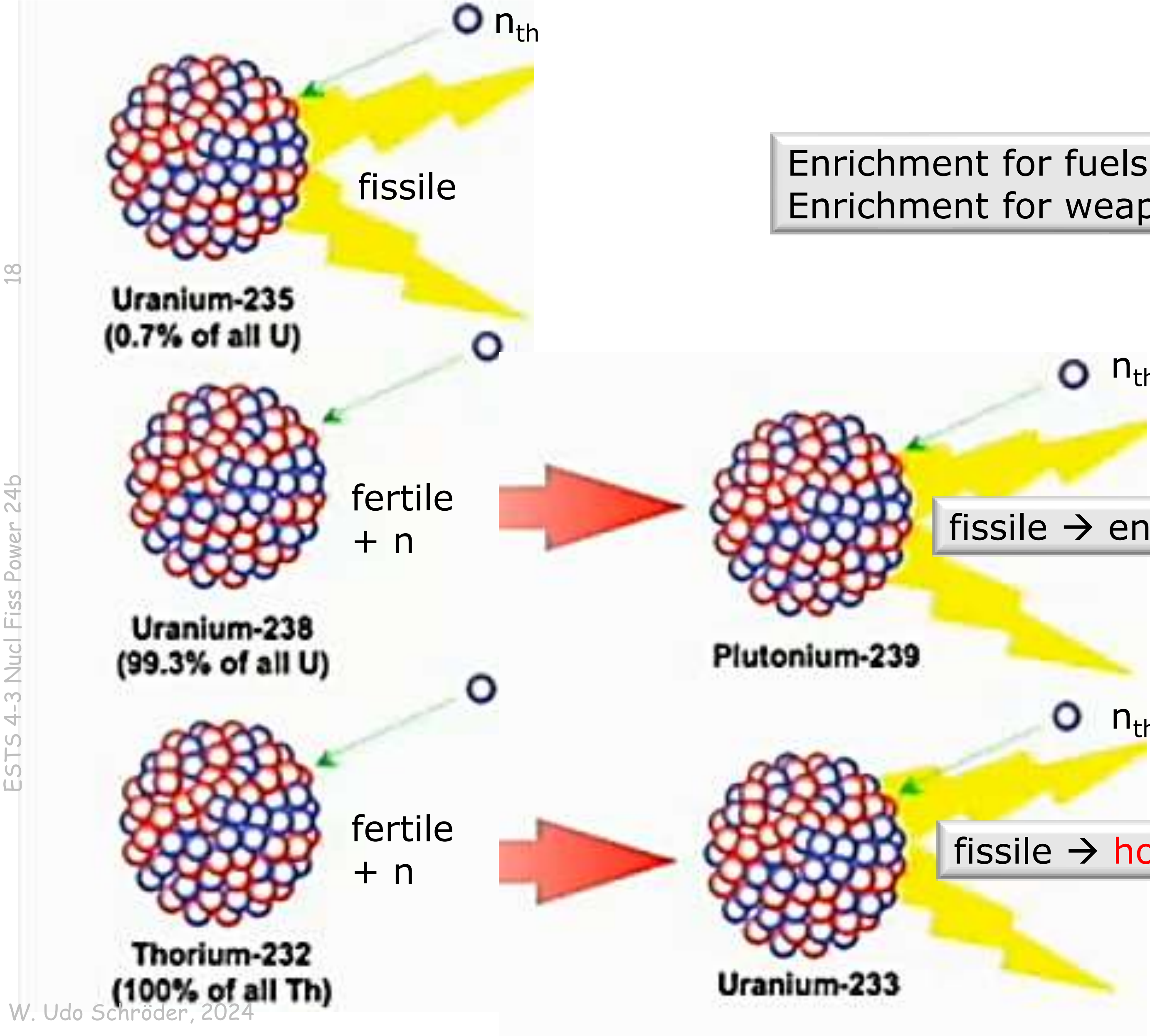
→ essentially sustainable energy source

Reserves in Earth crust



	16	LEAD
	15	GALLIUM
10 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

Fissile and Fertile Nuclear Fuels



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

fissile → enrichment→ weapons

fissile → hot enrichm.→weapons

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

Technologically well understood, several working research/test reactors

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

Additional n capture

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

U – Pu Cycle

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

Fissile by n_{th}

Unwanted continued fast-n capture/β decay

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

β^- decay

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

Isotope mix: Not useful for nuclear fuel/weapons

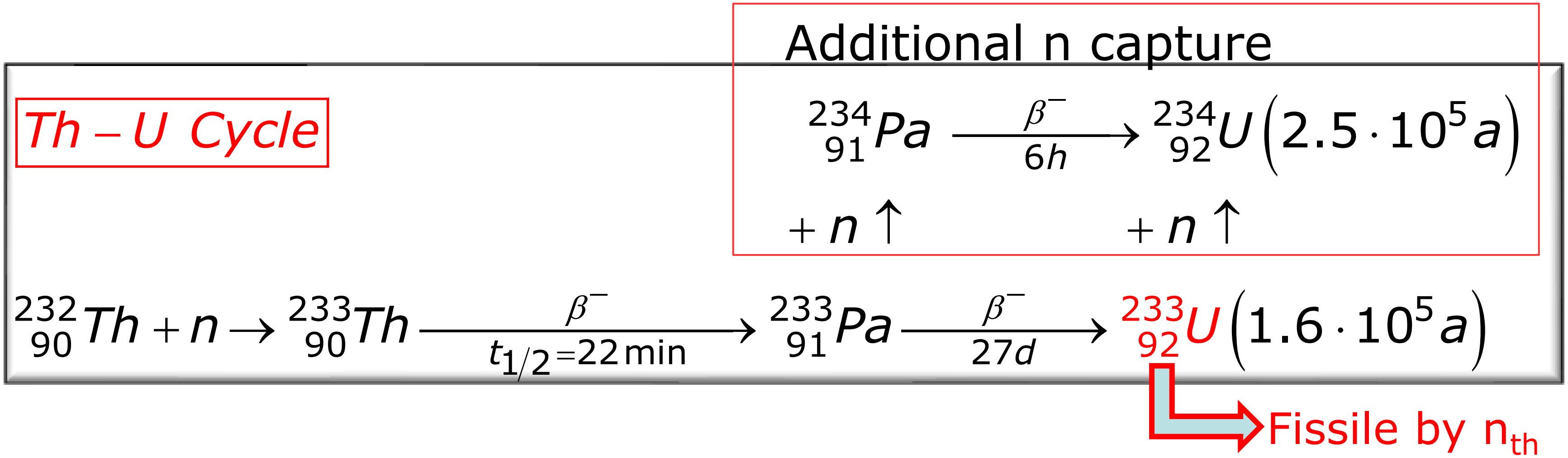
→ extensive isotope separation

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

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

Technologically well 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



Th – U Cycle

Additional n capture

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

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

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

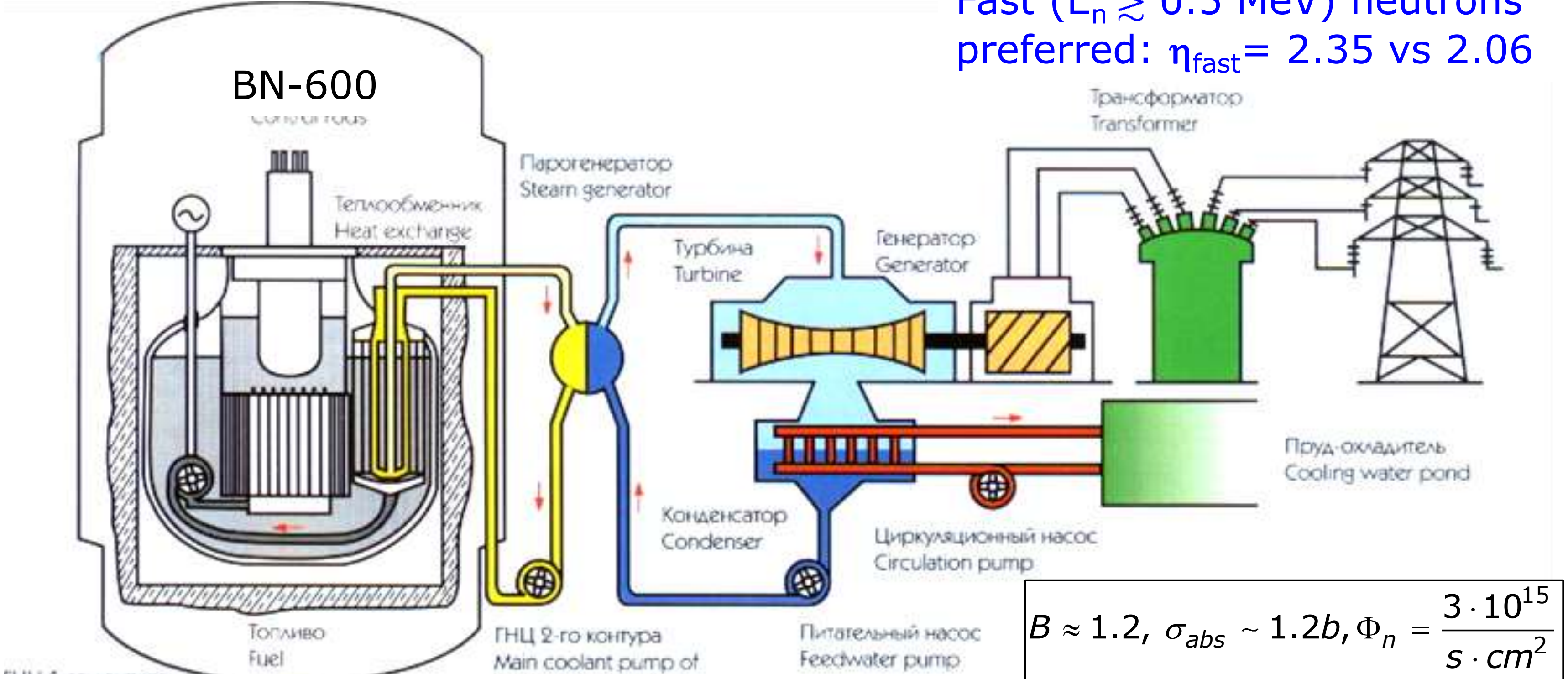
Fissile by n_{th}

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

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

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

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



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

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

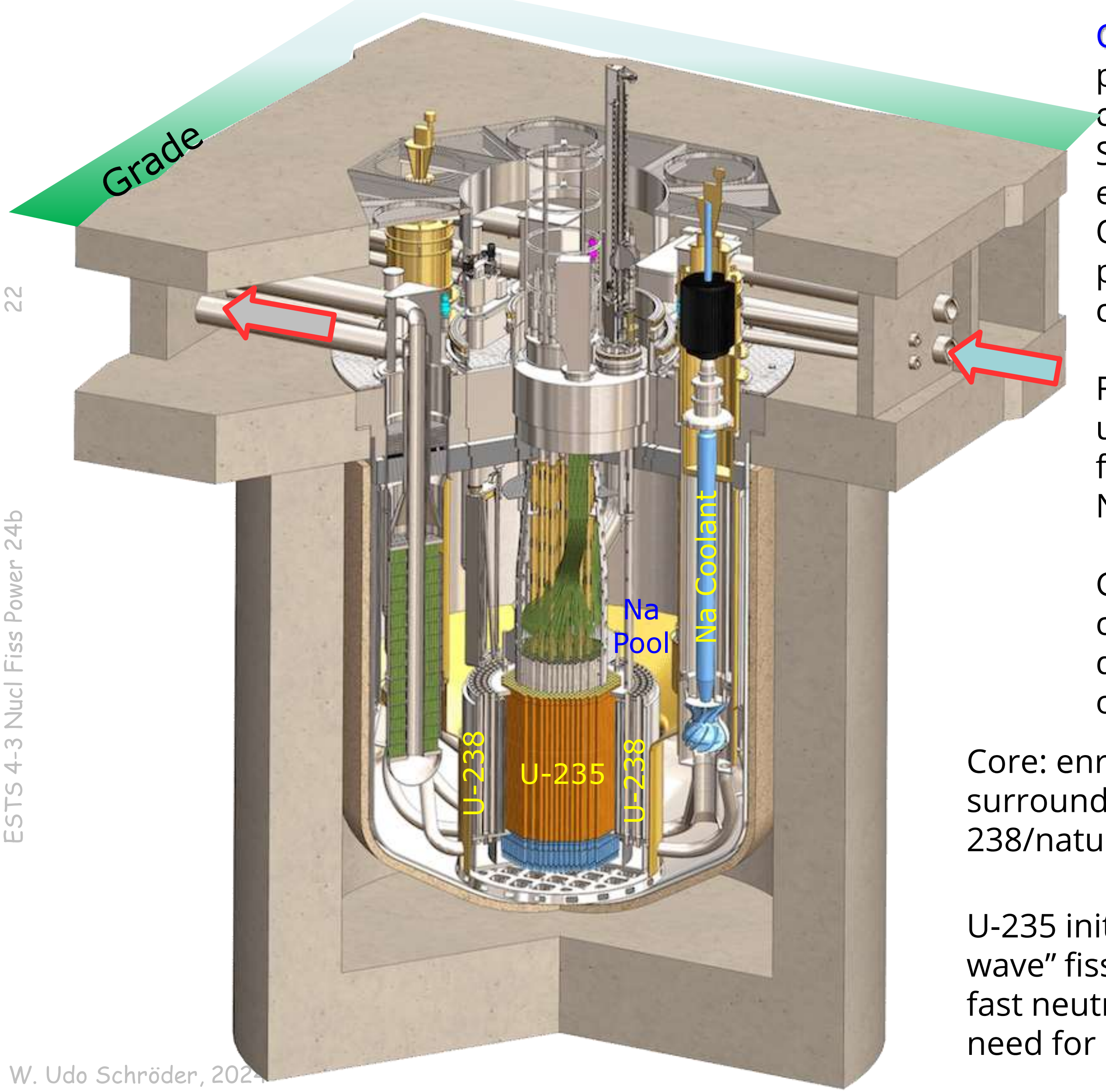
Core:45.5% ^{235}U; Blanket: 20 t UO_2
cooling/mod.: molten Na, K, magnetic pumps.

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) !

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

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

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.

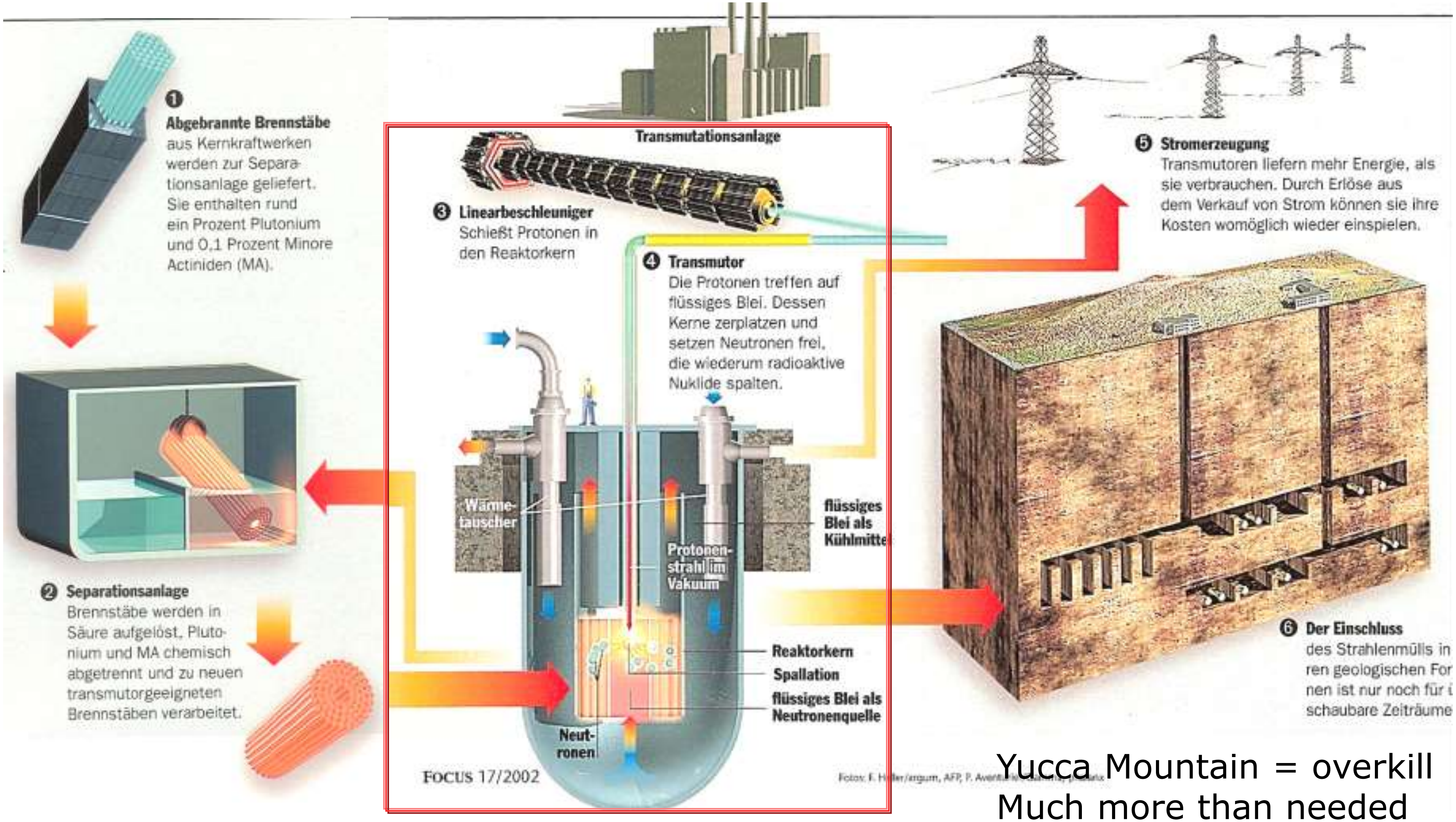
Generates heat by Rankine cycle and electricity over decades of continuous operation.

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



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

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

❸ **Linearbeschleuniger** Schießt Protonen in den Reaktorkern

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

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

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

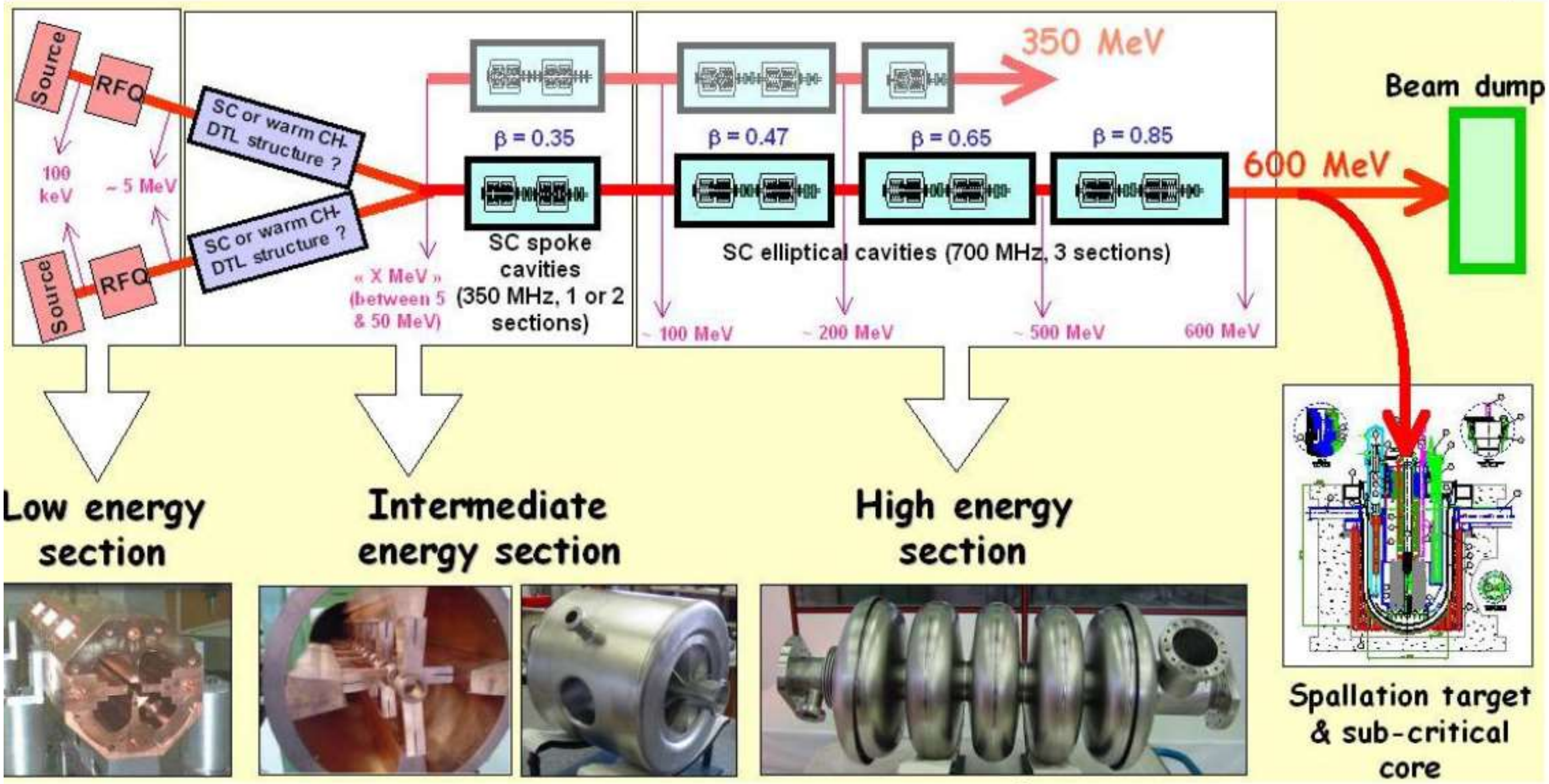
FOCUS 17/2002

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

Yucca Mountain = overkill
Much more than needed
with reprocessing

W. Udo Schröder, 2024

Myrrha ADS Demonstration Facility (Belgium)

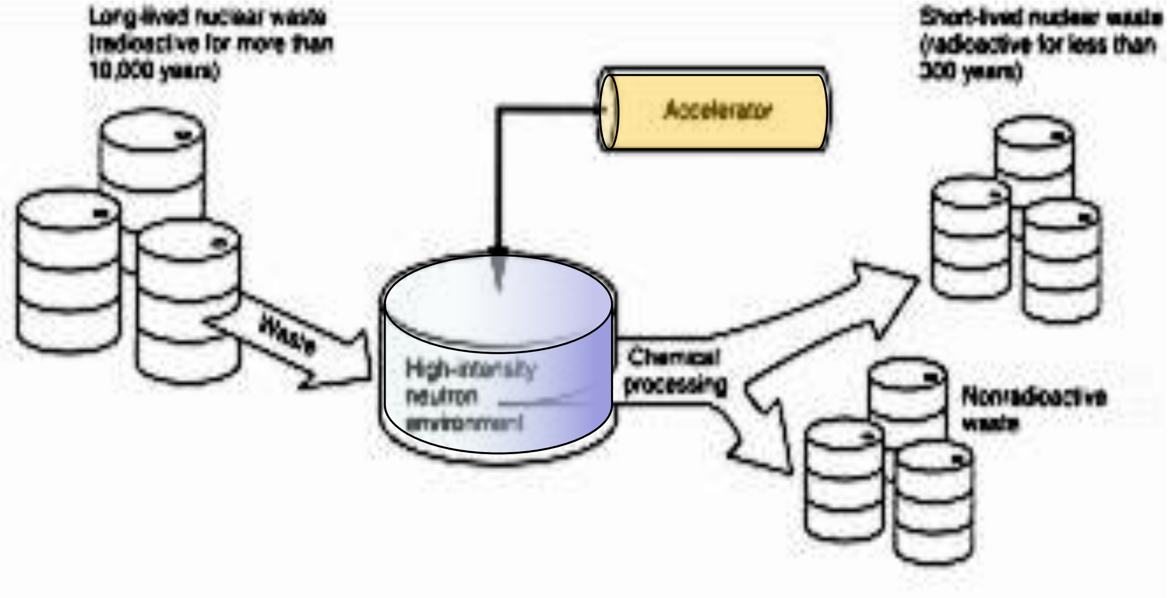


Strong R&D & construction programs for LINACs underway worldwide for many applications

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

Alex Müller, NN2012, San Antonio/TX, 2012

Nuclear Transmutation of Fission Products



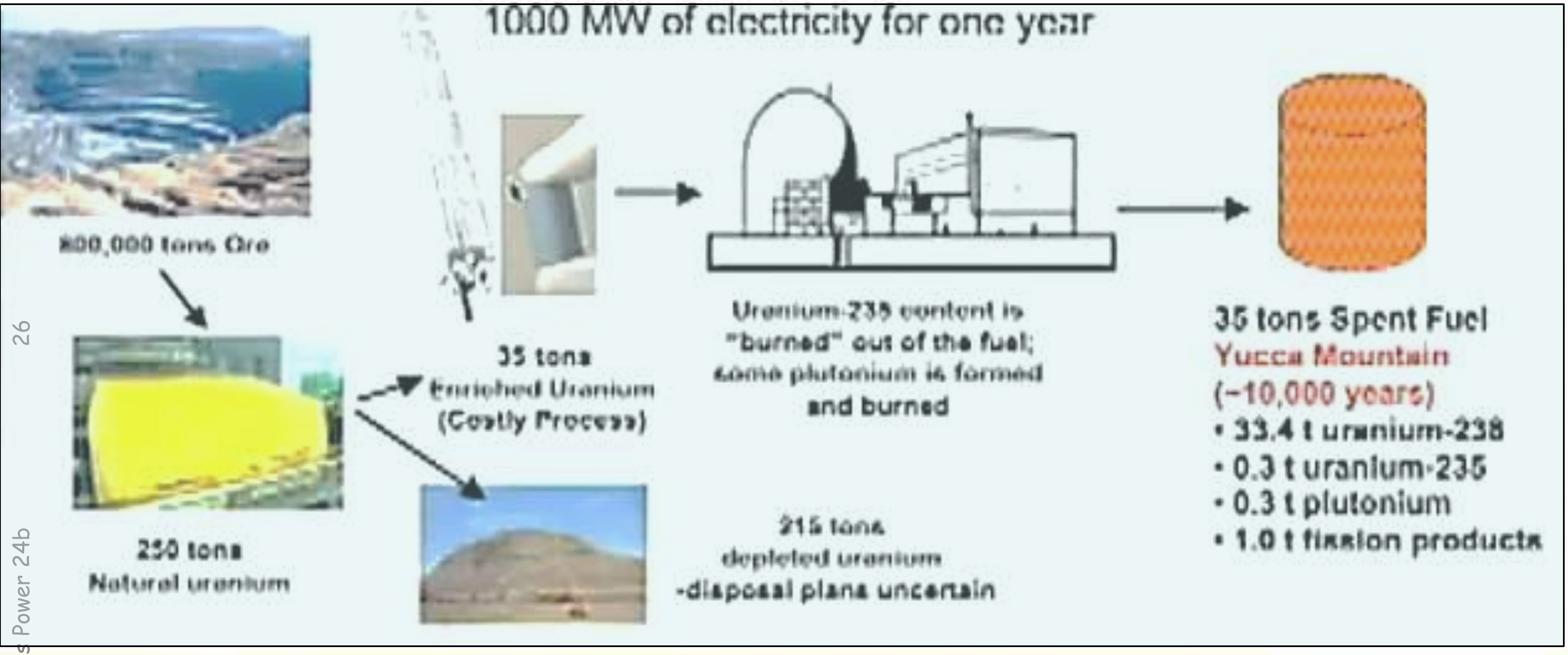
$$\left.\begin{aligned} {}^{99}Tc + n &\rightarrow {}^{100}Tc \xrightarrow[15.8s]{\beta^-} {}^{100}Ru \\ {}^{129}I + n &\rightarrow {}^{130}I \xrightarrow[12.4h]{\beta^-} {}^{130}Xe \end{aligned}\right\} \text{stable isotopes}$$

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

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

Uranium Fuel Cycle vs. Thorium



1000 MW of electricity for one year

800,000 tons Ore

250 tons
Natural uranium

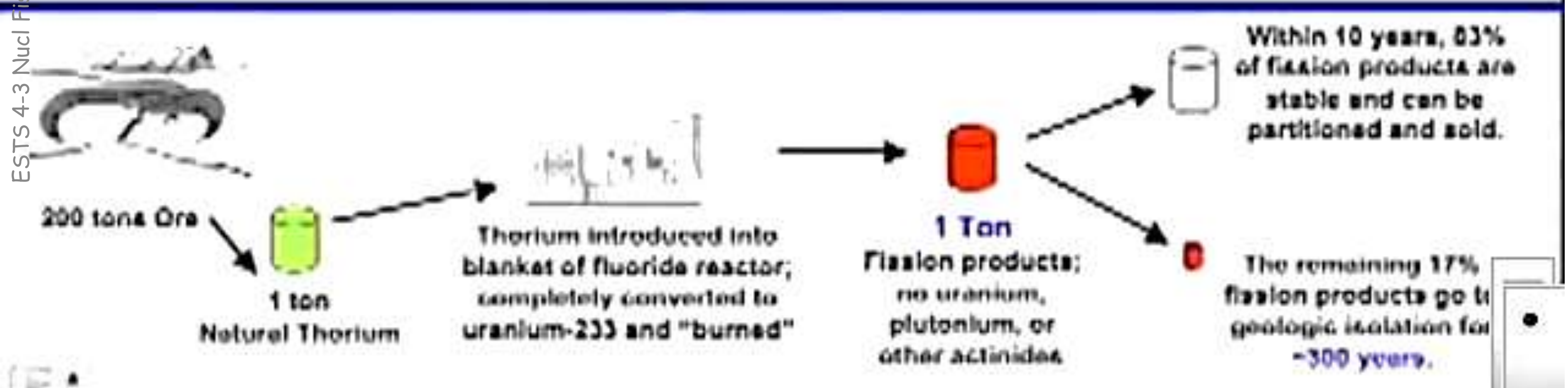
35 tons
Enriched Uranium
(Costly Process)

215 tons
depleted uranium
-disposal plans uncertain

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

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.

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
  - Advanced (Gen II+, Gen IV) reactor designs,
  - U & Th breeder reactors, subcritical reactors,
  - Small modular reactors (SMR plants),
  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)
  - Closed fuel cycle,

- 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

Reading Assignments

A&J; Ch. 9-10
LN 4.3