Broad topic	Lecture title
Basic principles of NPP	Introduction / Review of nuclear physics
	Interaction of neutrons with matter
	Nuclear fission
	Fundamentals of nuclear reactors
	LWR plants
Modeling the beast	The diffusion of neutrons - Part 1
	The diffusion of neutrons - Part 2
	Neutron moderation without absorption
	Neutron moderation with absorption
	Multigroup theory
	Element of lattice physics
	Neutron kinetics
	Depletion
Reactor Concepts Zoo	Advanced LWR technology
	Breeding and LFR
	AGR, HTGR
	Channels, MSR and thorium fuel
Review session	

THIS LESSON…

- Gas cooled reactors
- High Temperature Gas Cooled Reactors

Gas Cooled Reactors

- Concept
  - Thermal (prototypes existing) or fast reactors (no prototypes)
  - Gaseous coolant combined with a solid moderator and fuel located in channels in the moderator block, all inside a pressure vessel
- Advantages of the concept
  - Gaseous coolants much less corrosive, low to very low activation
  - Low neutron absorption by gaseous coolants, natural uranium reactors possible (in combination with graphite or heavy water)
  - High temperature reactors are feasible (in case of helium as coolant)
  - Refueling during operation possible in some concepts (some gas-cooled reactors were used to breed weapon grade plutonium…)
- Disadvantage
  - Low power density, bad heat transfer properties of gaseous coolant

Calder Hall (1956) = Magnox Reactor

Coolant: CO_2

Moderator: Graphite

Power: 61 $MW_{el,\ brutto}$, 270 MW_{th}

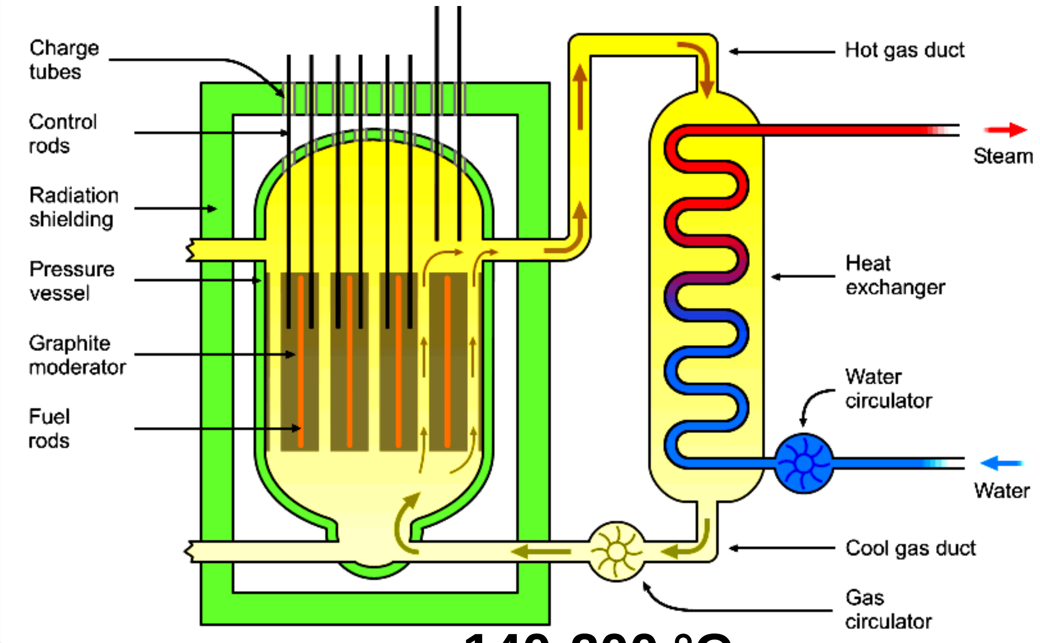
Fuel: Natural uranium

Cladding: Magnox

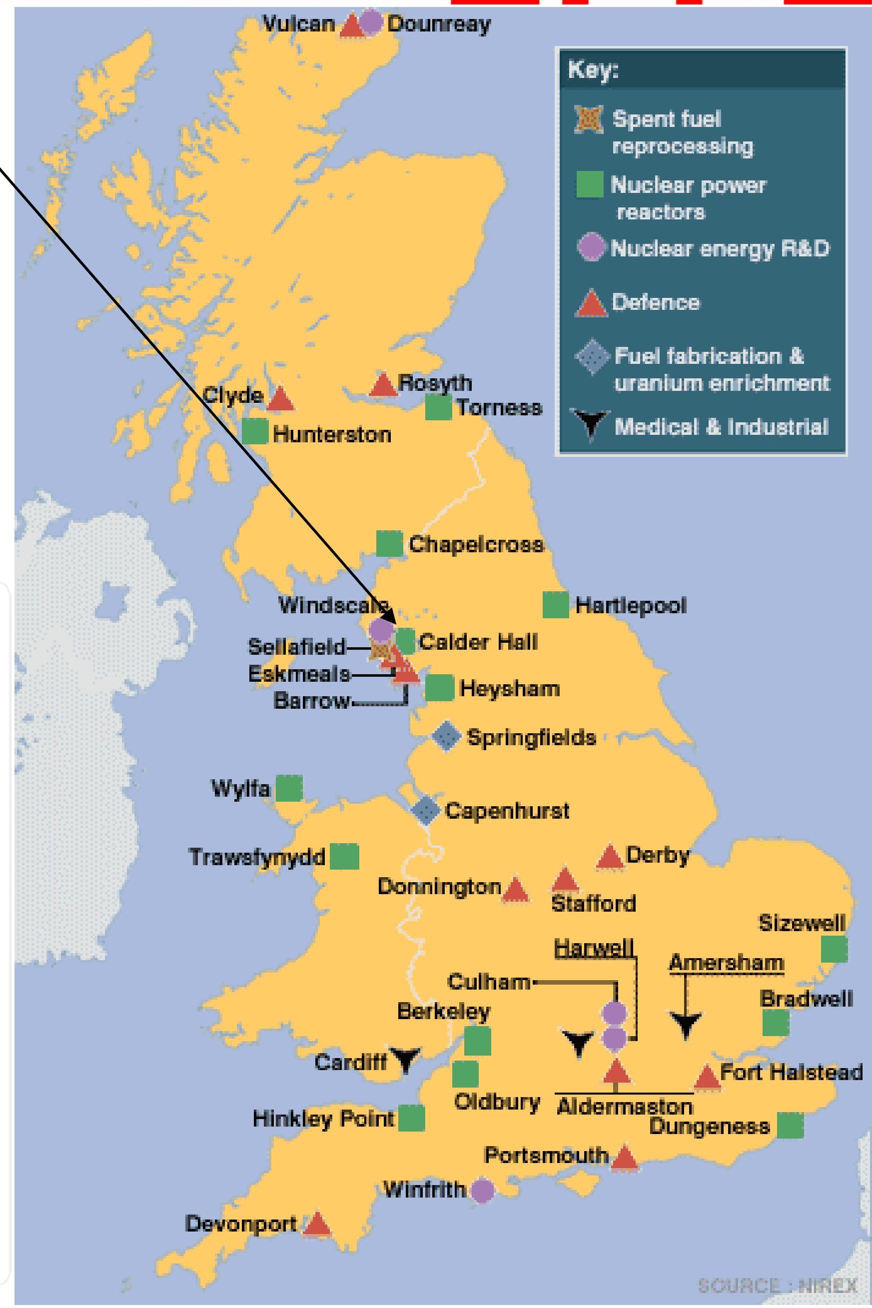
CO_2: up to 2.7 MPa

up to 410 °C

(Calder Hall: 0.7 MPa / 336 °C)



~140-200 °C



FUEL: MAGNOX VS. AGR

MAGNOX fuel

Length: ~ 1 m

Diameter: ~ 50 mm

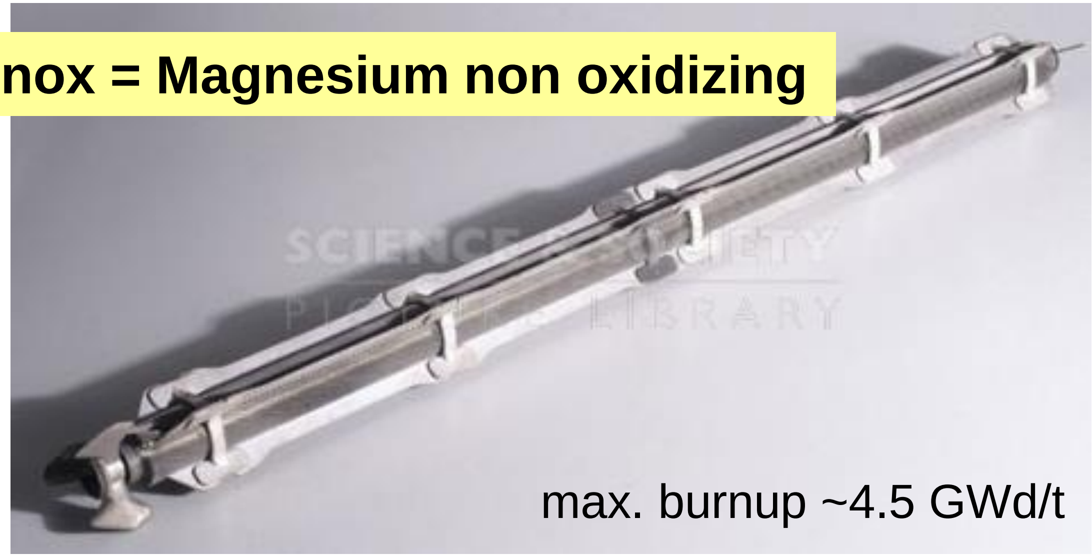
Fuel: Natural uranium

Cladding: Magnox = Mg (99 %) + Al, Be, Ca, Fe, Mn, Ni, Pb, Sn

Melting point: 650 °C

$T_{clad,max}$ = 470 °C, otherwise destruction by CO_2 + Mg → CO + MgO

Magnox = Magnesium non oxidizing



max. burnup ~4.5 GWd/t

AGR fuel – overcomes temperature limitations of MAGNOX

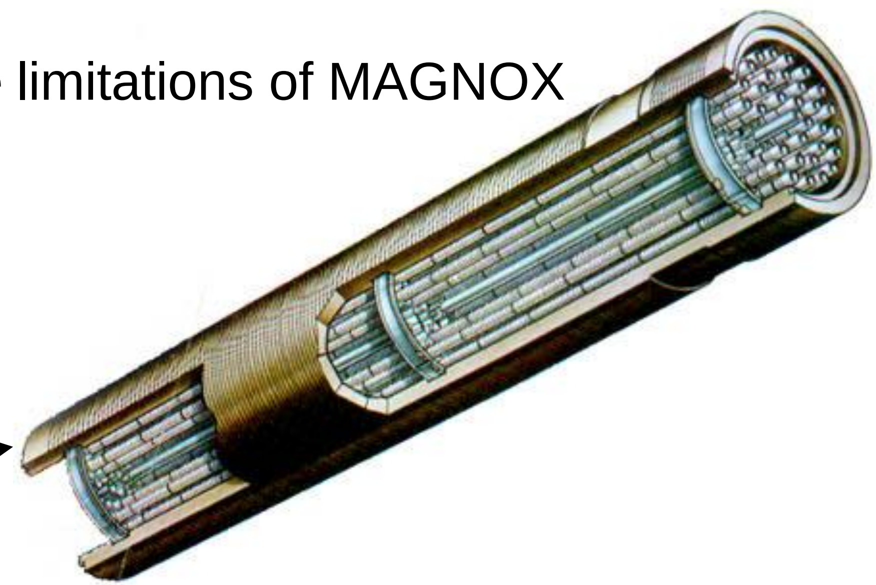
Length: ~ 1 m

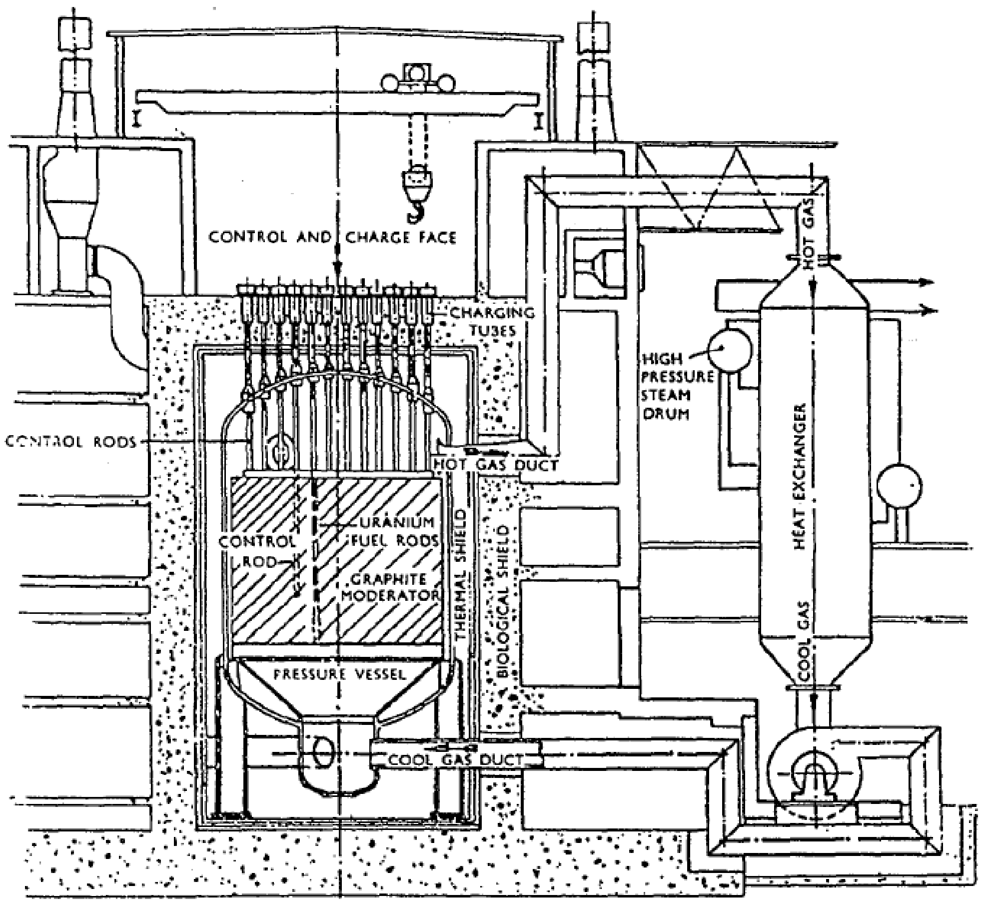
Fuel: UO_2 (ceramic) Pellets

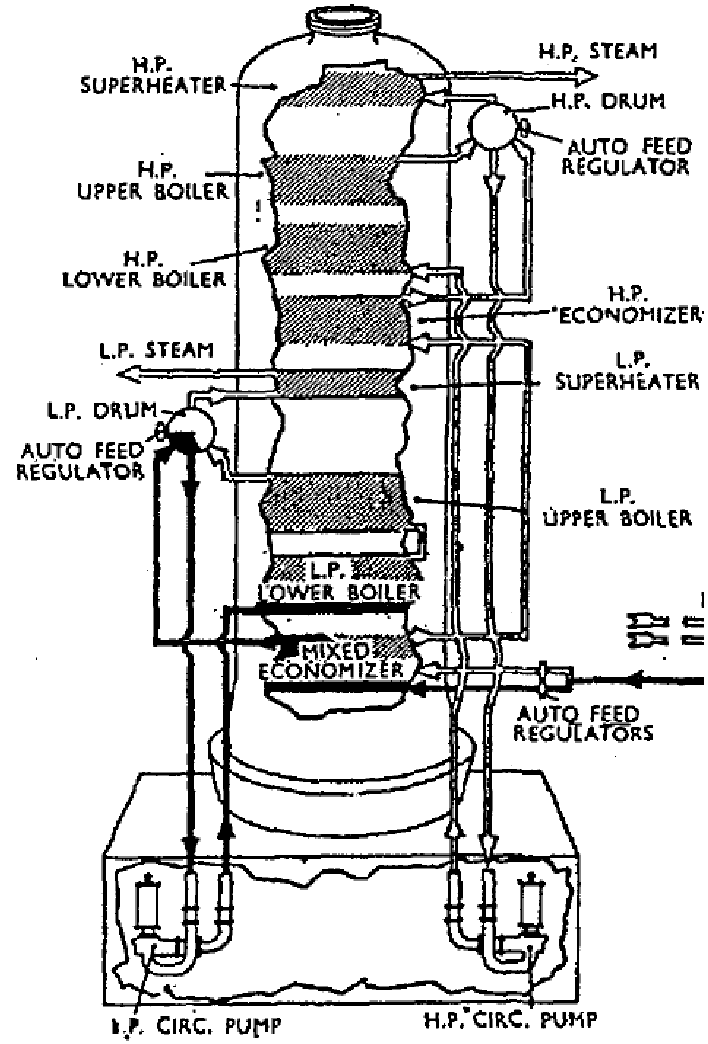
Diameter: ~ 12 mm

Cladding: Stainless steel

Sleeve: Graphite

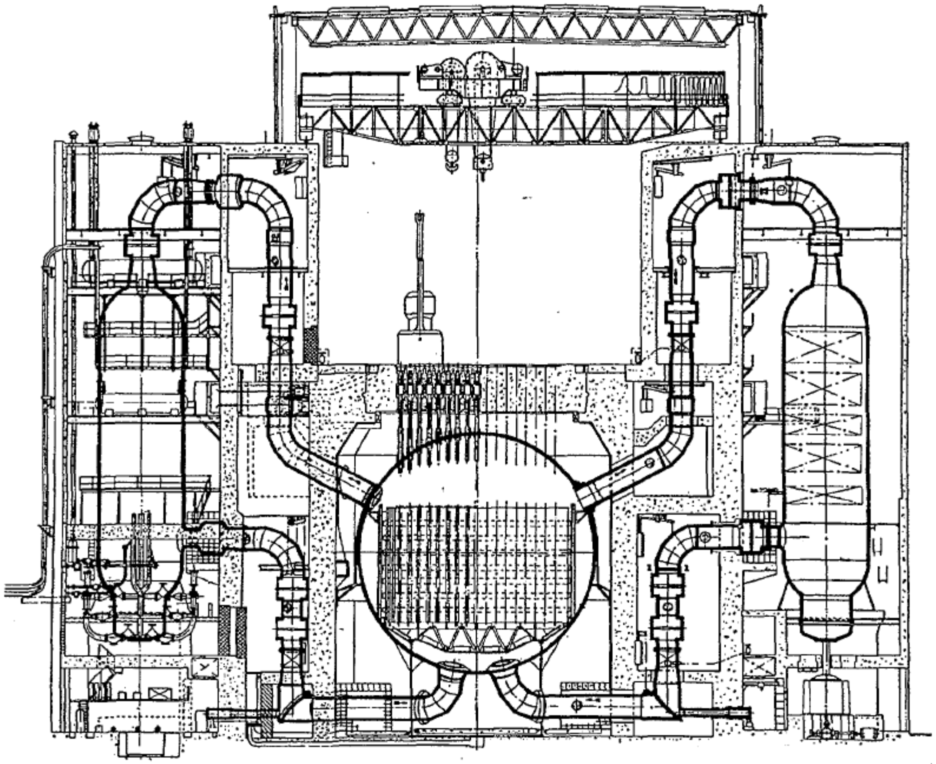




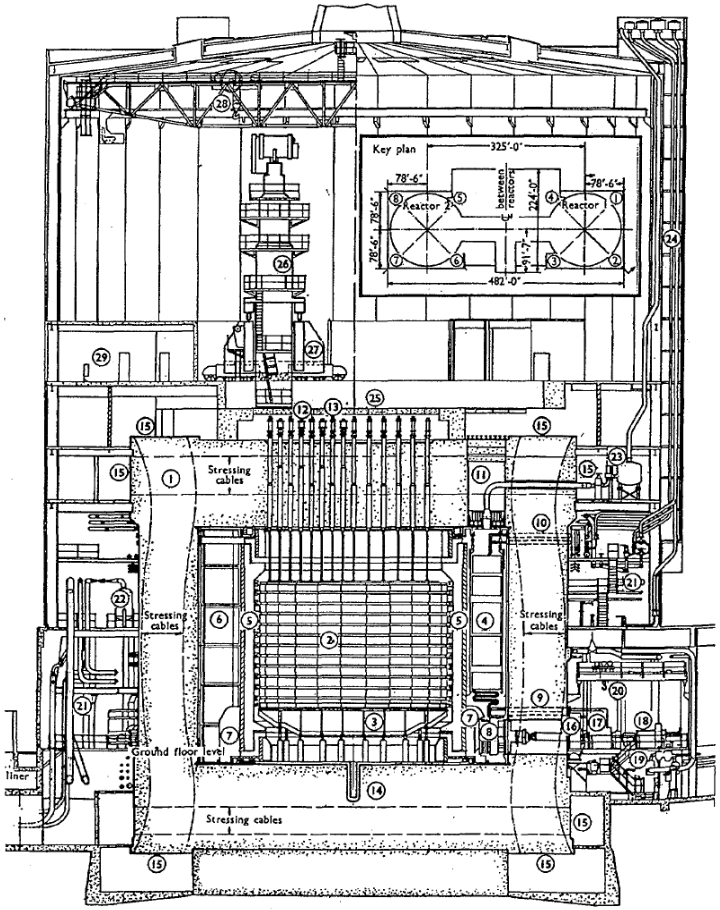


Calder Hall, 46 MWe (4x)
Berkeley, 139 MWe (2x)

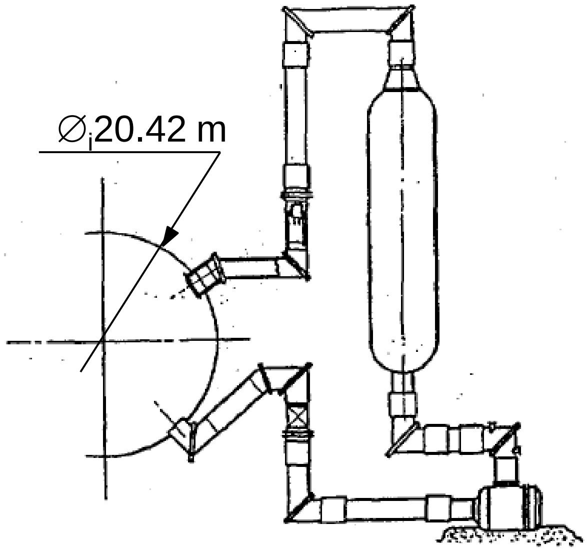
EVOLUTION FROM STEEL TO PRE-STRESSED CONCRETE VESSELS



Bradwell, 150 MWe (2x)
Hunterston, 160 MWe (2x)
Dungenes, 275 MWe (2x)
Hinkley Point, 250 MWe (2x)
Trawsfynydd, 250 MWe (2x)
Sizewell, 290 MWe (2x)

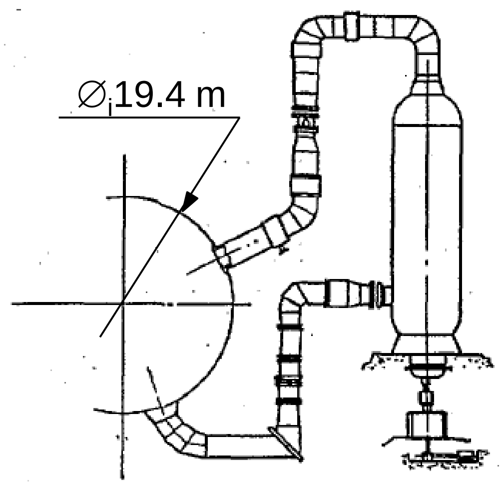


Oldbury, 280 MWe (2x)



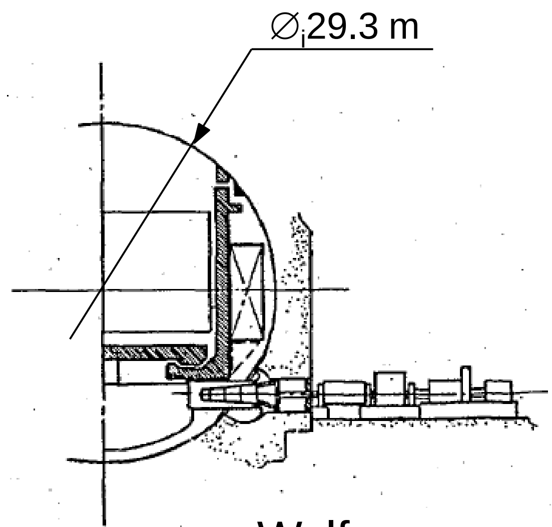
Hinkley Point

- Spherical steel vessel (12.2 bar)
- External CO_2 circulator
- Steam generator with economizer, evaporator + steam drums, super-heater
- Primary: 180→375 °C, 4536 kg/s
- Secondary: 363 °C, 45.7 bar
- Q_{th} = 980 MW (2x)
- Q_{el} = 250 MW (2x)



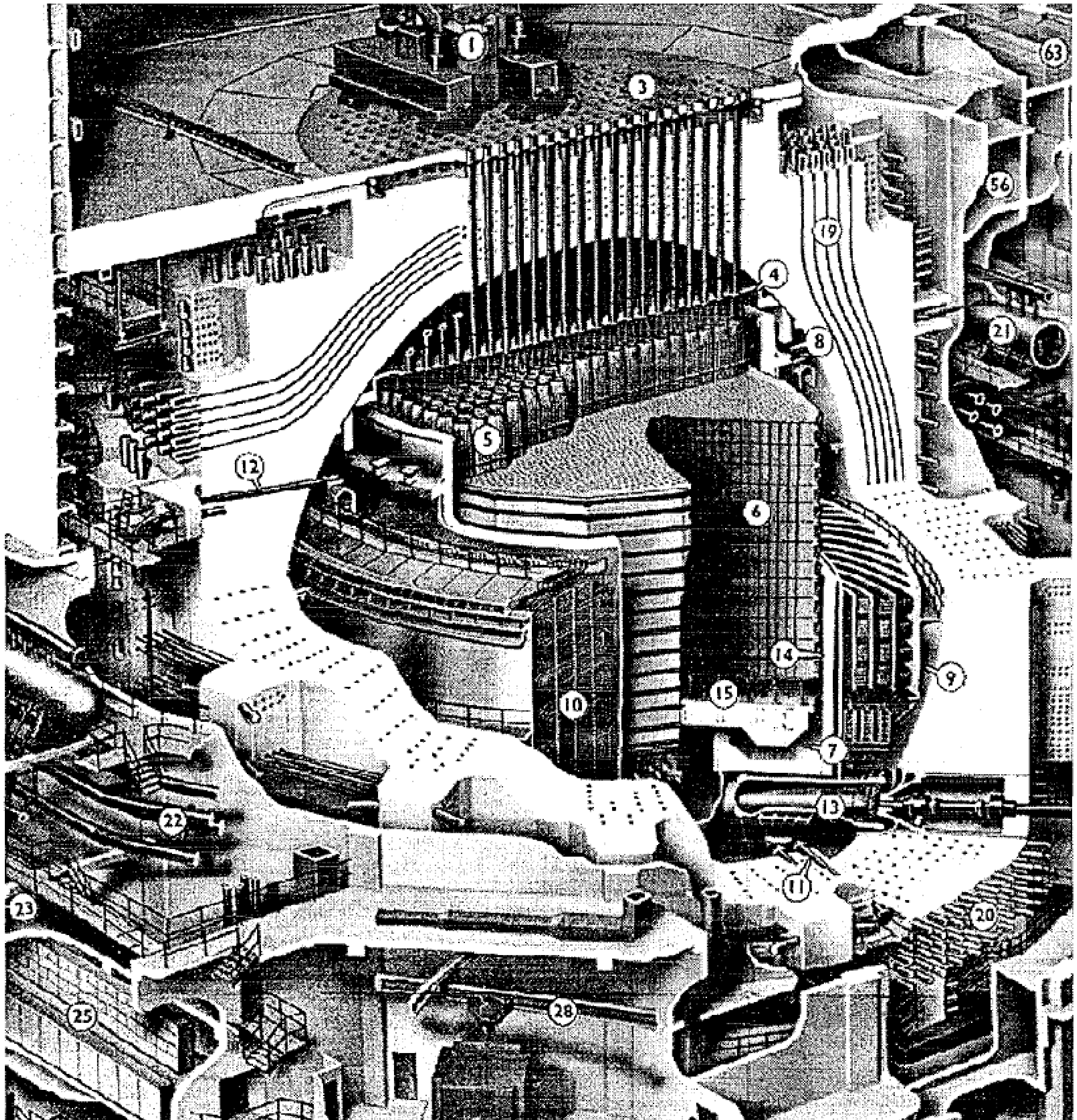
Sizewell

- Spherical steel vessel (17.9 bar)
- CO_2 circulator, integrated in steam generator, shaft sealing
- Steam generator with economizer, evaporator + steam drums, super-heater
- Primary: 214→410 °C, 4470 kg/s
- Secondary: 389 °C, 47.6 bar
- Q_{th} = 950 MW (2x)
- Q_{el} = 290 MW (2x)



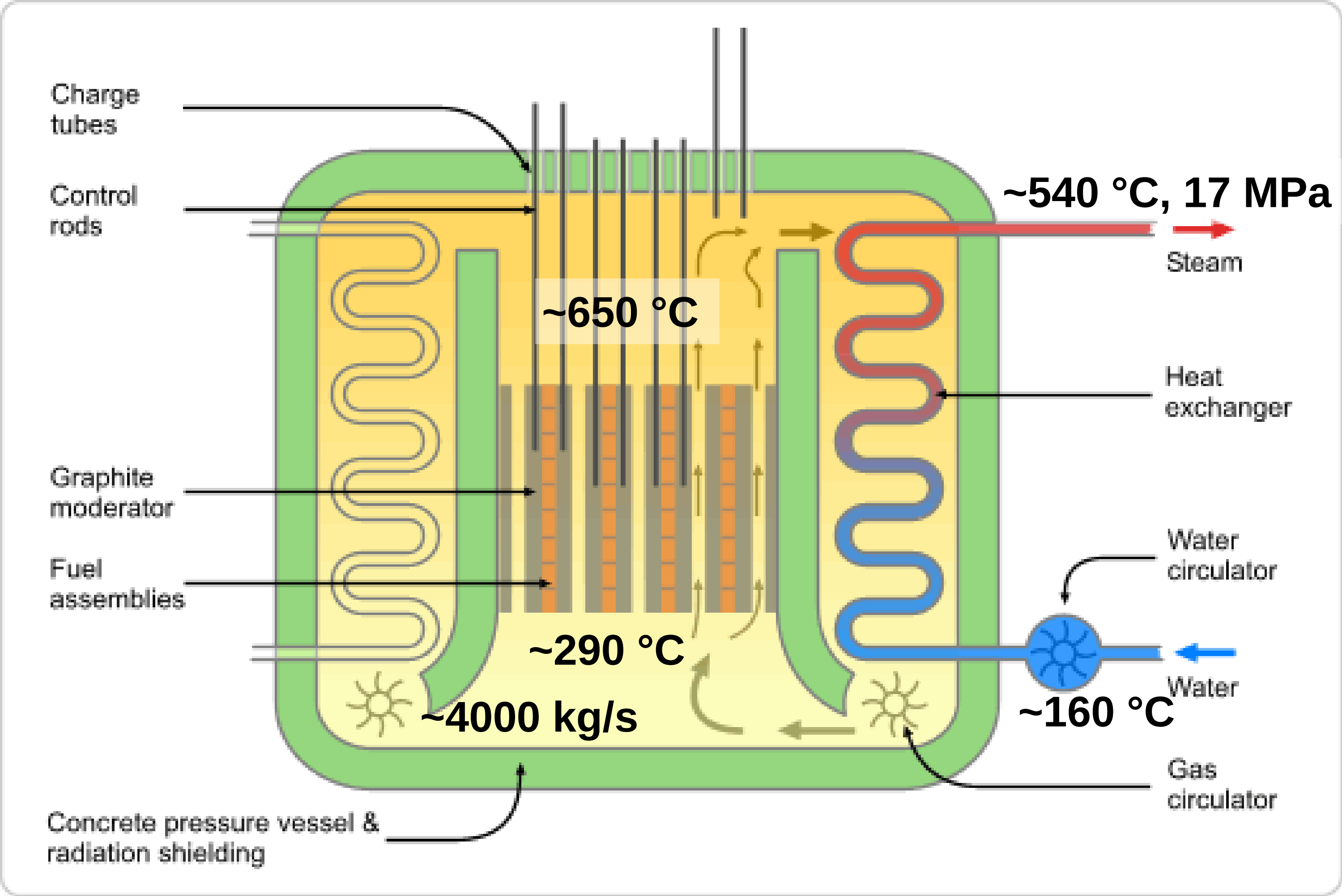
Wylfa

- Spherical pre-stressed concrete vessel (26.2 bar)
- Integrated CO_2 circulator with shaft sealing
- Once-through steam generator, integrated in reactor vessel
- Primary: 247→414°C, 10'254 kg/s
- Secondary: 410 °C, 46 bar
- Q_{th} = 1875 MW (2x)
- Q_{el} = 590 MW (2x)



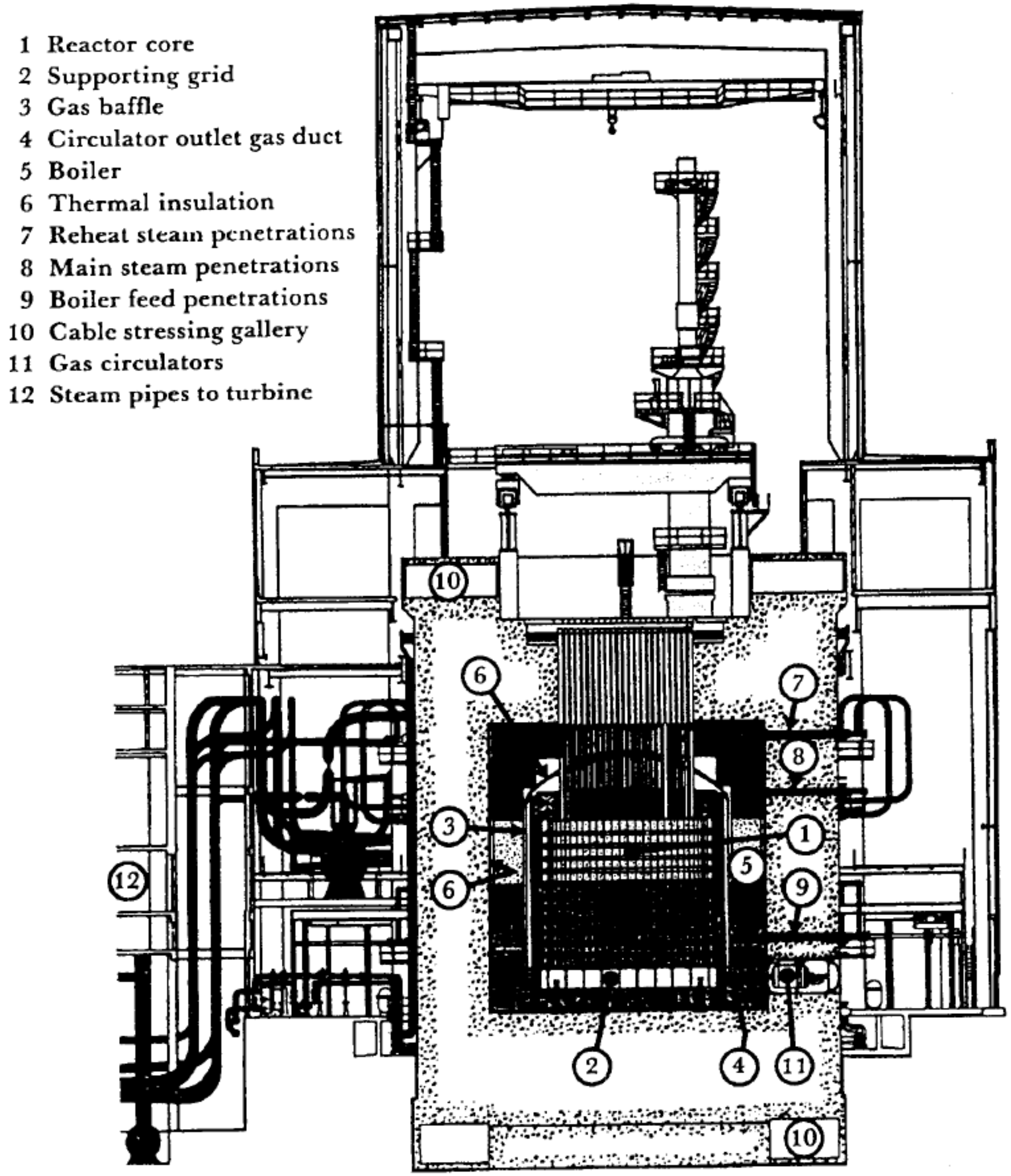
590 MWe
(2x)

EPFL



Coolant:	CO_2	Uranium mass:	ca. 170 t U/GW$_{el}$
Moderator:	Graphite	Pressure (gas):	ca. 40 bar
Fuel:	UO_2, 2.5 % U-235	Temp. max (gas):	ca. 650 °C
Cladding:	Stainless steel	Max. Power:	ca. 600 MW$_{el}$

Torness AGR nuclear power station



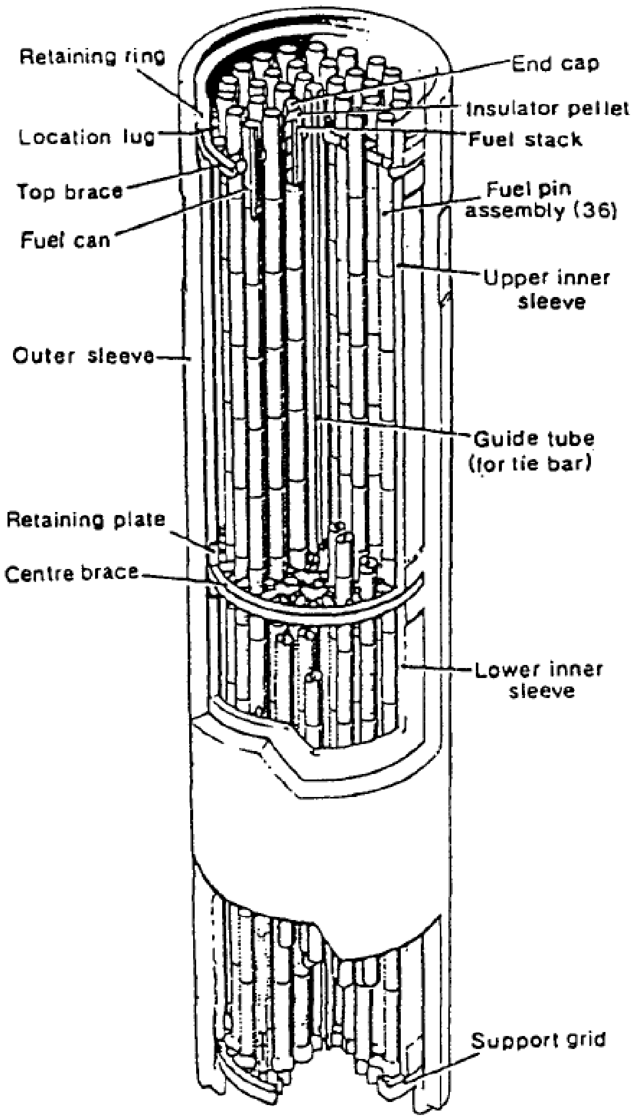
Q_{th} = 1623 MW (2x)
Q_{el} = 660 MW (2x)

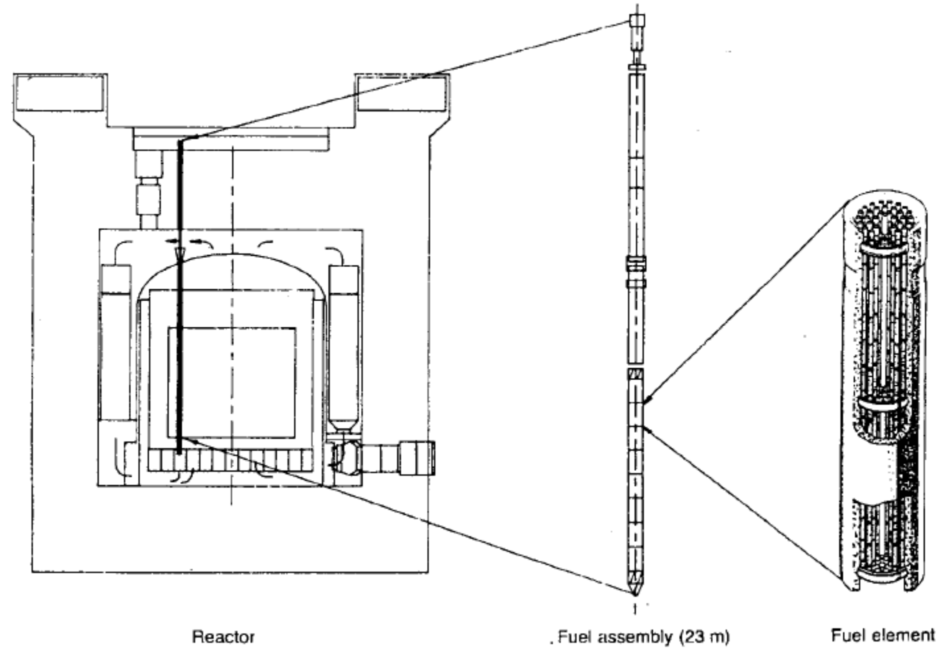
Pressure vessel
Pre-stressed concrete
D_i = 20.3 m
D_o = 31.9 m
p = 45.7 bar

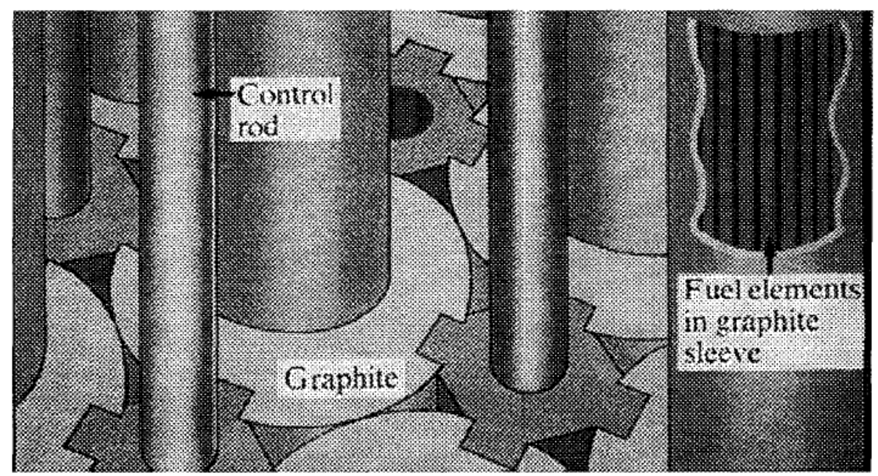
Gas circulator (CO_2)
Number: 8
Power (total): 42 MW
Flow: 4067 kg/s

Primary: 339→639 °C
Secondary: 158→541 °C @ 173 bar

NUCLEAR FUEL AND LATTICE STRUCTURE







Typical lattice pitch: 197 mm

- **Goal: Reach reactor outlet temperatures beyond 650 °C**

- **Solution: Change from CO_2 to the noble gas helium (pressurized)**

Reasons:

- Increase of reactor outlet temperature → exclude CO_2 redox reactions at higher temperatures (significant above 650 °C)

$$CO_2 + C \rightarrow 2\,CO$$

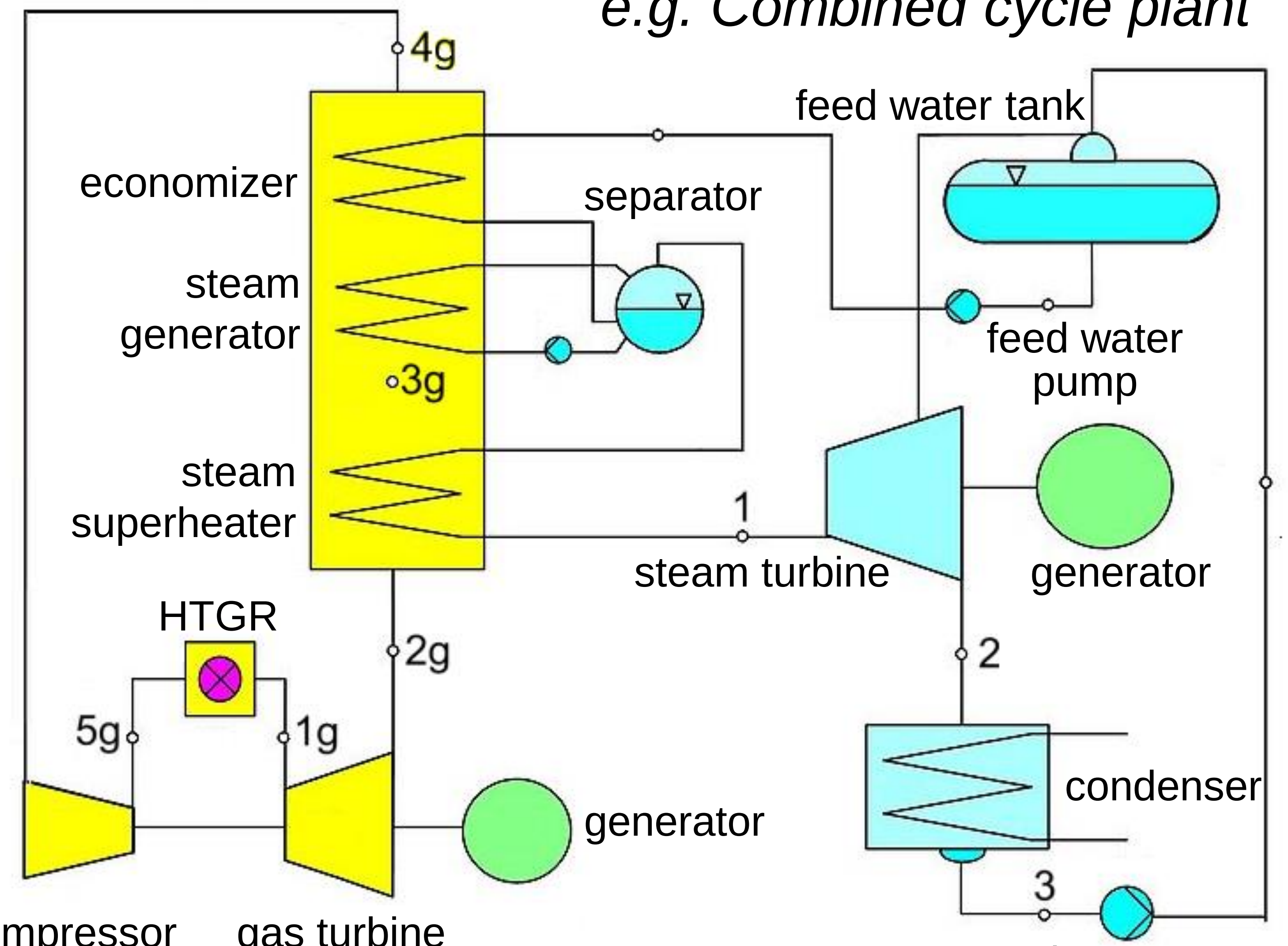
- Enhance heat transfer by gas with better thermal conductivity

He	**0.14264 W/(m·K)**
Ne	0.0458 W/(m·K)
Ar	0.01636 W/(m·K)
Kr	0.00883 W/(m·K)
Xe	0.00519 W/(m·K)
H_2	0.16835 W/(m·K)
CO_2	0.01465 W/(m·K)

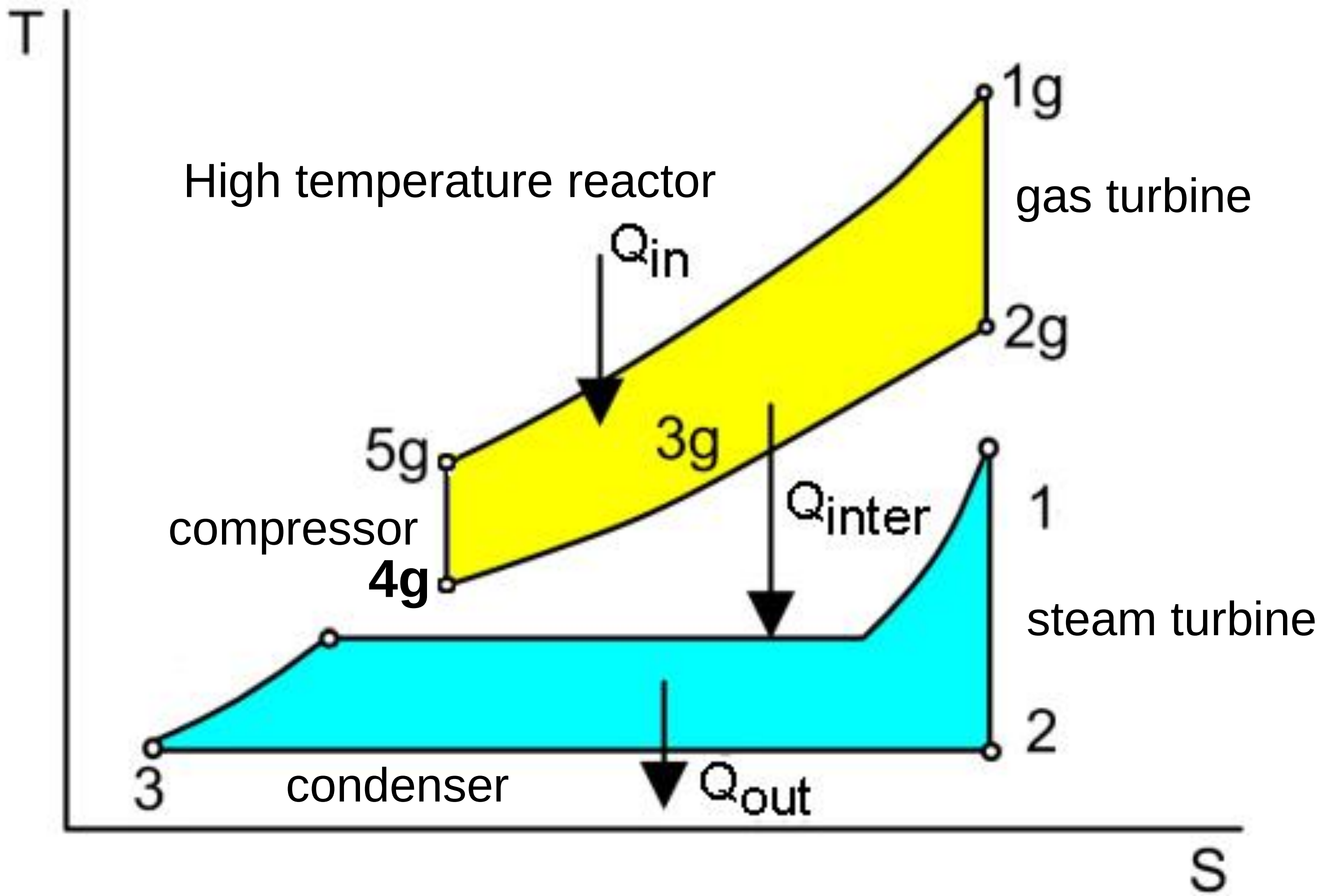
Helium best after hydrogen (hydrogen is used as coolant for the rotor of the generator)

Purpose 1: Increase thermal plant efficiency by higher heat supply temperature

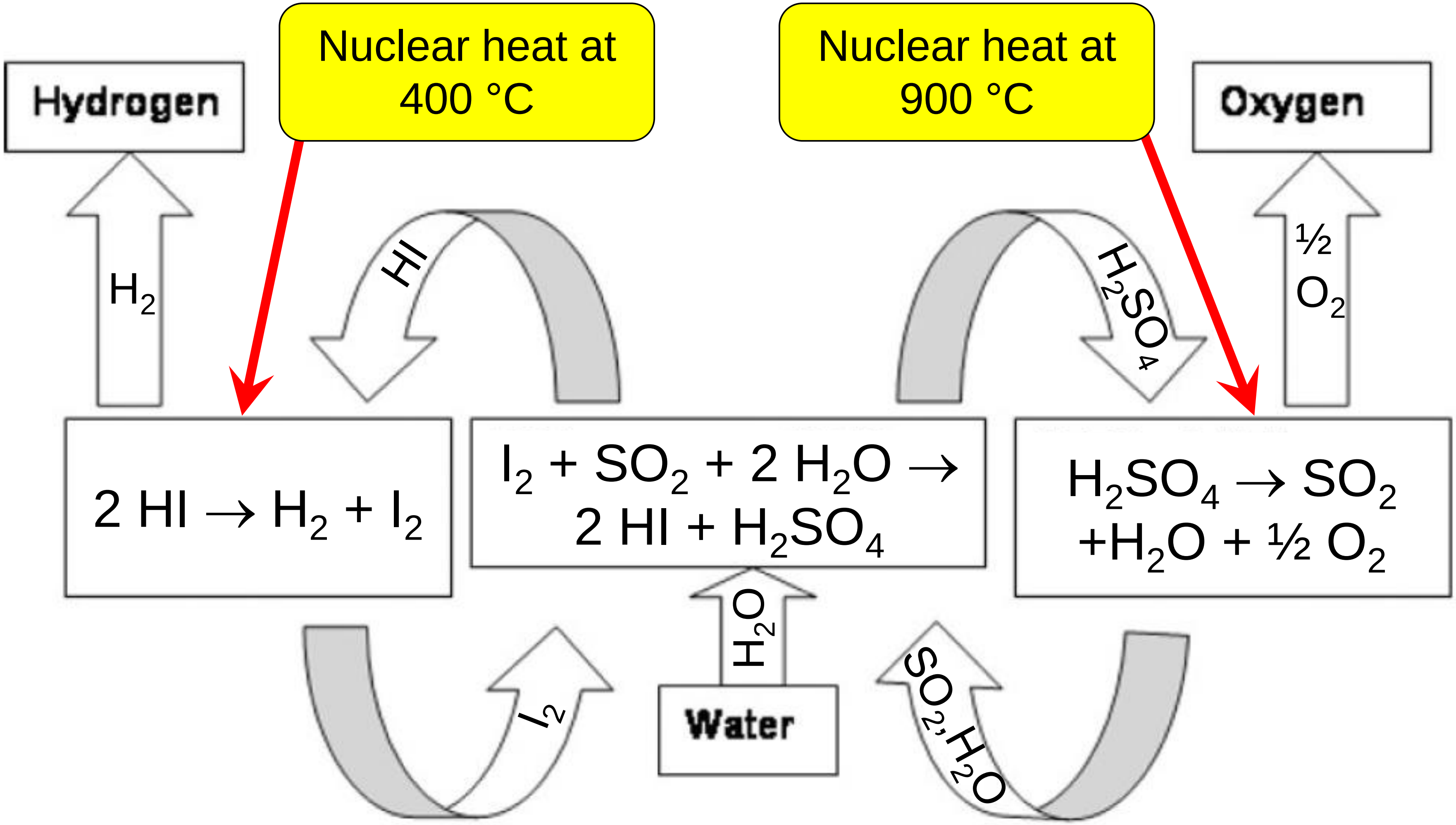
e.g. Combined cycle plant



COMBINED CYCLE PLANT IN T-S DIAGRAM



Purpose 2: Provide process heat for chemical reactions
e.g. H_2 production by H_2SO_4 - Iodine process

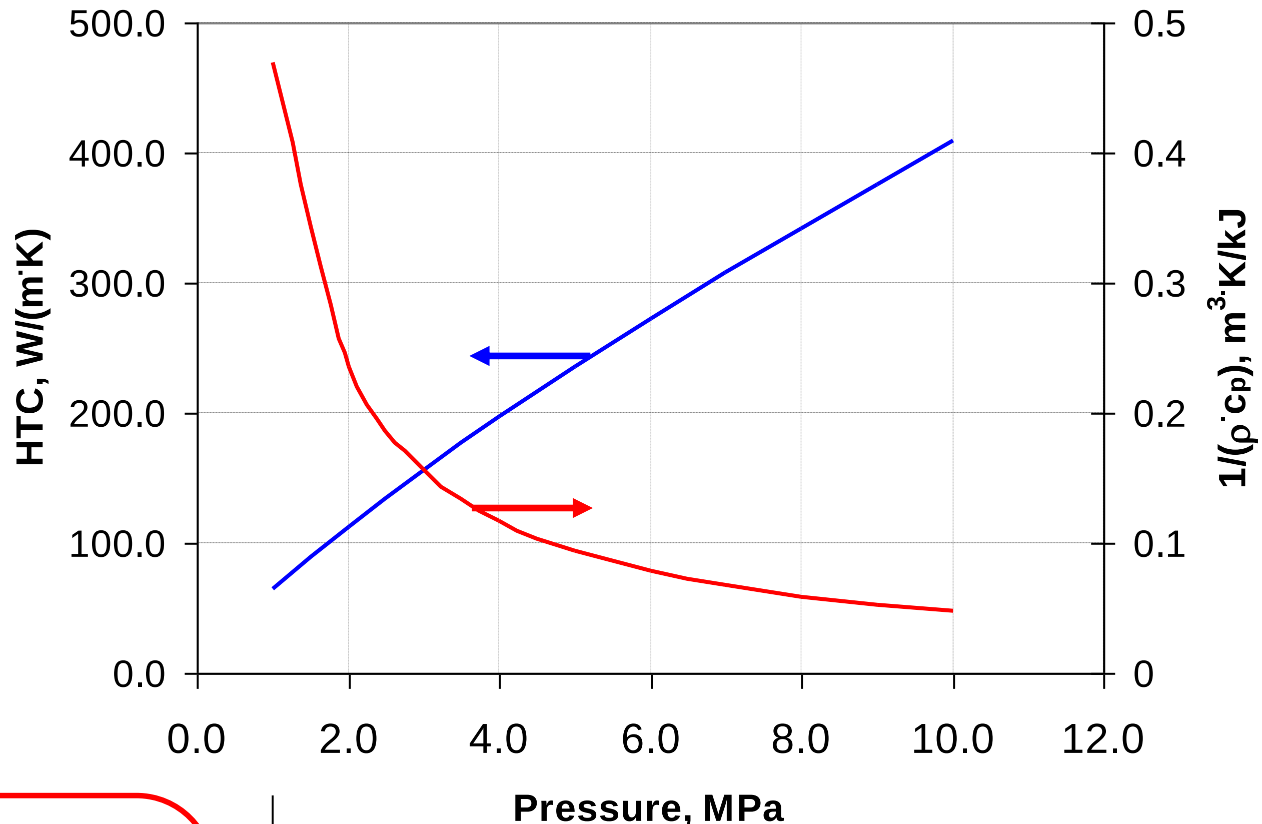


Ideal gas:

$$p \cdot v = R \cdot T \rightarrow \rho = \frac{p}{R \cdot T}$$

Thermal conductivity and viscosity no function of pressure

$$\eta \neq f(p) \quad \lambda \neq f(p)$$
$$c_p \neq f(p)$$



→ at higher pressure:

Heat transfer better

$$\eta \neq f(p) \rightarrow \nu = \frac{\eta}{\rho} \sim \frac{1}{p} \rightarrow$$

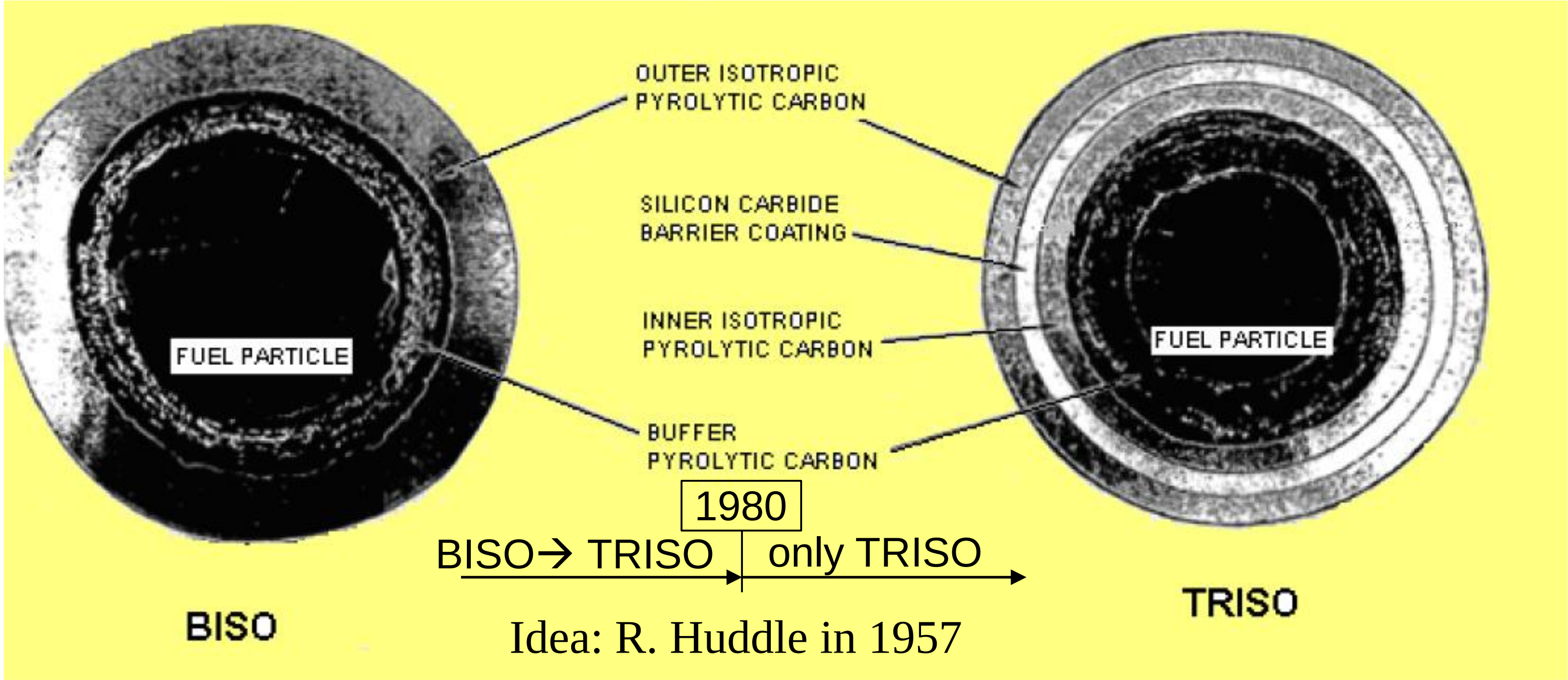
$$Re = \frac{L \cdot w}{\nu} \sim p \rightarrow HTC \sim p^{\sim 0.8}$$

Fan power lower

$$\dot{m}_{cool} = \frac{\dot{W}_{core}}{\Delta T_{core} \cdot c_p} \rightarrow \dot{V}_{cool} = \frac{\dot{m}_{cool}}{\rho} \sim \frac{1}{\rho}$$

$$\dot{W}_{fan} \approx \Delta p \cdot \dot{V}_{cool} \sim \dot{V}_{cool}^2 \cdot \dot{V}_{cool} \sim \frac{1}{\rho^3} \sim \frac{1}{p^3}$$

- ❖ **Improve stability of fuel at high temperatures**
- Introduction of coated particle fuel (coating = barrier against fission product release)
- Use of a chemically inert coolant (noble gas + good heat removal → helium)



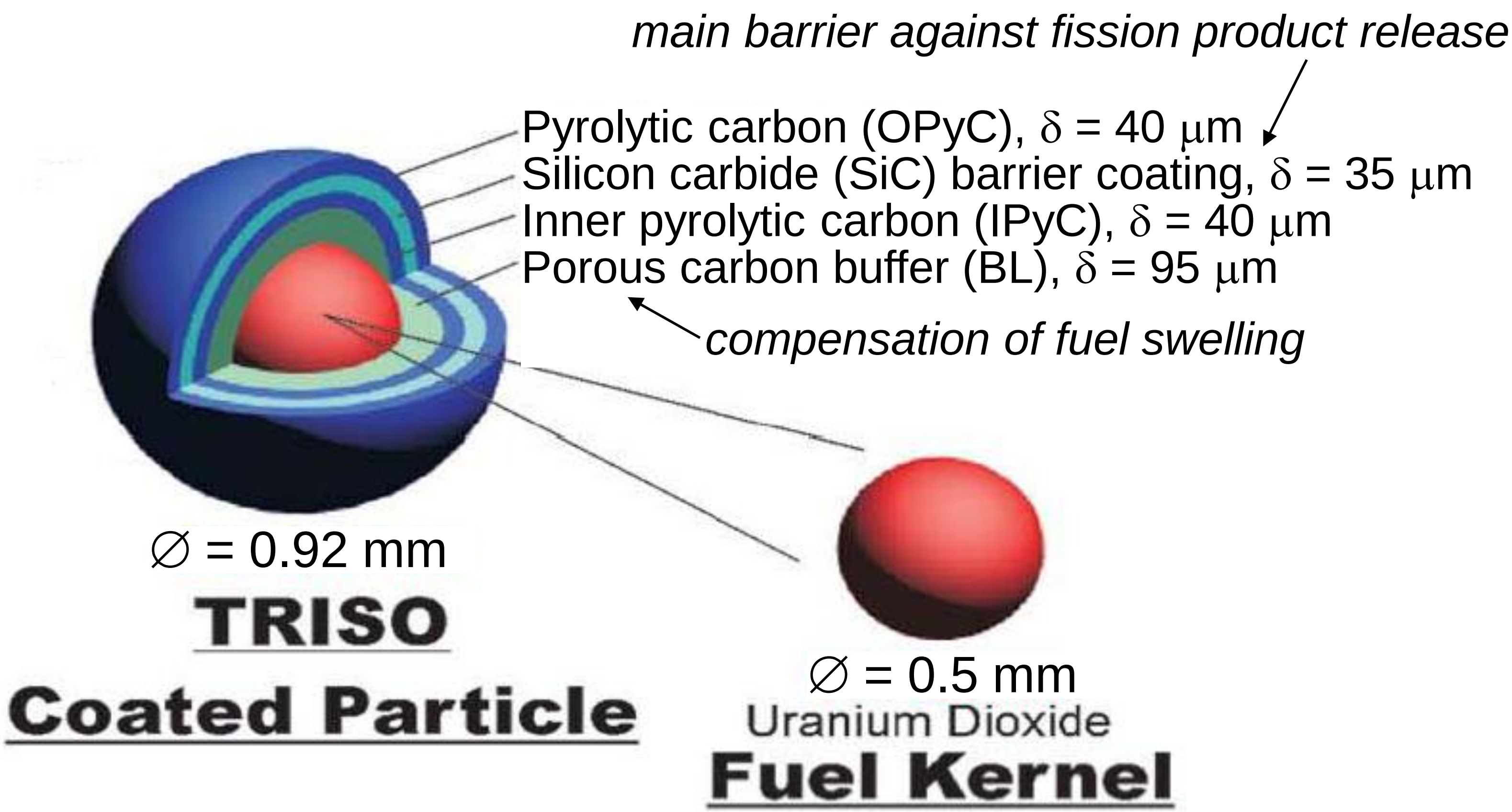
BISO and TRISO coated fuel particles (General Atomics Co.)

BISO = Bi-coated Isotropic
TRISO = Tri-coated Isotropic

Fuel particle = fuel kernel
Options: UO_2, UCO, UC, UC_2 or mixtures
ThO_2, ThC_2
PuO_2

❖ Transfer from BISO to TRISO particles

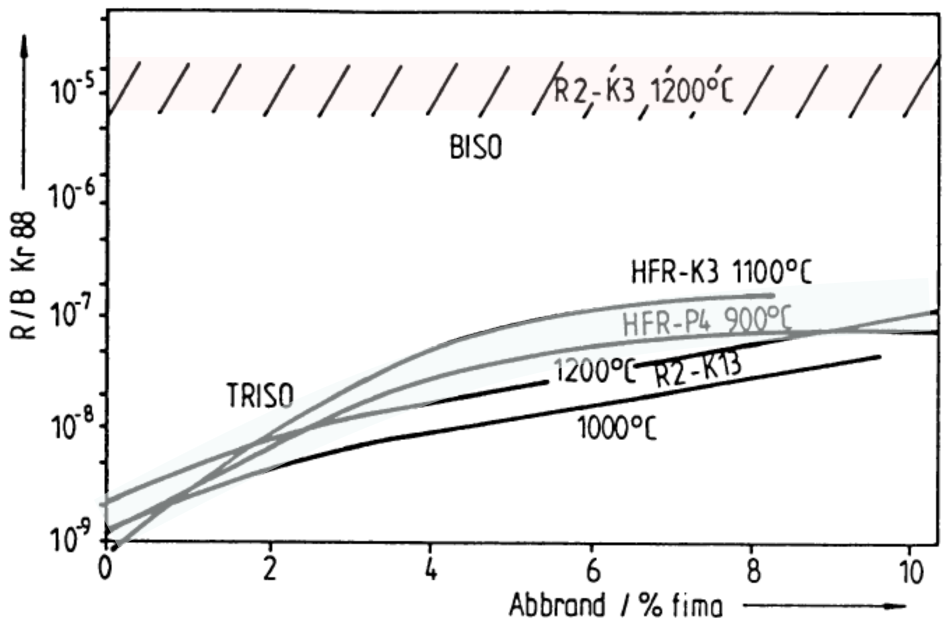
- Introduction of an intermediate silicon carbide layer



- SiC layer = mini-containment to retain fission products

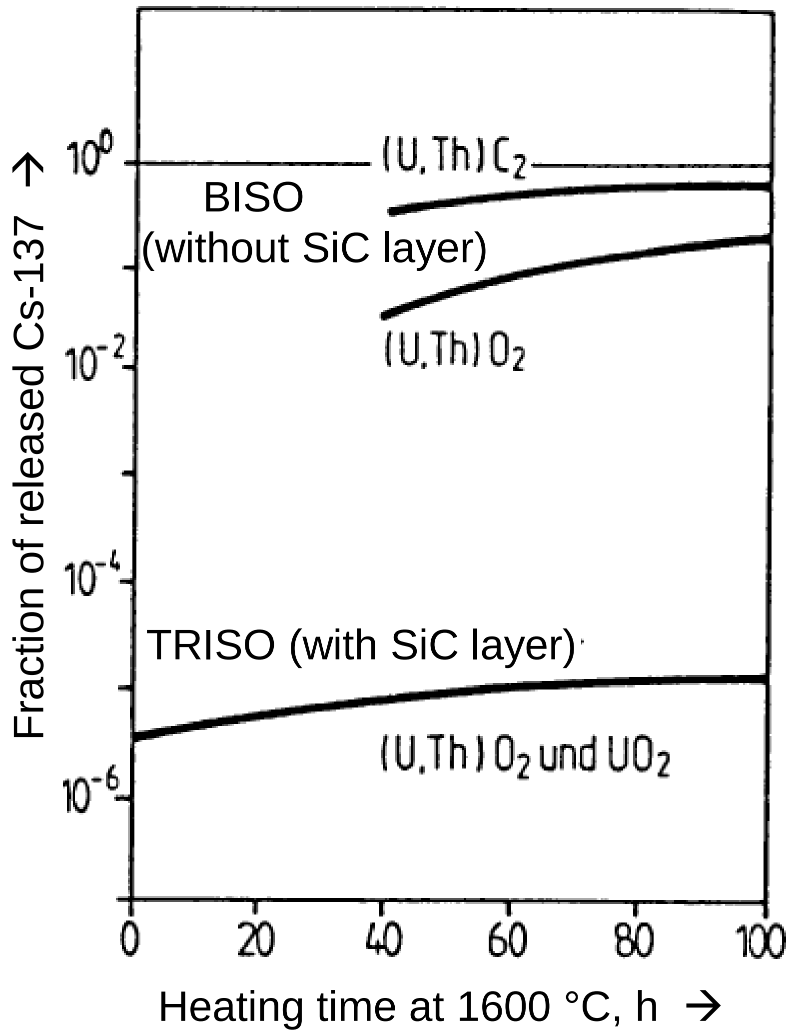
ADVANTAGE OF TRISO OVER BISO FUEL

Examples of the retention capability of BISO and TRISO



Krypton releases at **normal operation** conditions

→ both BISO and TRISO show acceptable to very good performance



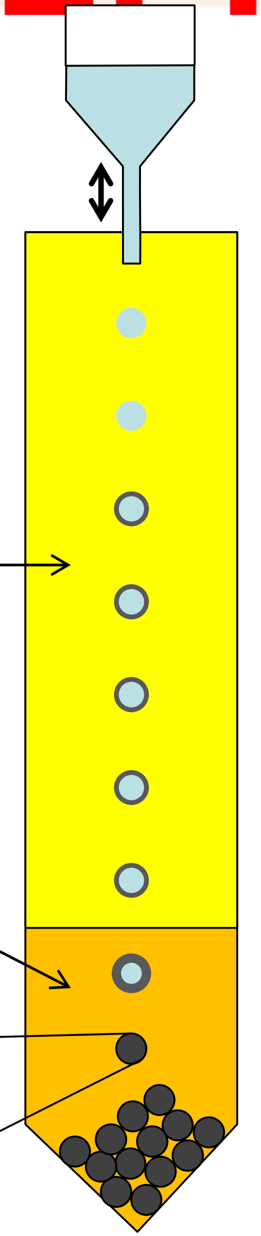
Cs-137 releases at **accident conditions**

→ BISO fails to retain Cs-137

→ TRISO shows good performance

Aqueous solution of uranyl nitrate $(UO_2)(NO_3)_2$

Droplets of the broth are generated by a 600Hz vibrator



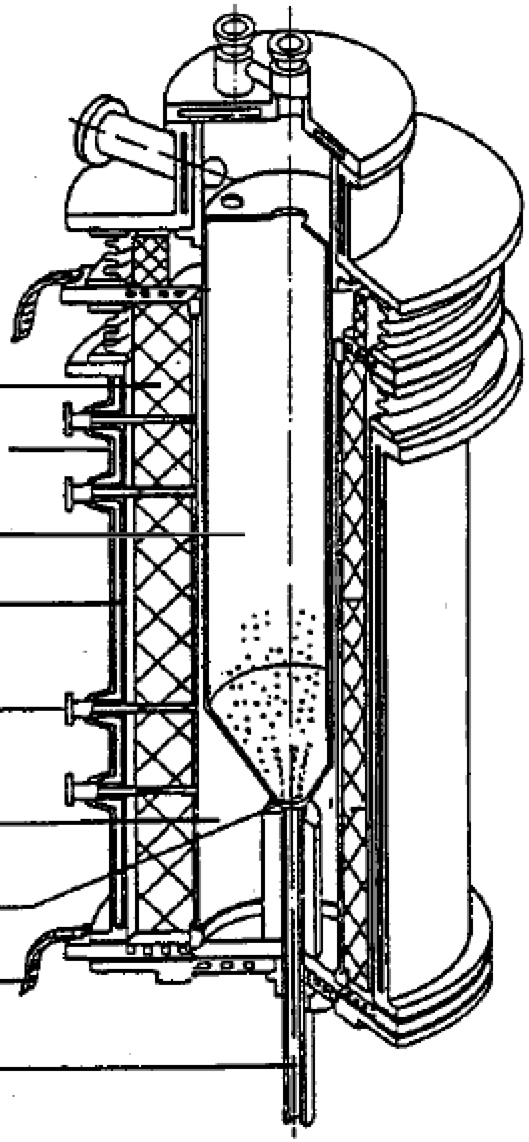
Droplets fall through gaseous NH_3

into concentrated aqueous solution of NH_3
for bulk gelation

Finishing steps:

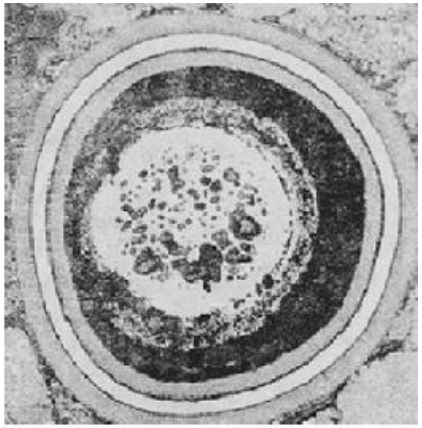
- Drying at 80°C
- Calcination in air at 300°C (remove CO_2, NH_3, H_2O) $\rightarrow$ UO_3
- Reduction to UO_2 by H_2 stream at 1600-1700°C

Fluidized bed reactor



Process:

1. Buffer layer (BL) deposited from a mixture of C_2H_2 and Ar at 1250°C
2. IPyC layer deposited from mixture of C_2H_2, C_3H_6 and Ar at 1300°C
3. SiC layer is deposited from a mixture of CH_3SiCl_3, and H_2 at 1500°C (~0.2 µm/min)
4. OPyC layer deposited like IPyC



5. Odd-shaped particles eliminated by means of vibrating tables

Two fuel concepts using coated particles

Spherical fuel elements

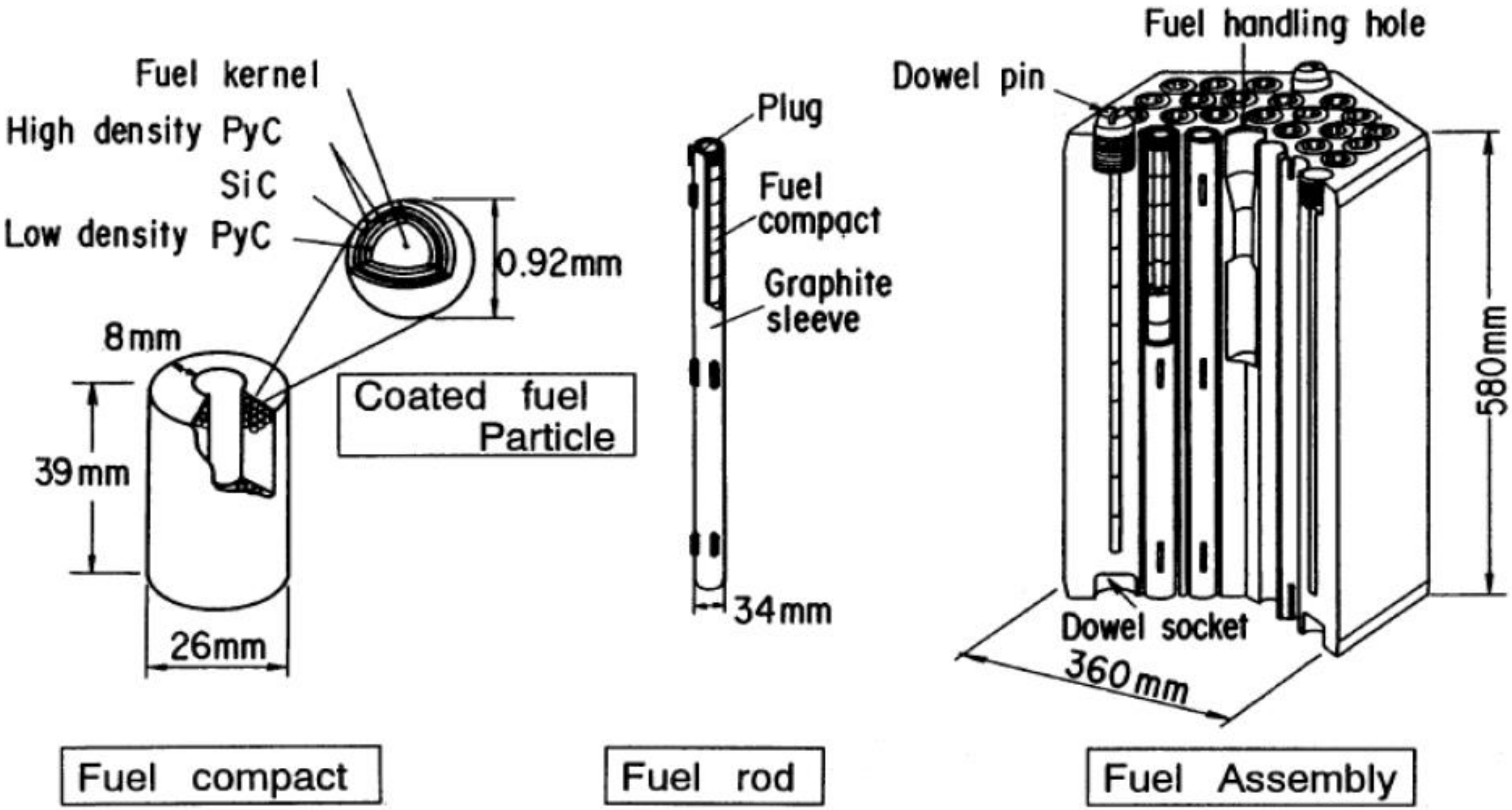
Allow continuous refueling
→ no excess reactivity needed
→ wear while moving through reactor

Prismatic fuel elements

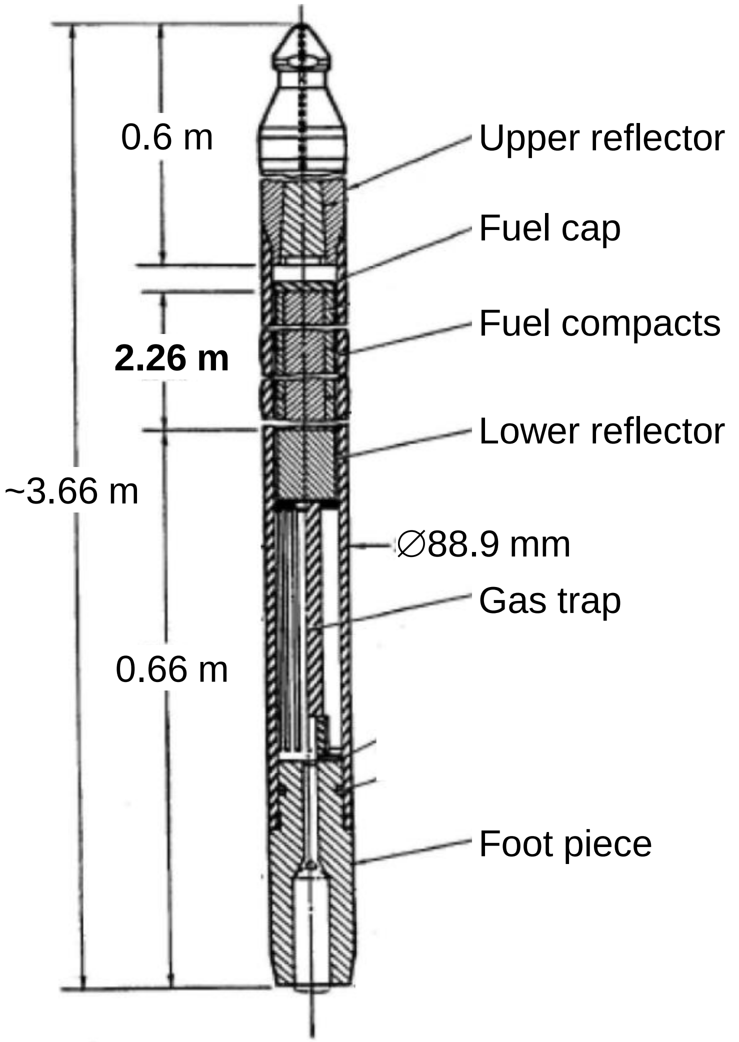
Only periodic refueling
→ excess reactivity needed
→ no wear during reactor operation

HIGH-TEMPERATURE GAS COOLED REACTOR PROTOTYPE PLANTS AND PROJECTS

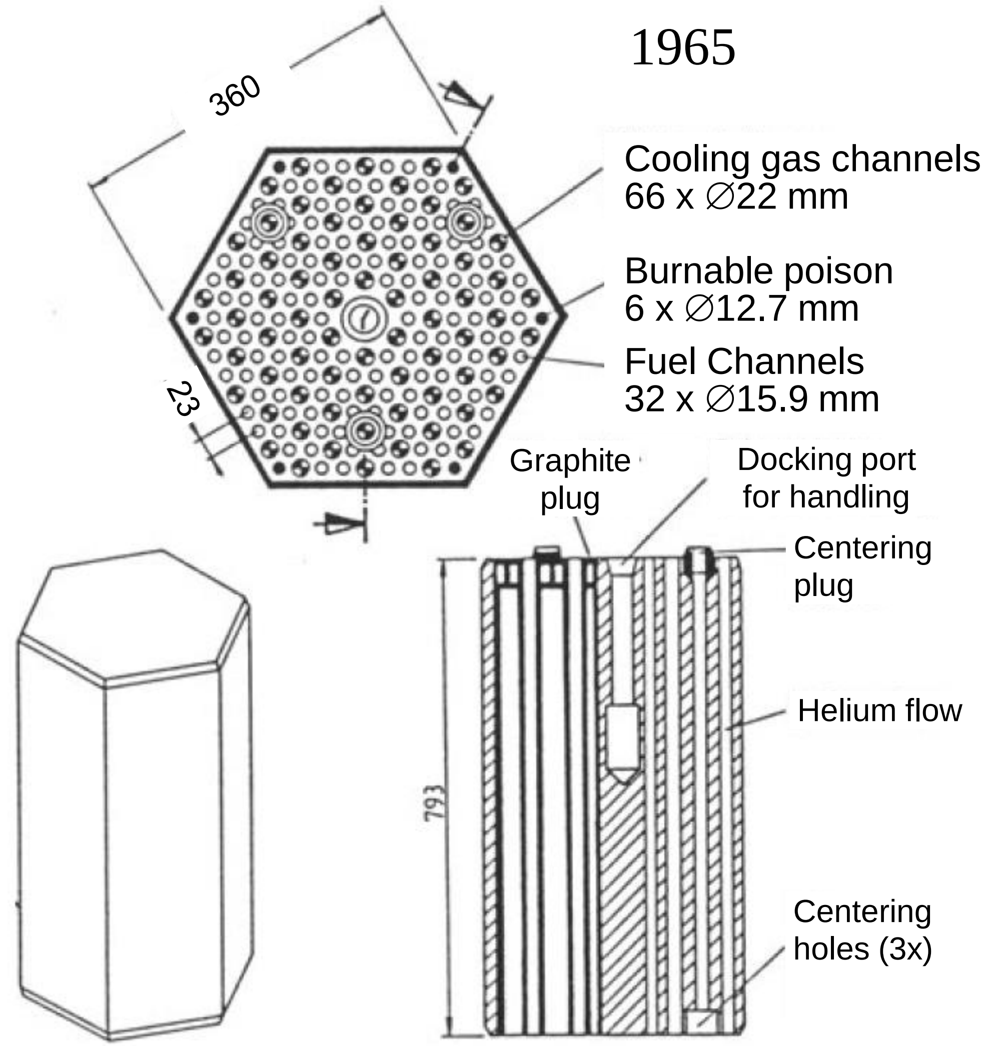
Reactor Type		Power	Operation
Pebble bed reactors			
AVR Germany	**FZ Jülich**	46 MWth/15 MWel	1966–1988
THTR-300 Germany	**Hamm-Uentrop**	750 MWth/296 MWel	1985–1989
HTR-10 China	**Uni Tsinghua**	10 MWth	Since 2000
HTR-PM China		2x250 MWth/210 Mwel	since Dec, 2021
Prismatic core			
Peach Bottom 1 US		40 MWel	1966–1974
Fort St Vrain US		842 MWth/330 MWel	1976–1988
HTTR Japan		30 MWth	Since 1998
GT-MHR US/Russia		600 MWth/293 MWel	Point Design



Fuel of the High Temperature Engineering Test Rector (HTTR) (Japan)

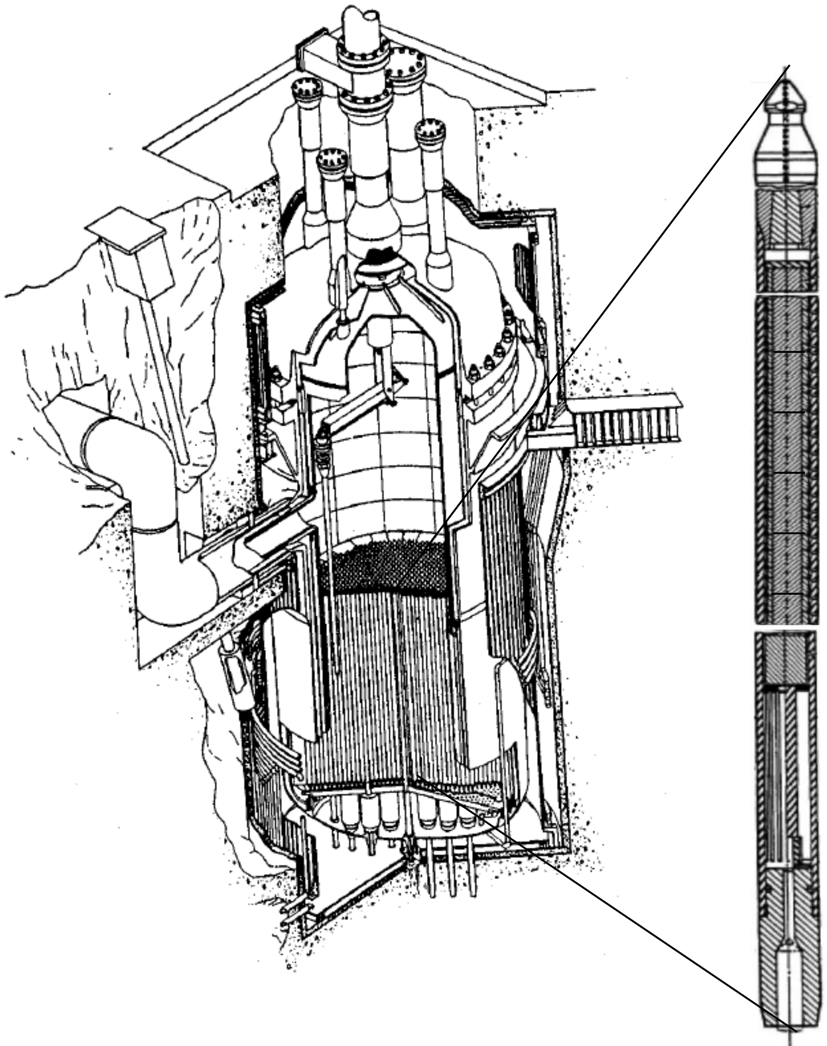


Peach Bottom

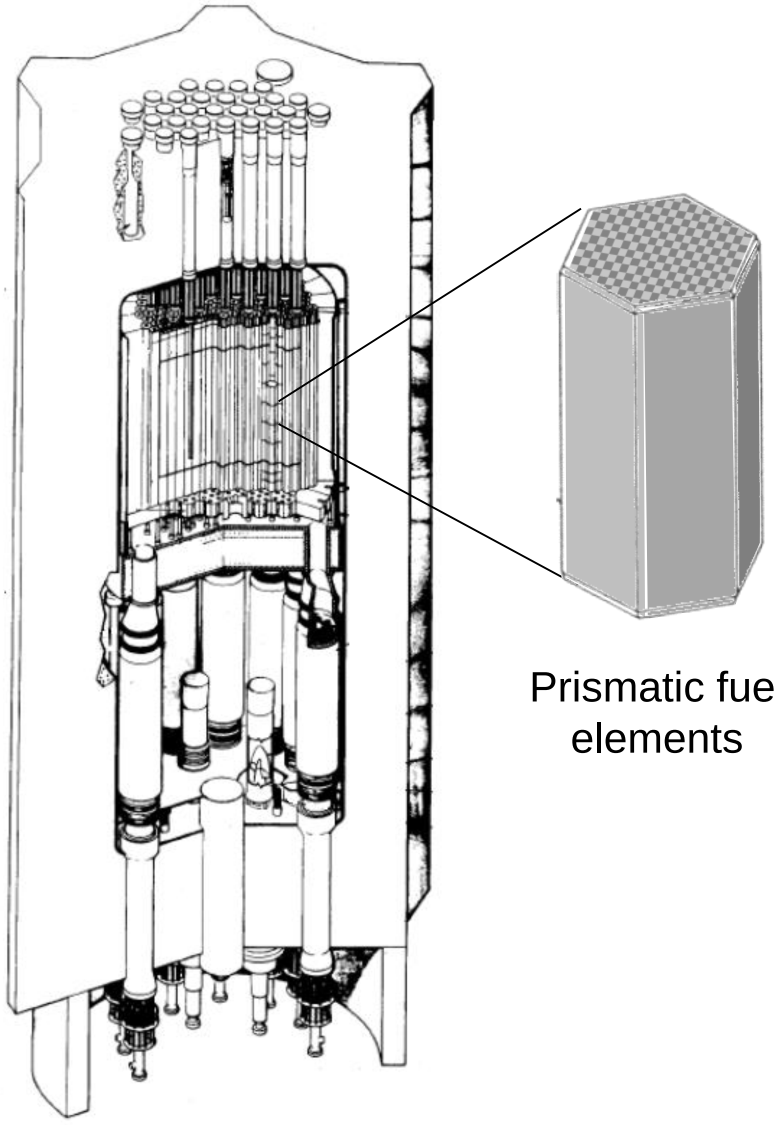


Fort St. Vrain

HTGR demonstrators with coated particle fuel in US



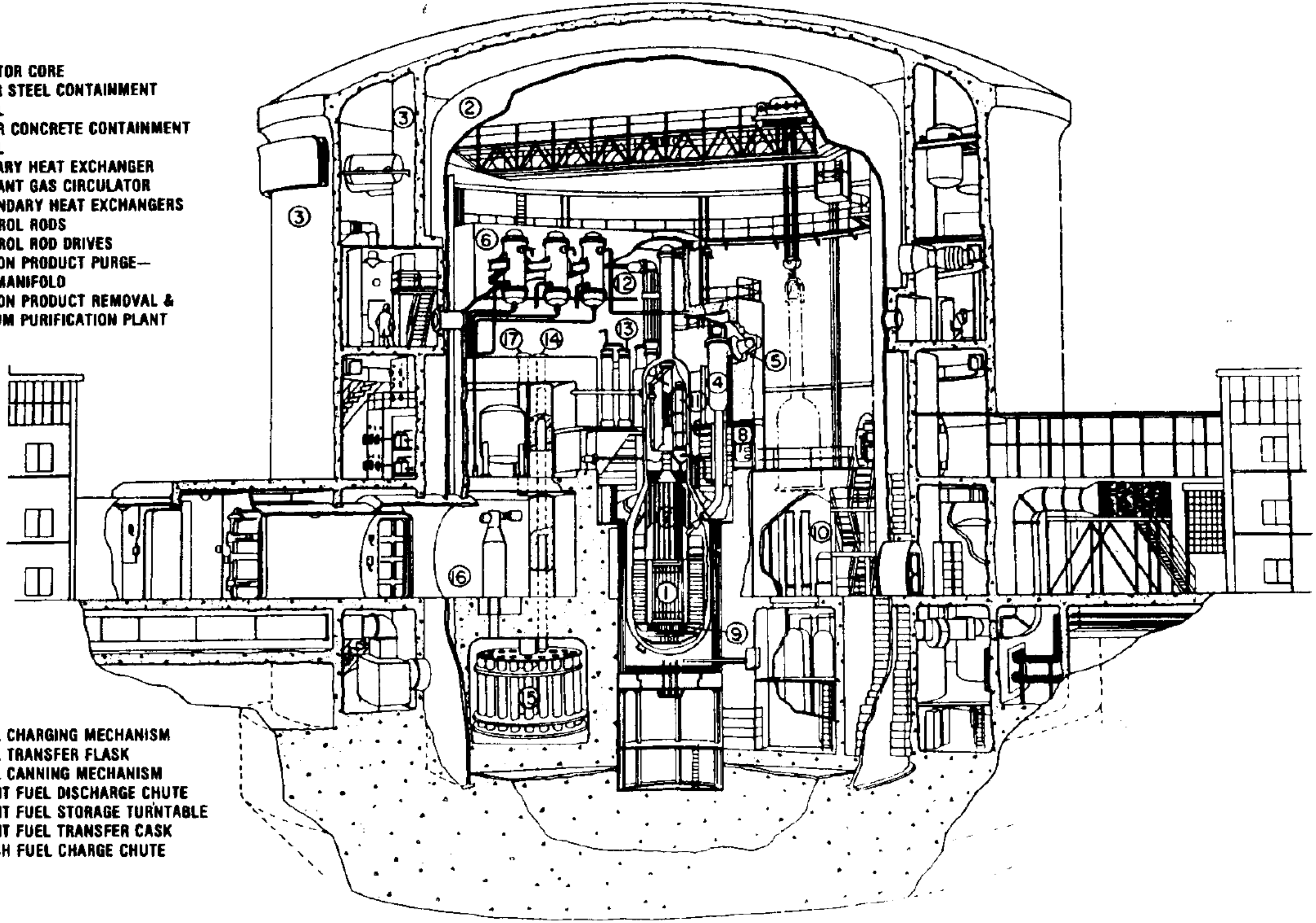
Peach Bottom



Fort Saint Vrain

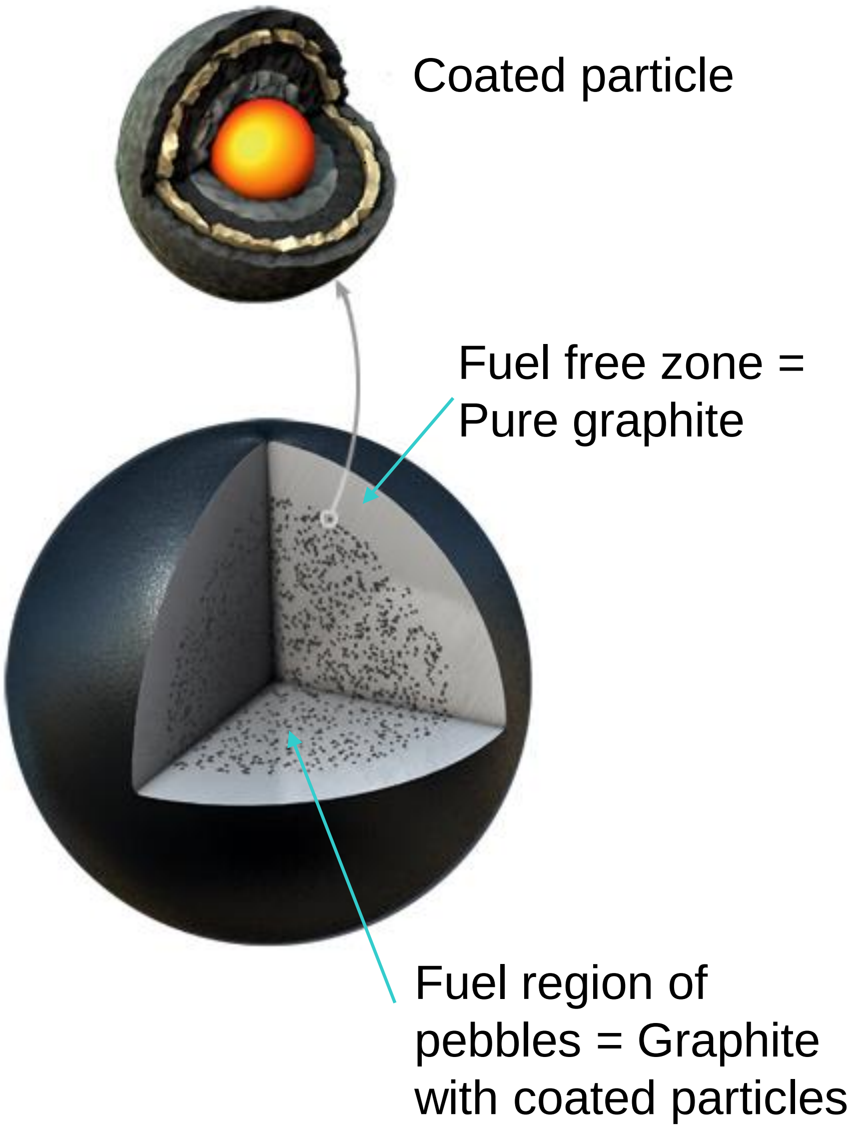
DRAGON / GB

1 REACTOR CORE
2 INNER STEEL CONTAINMENT SHELL
3 OUTER CONCRETE CONTAINMENT SHELL
4 PRIMARY HEAT EXCHANGER
5 COOLANT GAS CIRCULATOR
6 SECONDARY HEAT EXCHANGERS
7 CONTROL RODS
8 CONTROL ROD DRIVES
9 FISSION PRODUCT PURGE—GAS MANIFOLD
10 FISSION PRODUCT REMOVAL & HELIUM PURIFICATION PLANT

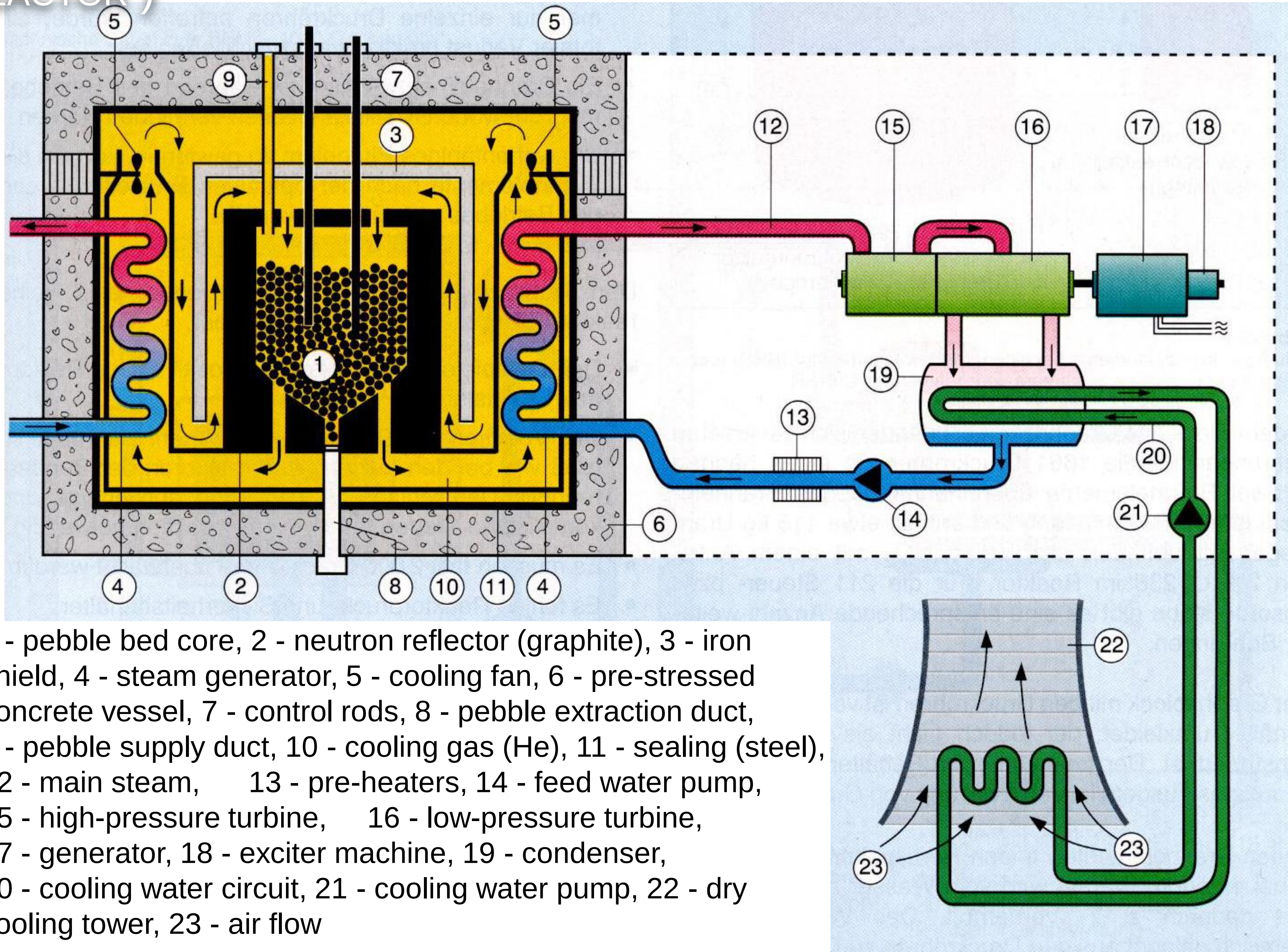


11 FUEL CHARGING MECHANISM
12 FUEL TRANSFER FLASK
13 FUEL CANNING MECHANISM
14 SPENT FUEL DISCHARGE CHUTE
15 SPENT FUEL STORAGE TURNTABLE
16 SPENT FUEL TRANSFER CASK
17 FRESH FUEL CHARGE CHUTE

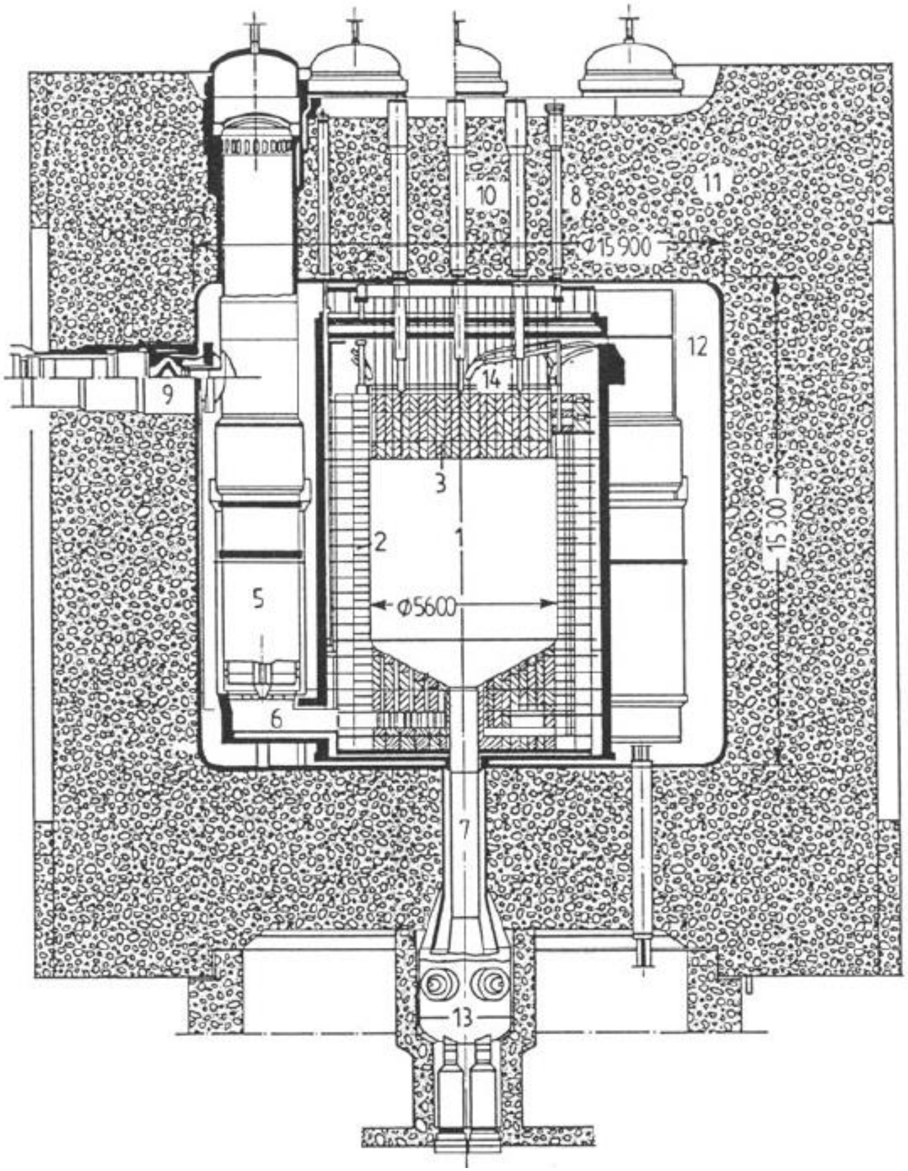
1. Mixing ***coated particles*** with resinated powder of graphite
2. Pre-molding at about 30 MPa and room temperature in silicone rubber molds → ***fuel region of pebbles*** (∅50 mm)
3. Add resinated powder in molds to form ***fuel-free zone*** (∅60 mm)
4. Isostatic pressing at 300 MPa and room temperature in silicone rubber molds
5. Resin binder carbonization at 800-900°C in inert gas
6. Sintering and extract residual gases and other impurities at 1950°C under vacuum



Scheme of a NPP with High-Temperature Gas-cooled Reactor (Pebble Bed Reactor)



1 - pebble bed core, 2 - neutron reflector (graphite), 3 - iron shield, 4 - steam generator, 5 - cooling fan, 6 - pre-stressed concrete vessel, 7 - control rods, 8 - pebble extraction duct, 9 - pebble supply duct, 10 - cooling gas (He), 11 - sealing (steel), 12 - main steam, 13 - pre-heaters, 14 - feed water pump, 15 - high-pressure turbine, 16 - low-pressure turbine, 17 - generator, 18 - exciter machine, 19 - condenser, 20 - cooling water circuit, 21 - cooling water pump, 22 - dry cooling tower, 23 - air flow



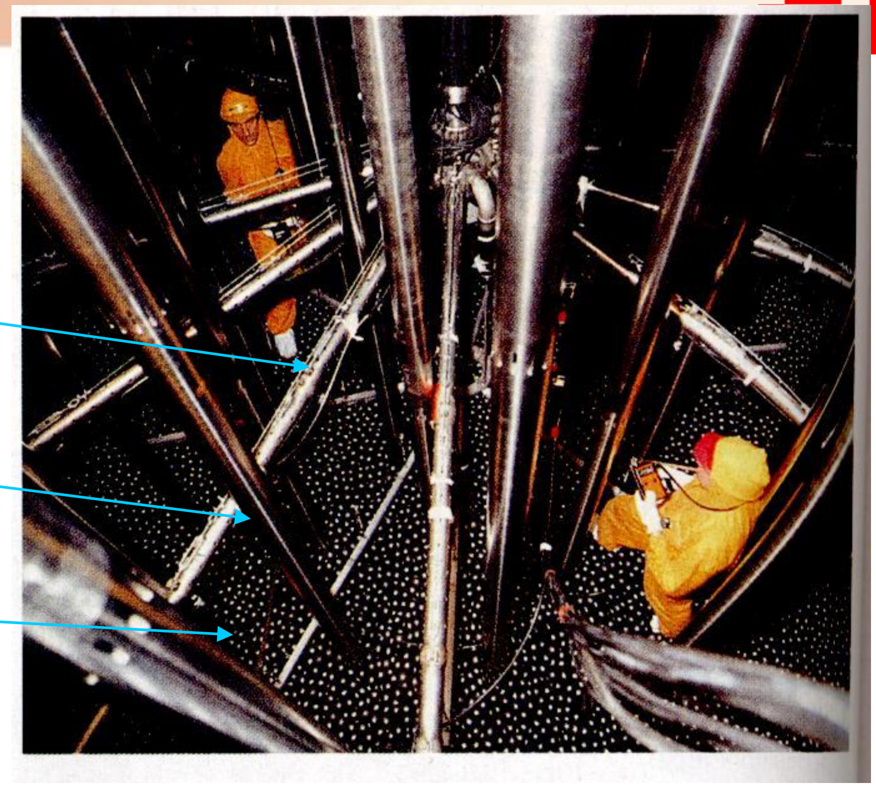
1. Core
2. Side reflector
3. Top reflector
4. Bottom reflector
5. Steam generator
6. Hot gas channel
7. Pebble extraction line
8. Control rods in the reflector
9. Helium circulator
10. Control rods pushed into the pebble bed
11. Pre-stressed concrete vessel
12. Liner with thermal insulation and cooling
13. Pebble extraction device
14. Pebble addition

THTR in Hamm-Uentrop

Pebble distributor

Control rods

Pebble bed



Refueling: Permanent → no excess reactivity

Safety: No excess reactivity + negative graphite temperature feedback + coated particles as "micro-containments" → inherent safety

Moderator: Graphite / ***But:*** Moderator-fuel lattice is strongly under-moderated

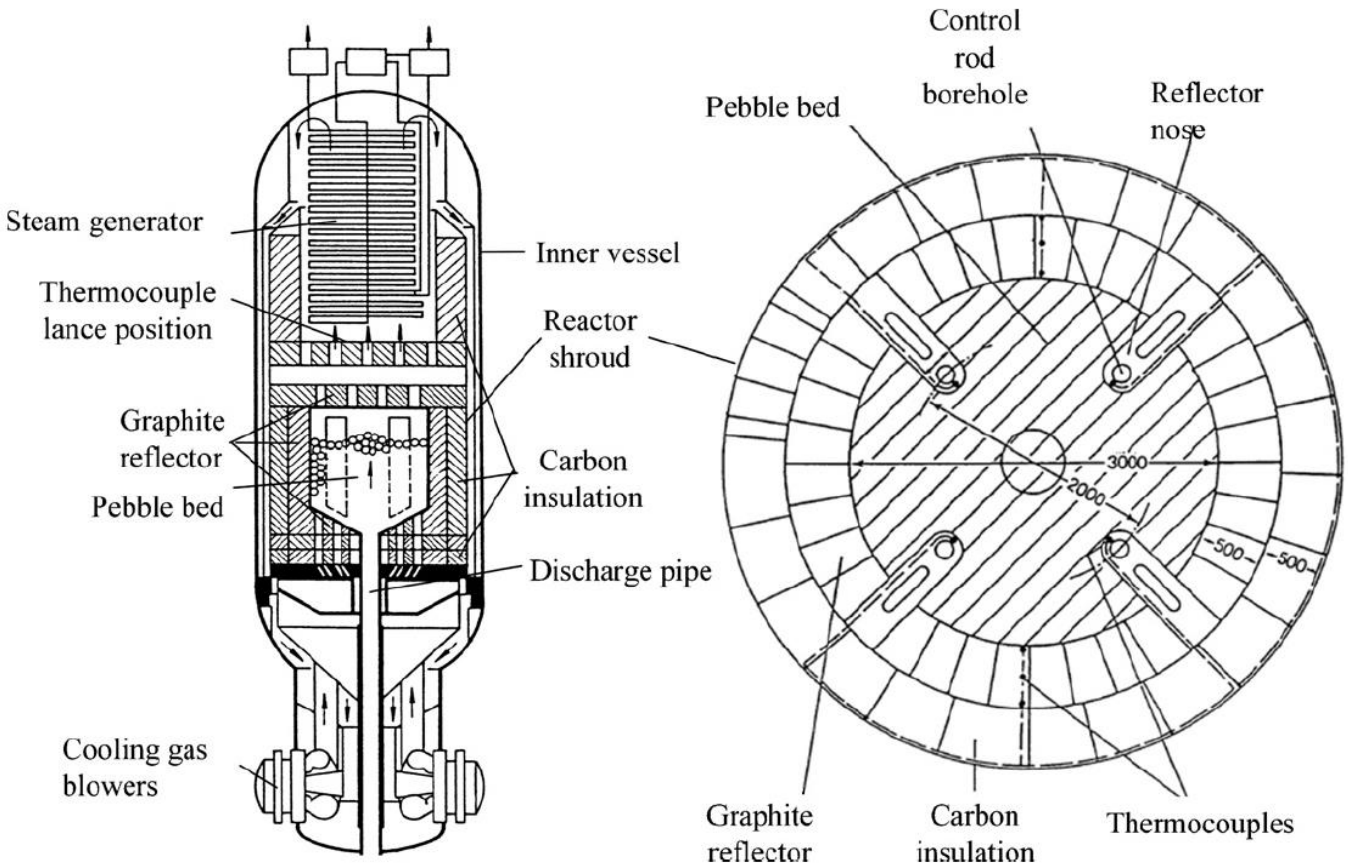
"epithermal spectrum" → higher enrichment necessary for criticality

→ breeding feasible:

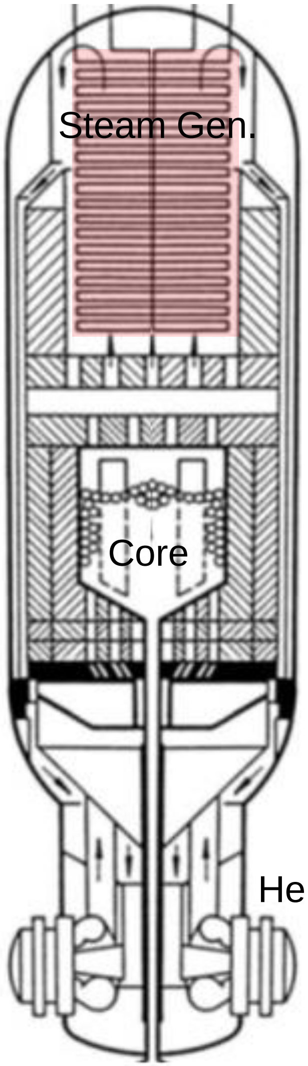
Thorium-Uranium cycle

$$^{232}_{90}\mathrm{Th} + ^{1}_{0}\mathrm{n} \rightarrow ^{233}_{90}\mathrm{Th} \xrightarrow{22.4\ \mathrm{min}} ^{233}_{91}\mathrm{Pa} + \beta^{-} \xrightarrow{2.35\ \mathrm{d}} ^{233}_{92}\mathrm{U} + \beta^{-}$$

AVR in Jülich

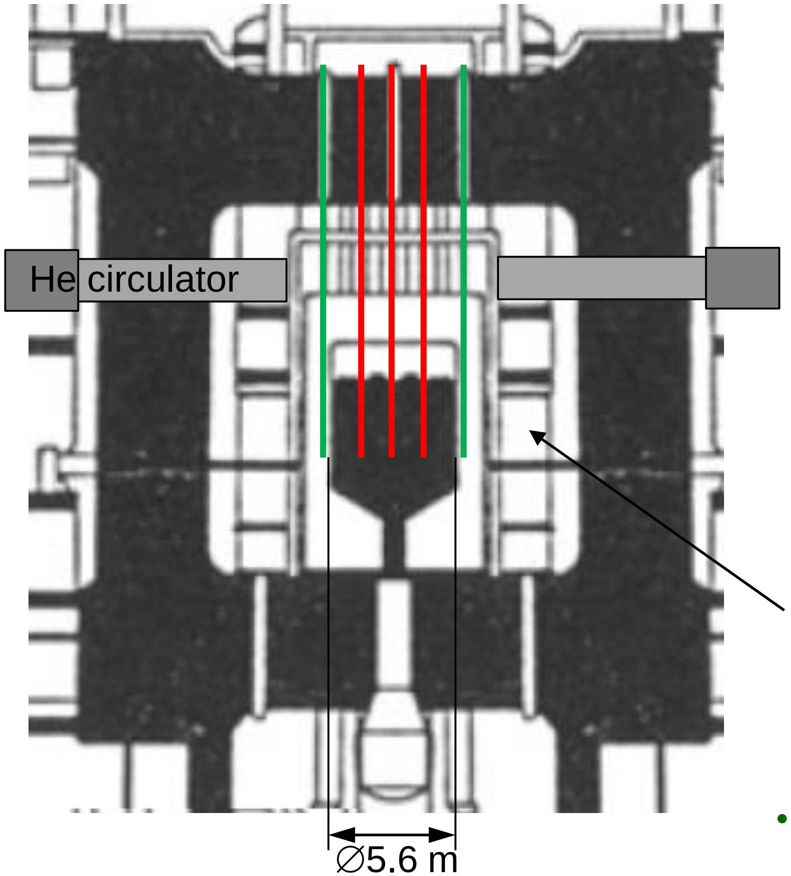


German Pebble Bed Reactors – Problematic Features



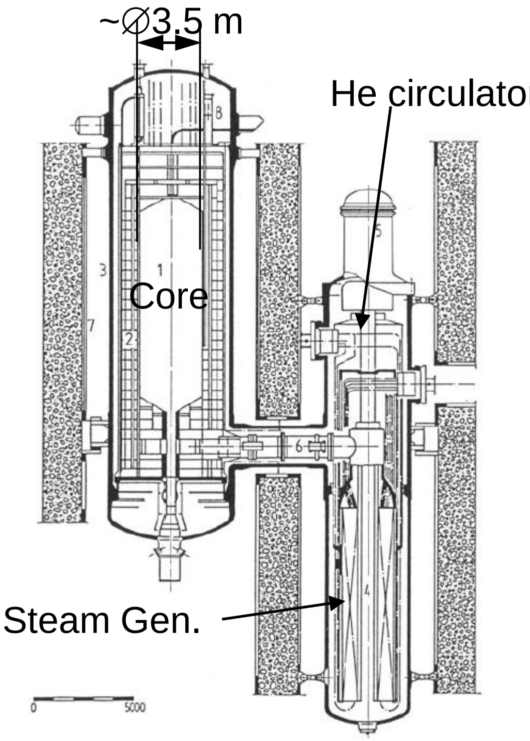
AVR (Jülich)

- Steam generator above core – eases water ingress in case of tube break



THTR (Hamm-Uentrop)

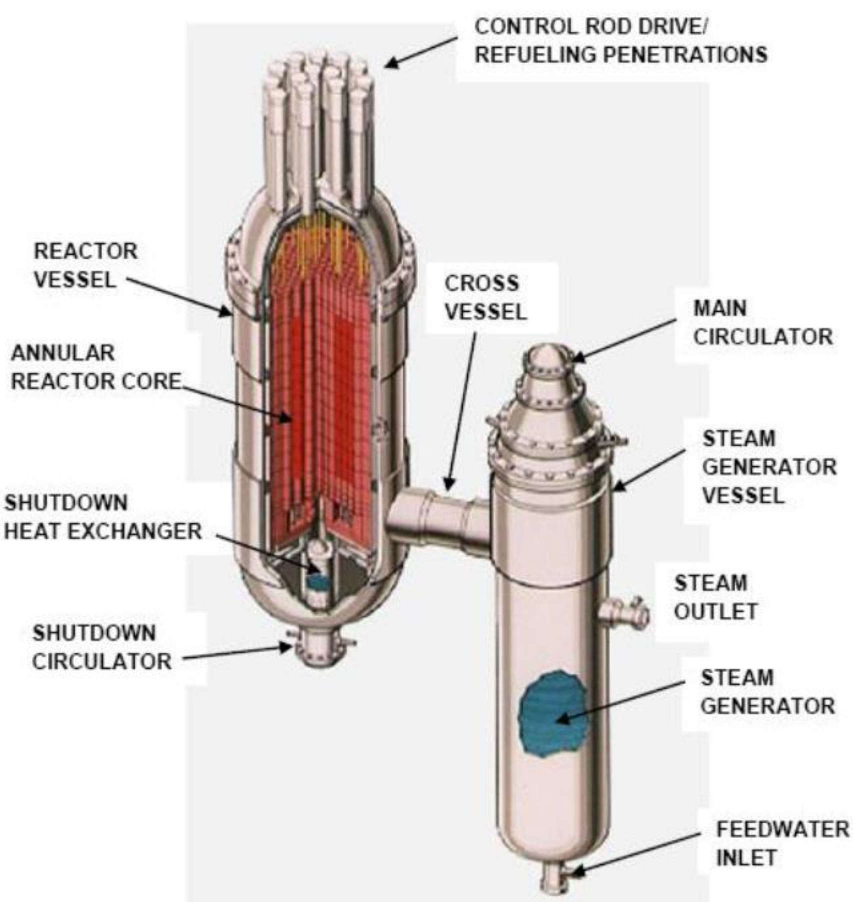
- Too large power → large core diameter → necessity of control rods for cold shutdown pushed into pebble bed without guide tubes → numerous broken pebbles
- Large core diameter → no inherently safe decay heat removal



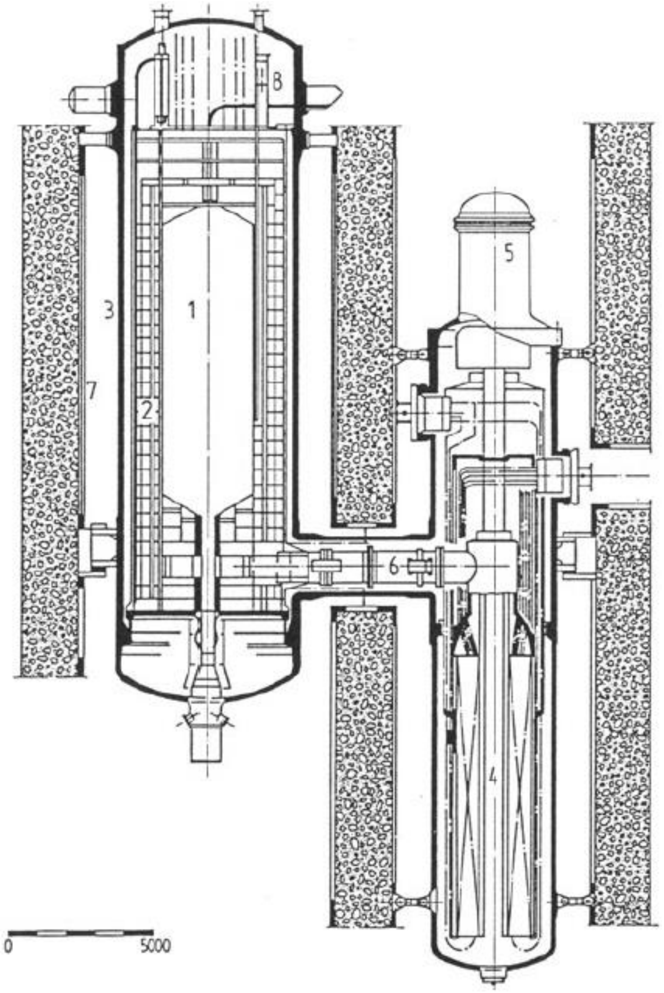
German modular HTR

- $Q_{th} \leq 250$ MW → Small enough diameter for control rods only in reflector (outside core)
- Small diameter → inherently safe decay heat removal via reactor pressure vessel wall
- Steam generator below reactor core → strong mitigation of water ingress by density difference He / H_2O vapor

- Modular HTGR designs with coated particle fuel due to inherent safety against cooling failure

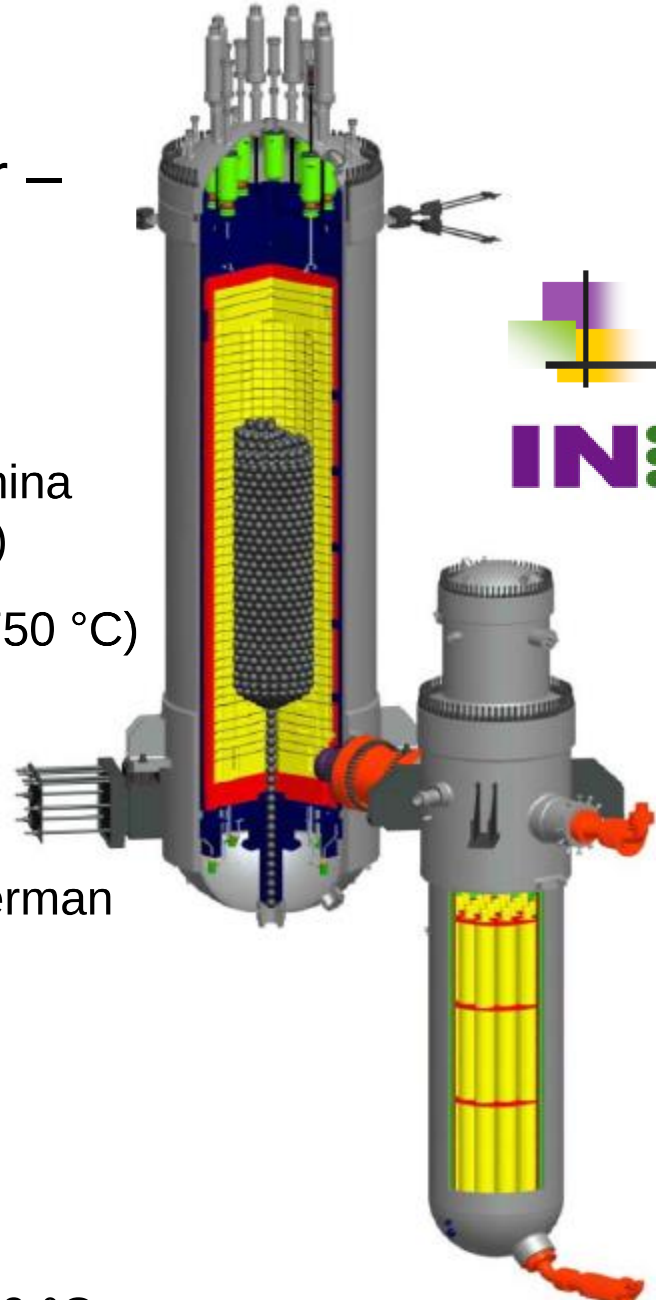


Modular HTGR with prismatic fuel



Modular pebble bed reactor

High Temperature Reactor – Pebble Bed / Modular



- Twin unit under construction in China (Rongcheng, Province Shandong)
- Coolant: Helium (7 MPa, 250 → 750 °C)
- Steam turbine
- 2 x 250 MWt → 210 MWe

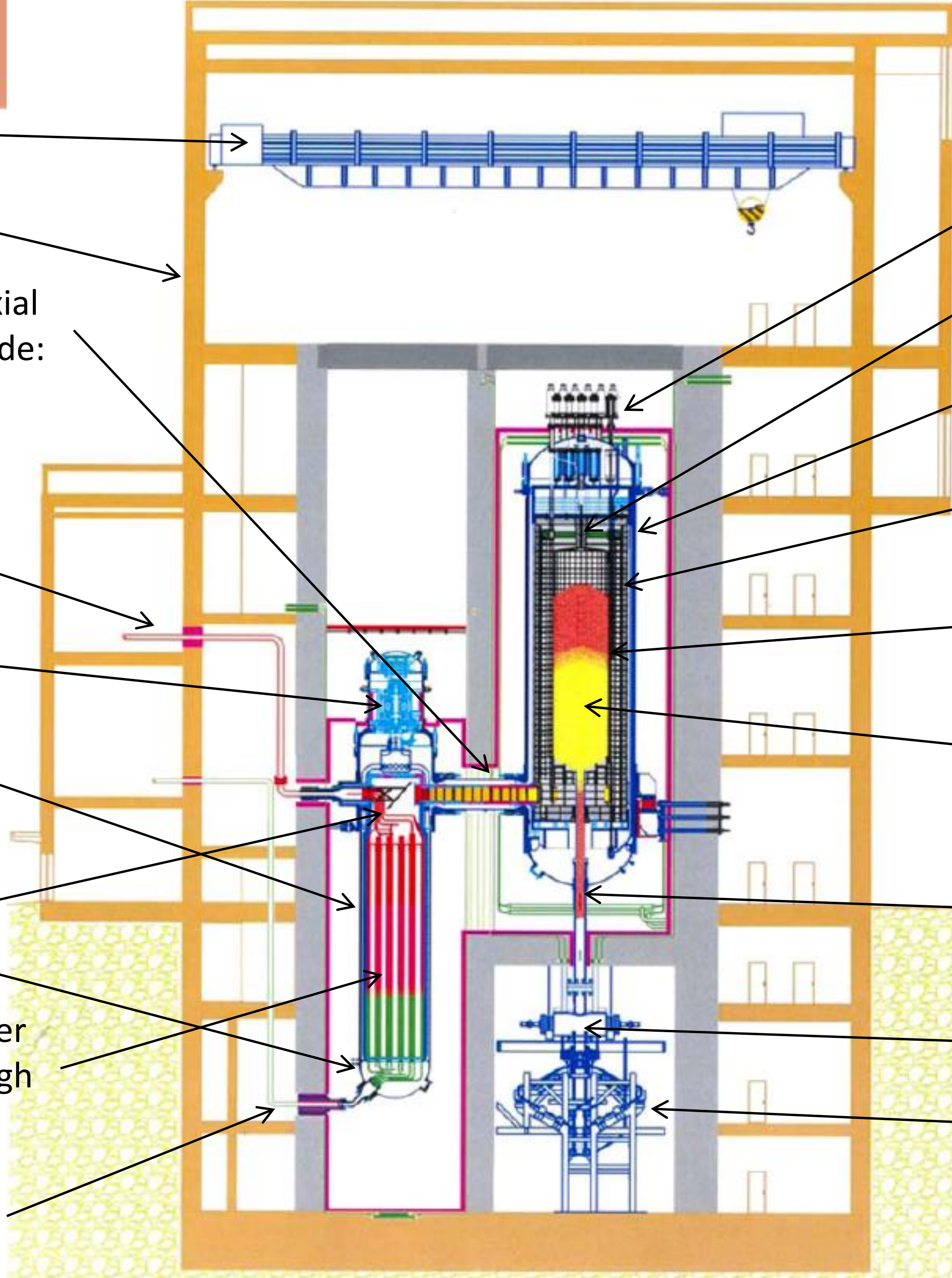
Improvements compared to early German prototypes:

- Improved pebble extraction
- Control rods in reflector
- Steam cycle (simple, less risk)
- Reduced outlet temperature of 750 °C

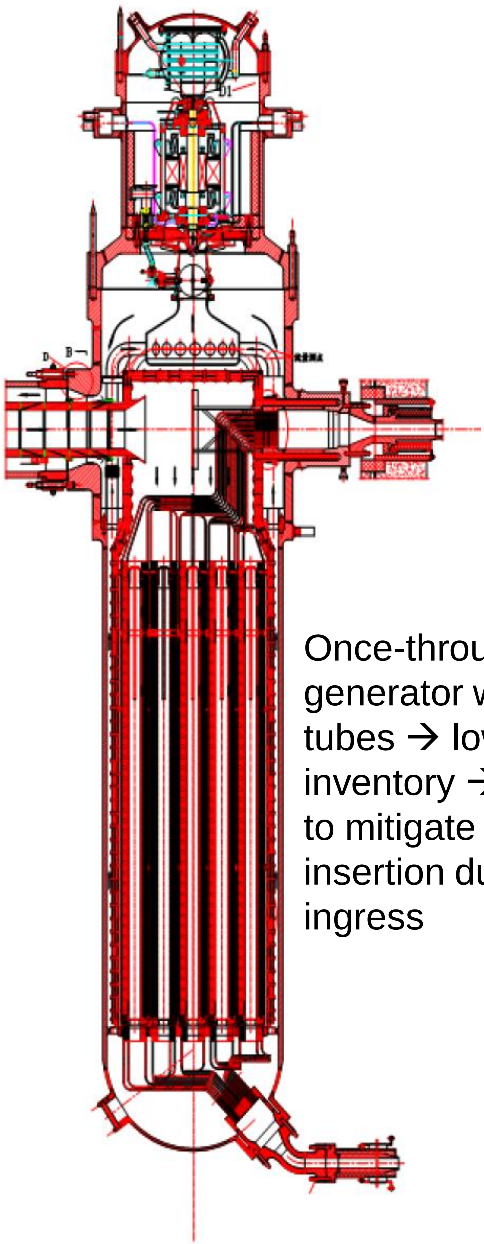
Main steam
13.24 MPa, 566 °C

Efficiency: 42 %

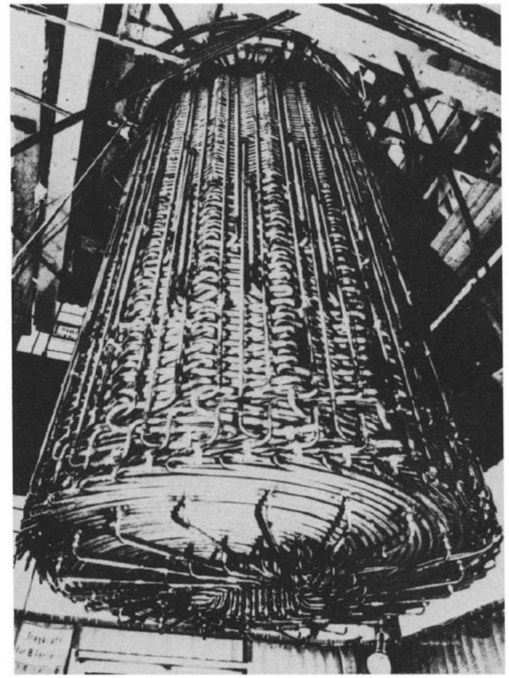
HTR-PM


Crane
Containment
Connection line, coaxial (inside: hot leg, outside: cold leg)
Main steam line
Helium compressor
Steam generator
Collectors
19 helical heat transfer modules (once through steam generation)
Feed water line
Control rod drives
Pebble supply
Reactor press. vessel
Graphite mantle /reflector
Control rod
Reactor core with pebble bed
Pebble extraction
Detector of broken pebbles
Pebble transport system,

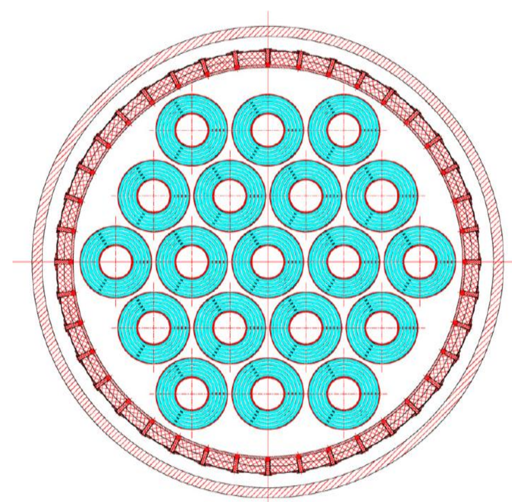
HTR-PM STEAM GENERATOR



Once-through steam generator with helical tubes → low water inventory → precaution to mitigate reactivity insertion due to water ingress

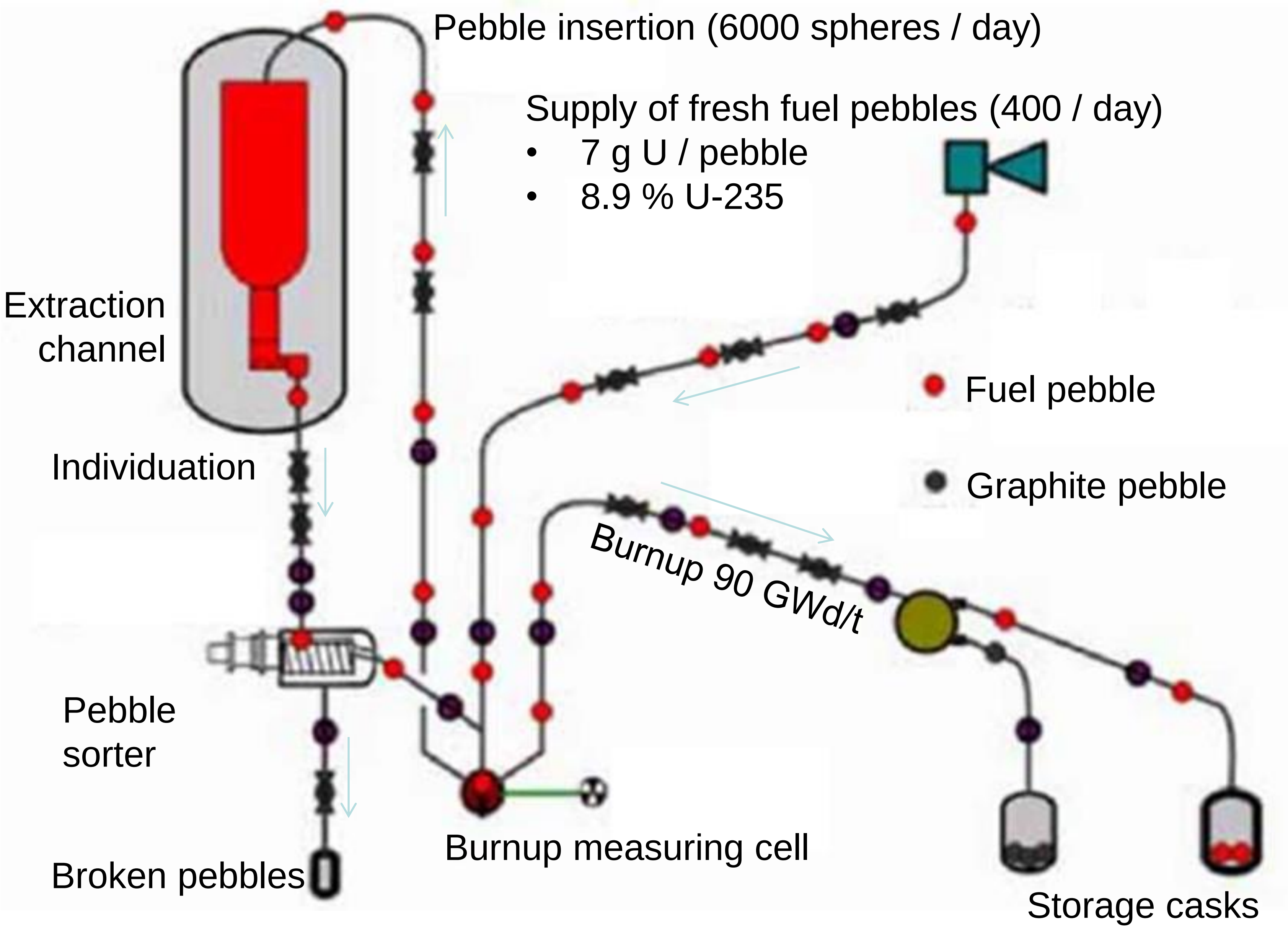


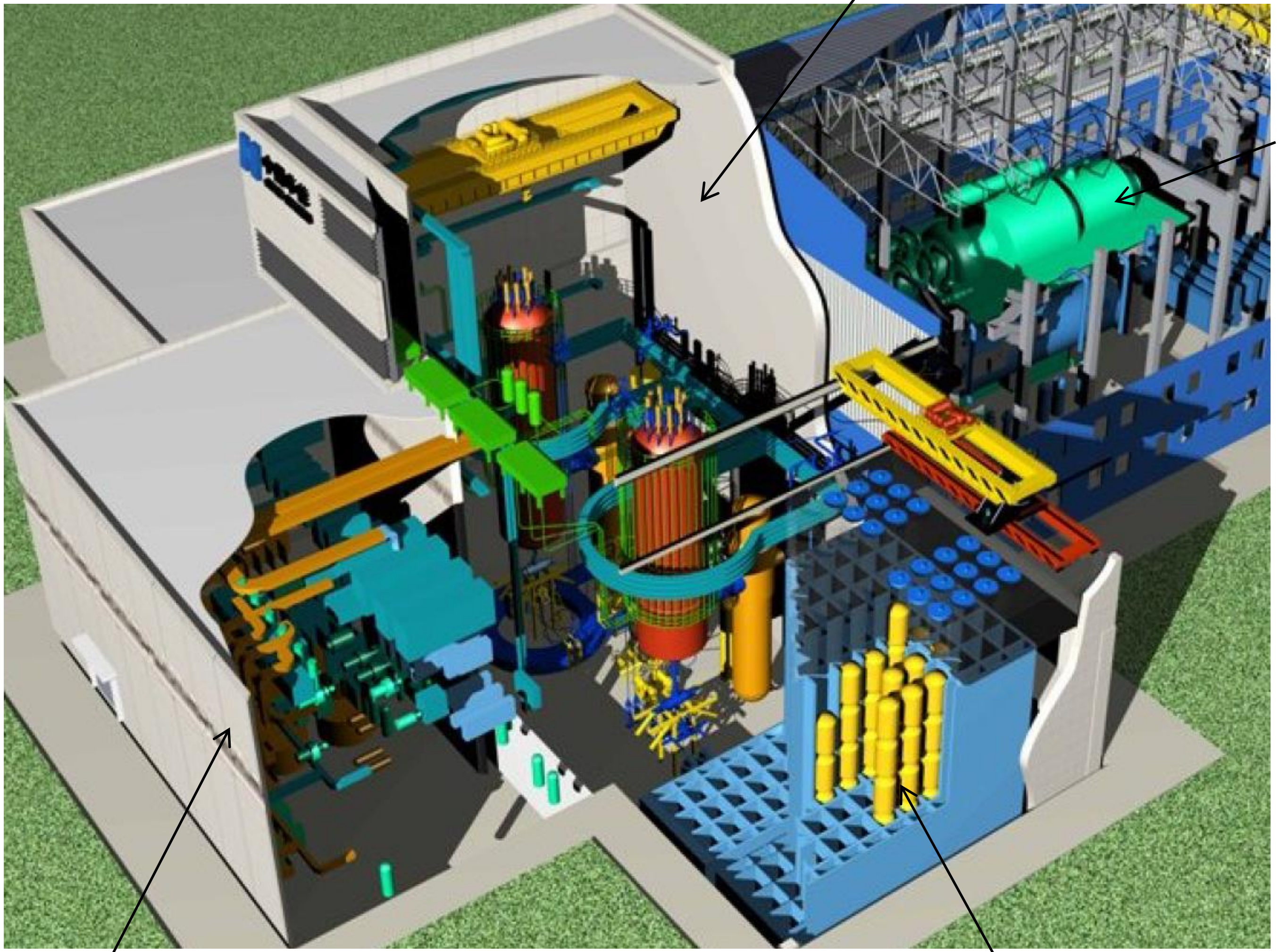
E. Ziermann / The AVR nuclear power facility
Nuclear Engineering and Design 78 (1984) 99–108



Zhang et al., Nuclear Engineering and Design 239 (2009) 1212–1219

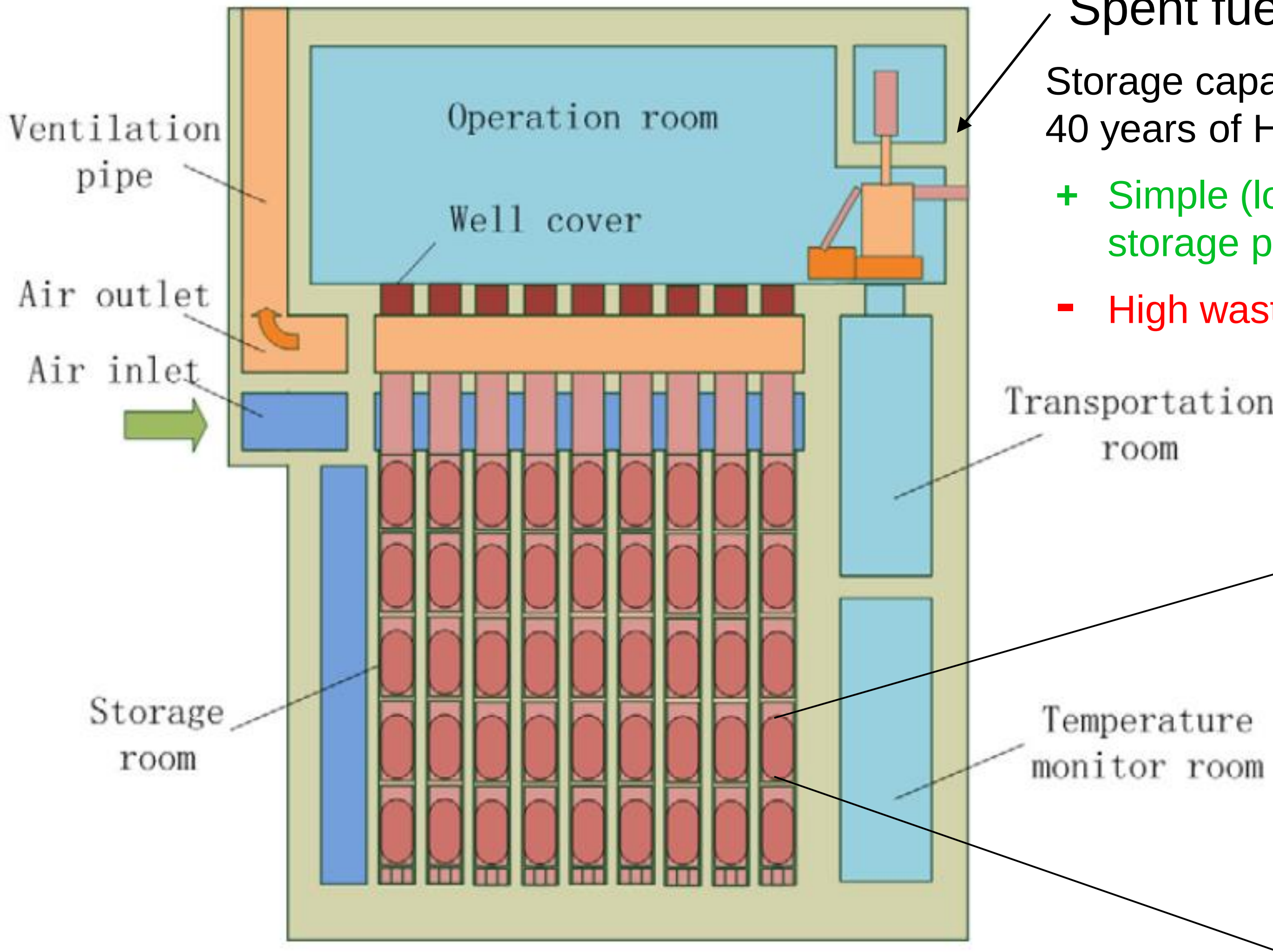
HTR-PM FUEL HANDLING SYSTEM





ZHANG Zuoyi: HTR-PM of 2014: toward success of the world first Modular High Temperature Gas-cooled Reactor demonstration plant, HTR-2014, 2014, Oct. 28-31, Weihai

ON-SITE INTERIM SPENT FUEL STORAGE



Spent fuel storage building

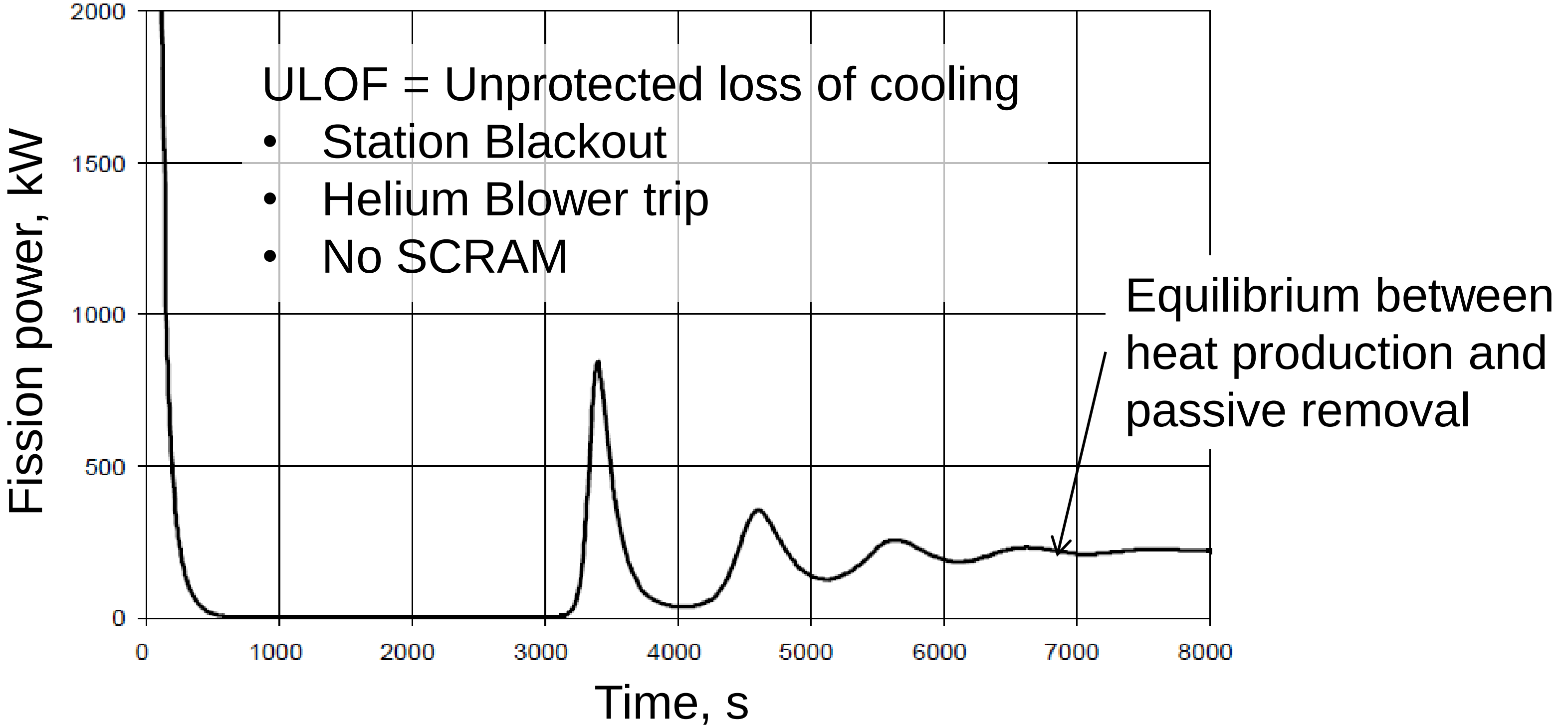
Storage capability for spent fuel from 40 years of HTR-PM operation

- \+ Simple (low decay heat – dry storage passive safety)
- \- High waste volume

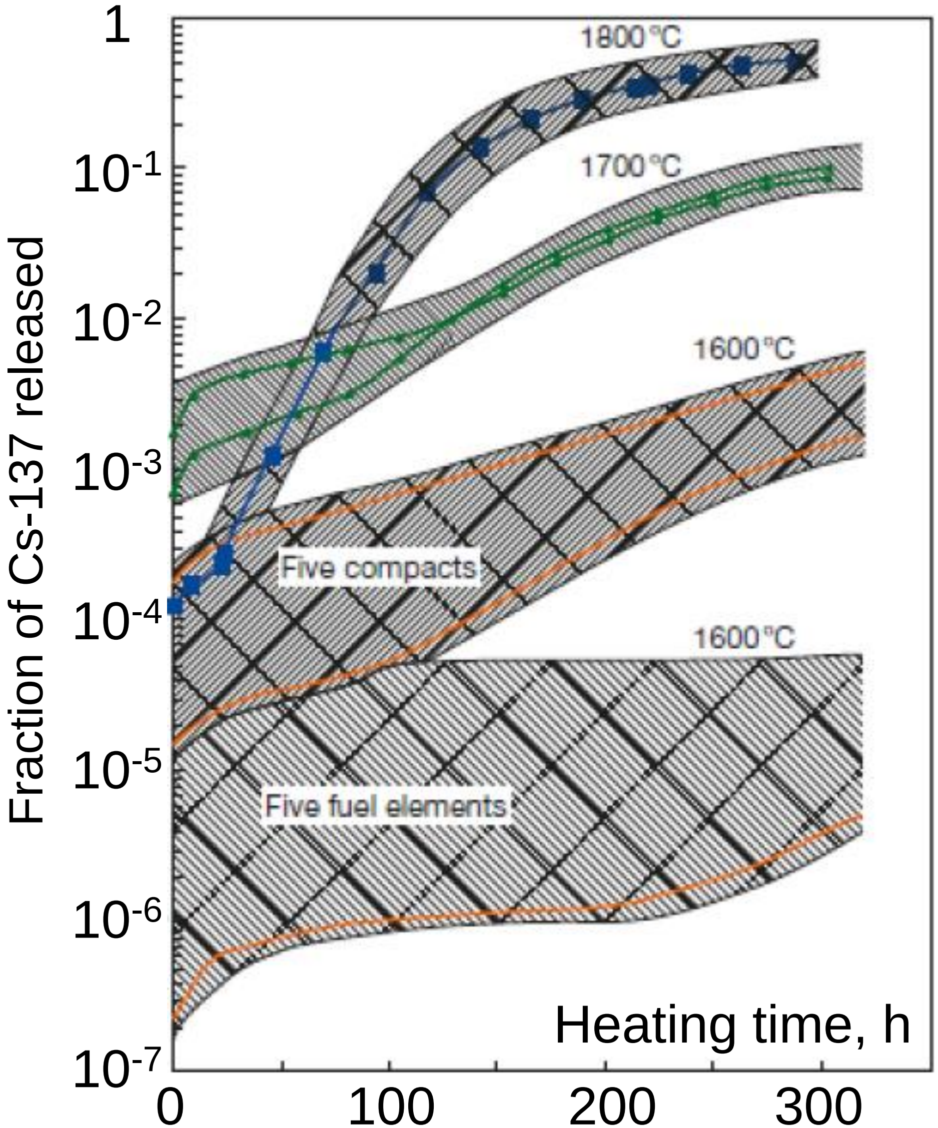
Canister for 40’000 spent fuel spheres

- Cooling by closed-circuit air flow in closed forced convection conditions (for the demonstration plant)
- If forced circulation fails, an open air natural flow can keep the fuel temperature under the limit of the coated particle integrity

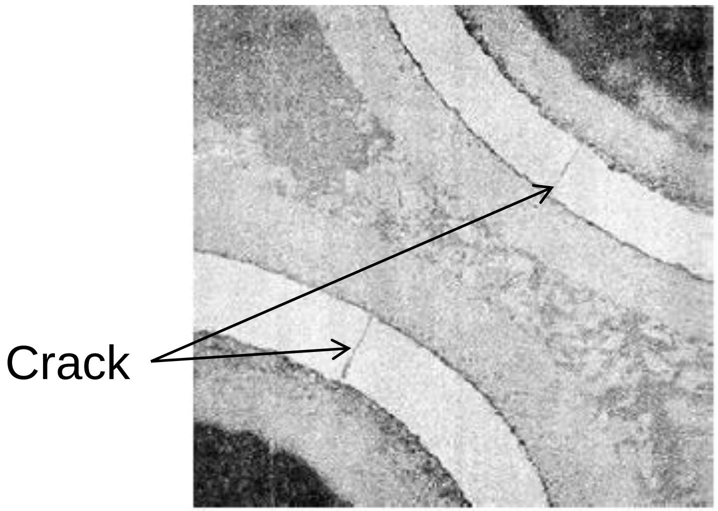
- Continuous refueling – no excess reactivity
- Thermal losses from the comparatively small and slim reactor can remove decay heat by natural convection and thermal radiation at below 1600 °C
- Strong negative feedback from fuel and moderator temperature to reactivity
- Temperature increase in case of cooling failure makes reactor subcritical while temperature stays below 1600 °C
- SiC layers stay effective as barrier against fission product release
- HTR-PM = inherently safe design regarding a full unprotected loss of cooling



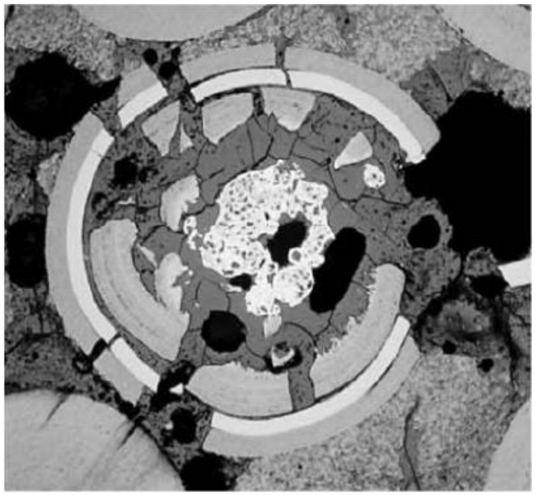
Release of fission products (Cs-137) by diffusion at too high temperatures



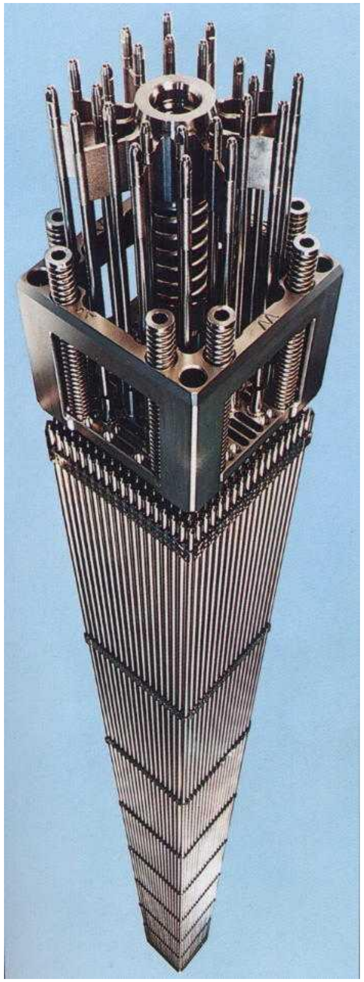
Fail of coated particles after too high burn-up

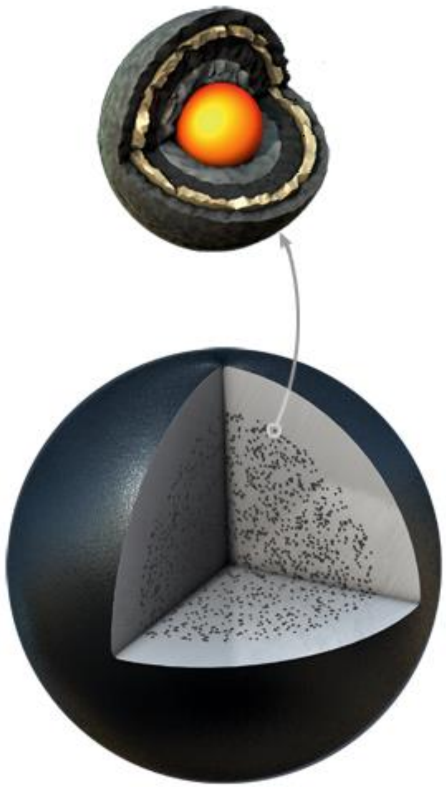


Crack formation in SiC



Breakdown due to fission gas pressure





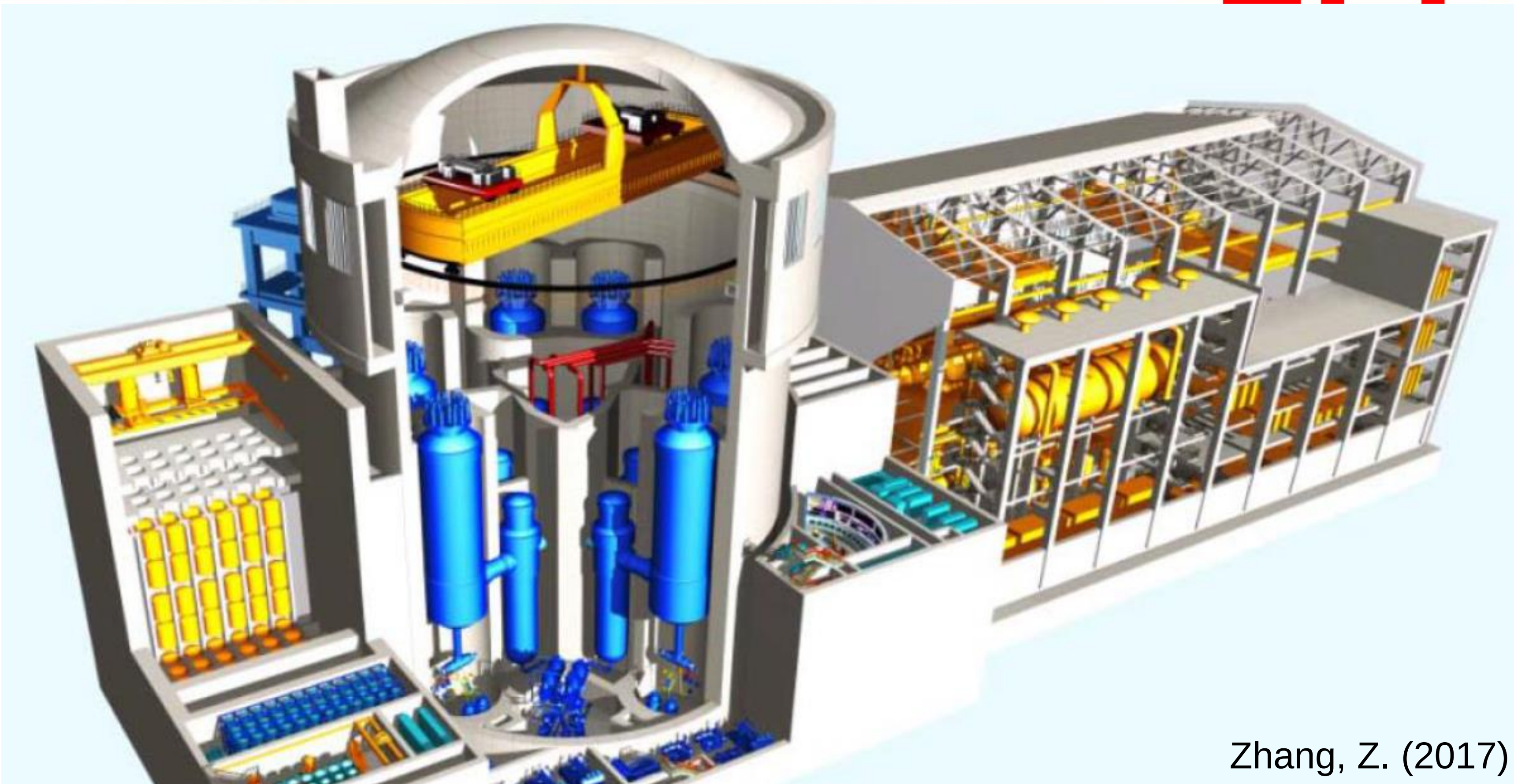
HTR-PM

Inventory:	420’000 Pebbles
Usage per year:	145’000 Pebbles
Uranium content:	7 g/pebble
Pebble diameter:	6 cm
Average density:	0.0458 g U/cm^3

PWR

Inventory:	~200 fuel elements
Usage per year:	~40 fuel elements
Average density:	~3 g U/cm3

Waste ratio: **65!**



Zhang, Z. (2017)

HTR-PM600 Parameters		
Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566
Steam pressure	MPa	13.24