

NUCLEAR POWER GENERATION TECHNOLOGIES

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NUCLEAR REACTOR CLASSIFICATION

Duty

Neutron energy

Moderator

Coolant

Design

CLASSIFICATION ACCORDING TO DUTY

Experimental and research reactors

- Nuclear physics and chemistry research
- Development of new reactor types
- Radioactive isotope production
- Radiation beam production for research and experiments

Power reactors

- Heat generation for electricity production process
- Heat generation for other industrial process (desalination, district heating, hydrogen production)

Propulsion reactors

- Large surface warships (cruisers, aircraft carriers)
- Submarines
- Arctic icebreakers
- Merchant vessels (proved unfeasible)

“Military” reactors

- Production of fissile isotopes for nuclear warheads



CLASSIFICATION ACCORDING TO NEUTRON ENERGY

Thermal neutron reactors

- Energy below 0.1 eV
- Needs moderator

Fast reactors

- Energy above 0.1 MeV
- Heavy coolants required
- Fuel breeding capability



CLASSIFICATION ACCODING TO MODERATORS

Graphite (C)

- GCR/AGR (GBR, FRA)
- RBMK (SUN)
- GT-MHR (RUS/USA), HTGR (DEU/ZAF/CHN)

Heavy water (D₂O)

- PHWR/CANDU (CAN, IND)
- ACR (CAN)

Light water (H₂O)

- BWR (USA, DEU, FRA, JPN, SWE)
- PWR (USA, DEU, FRA, KOR, JPN, CHN, SWE)
- VVER (SUN/RUS)

Other

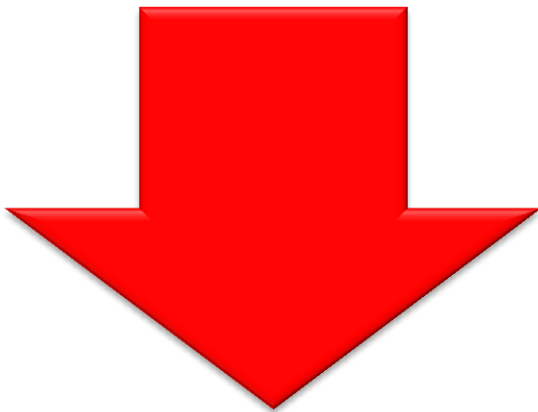
- Research reactors with other moderators or combination (e.g. Be+H₂O: Polish research reactor MARIA)

GRAPHITE AS MODERATOR



Easy to obtain and process

Resistant to high temperature
(allows to increase efficiency)



Combustible

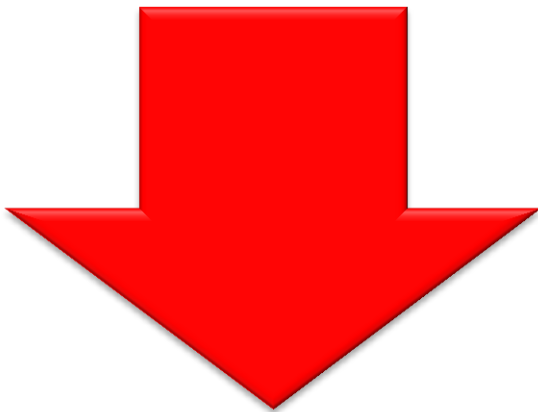
Relatively high atomic mass
(increases core volume)



HEAVY WATER AS MODERATOR



Allows to use natural uranium
Low neutron absorption
Not combustible



Deuterium has higher atomic mass
than hydrogen – increased core volume
Cumbersome technology

LIGHT WATER AS MODERATOR

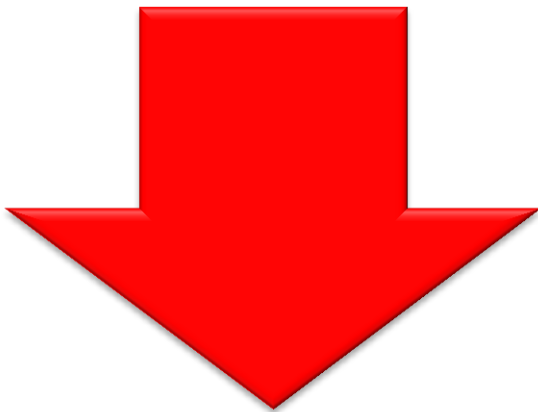


Easy to get

Lowest possible atomic mass of H – small core volume

Allows to use the same volume of water as moderator and coolant – increased safety

Low chemical activity



Absorbs neutrons – requires enriched fuel

Low boiling point at limited pressure – limits temperature in loop-type reactors

CLASSIFICATION ACCORDING TO COOLANT

Air

- Early research and military reactors

Carbon dioxide

- AGR, GCR

Helium

- GT-MHR, HTGR

Heavy water

- PHWR/CANDU

Light water

- PWR
- BWR
- VVER
- RBMK
- ACR

Liquid metal

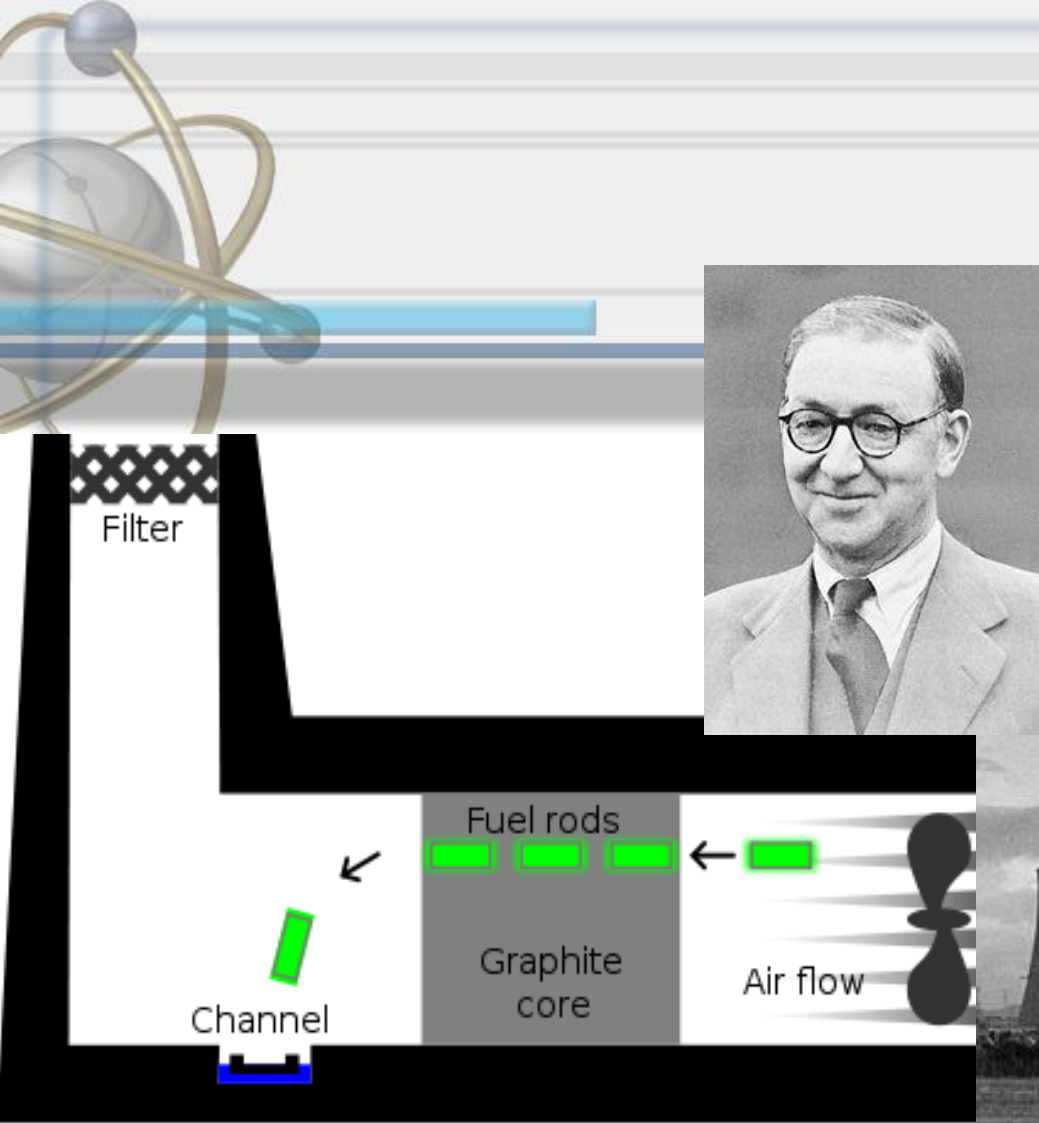
- FBR

AIR COOLING



Chicago Pile 1, USA 1942

AIR COOLING

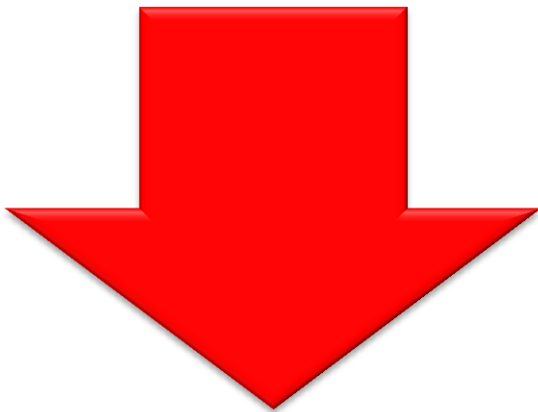


Windscale Pile 1
GBR, 1950

CO₂ COOLING



Allows to increase core operating temperature (up to 700°C)

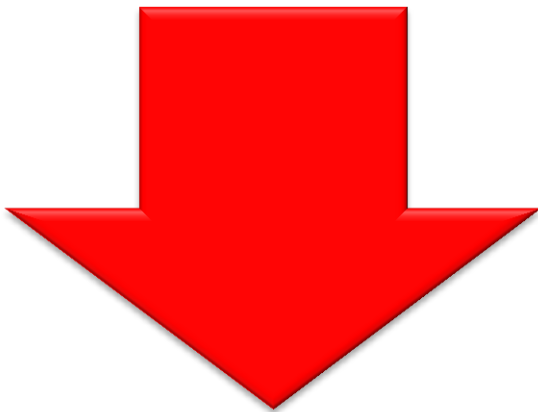


Low specific heat capacity
High power consumption in blowers
Over 700°C chemically active

HELIUM COOLING



Allows to reach very high temperatures
Chemically inactive



Cost
Low specific heat capacity
High energy consumption by
blowers/compressors

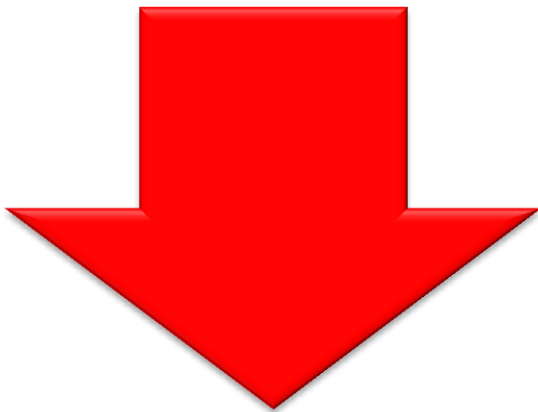
HEAVY WATER COOLING



Allows to use natural uranium fuel (if combined with heavy water moderator)

High specific heat capacity

Low power consumption by pumps



Operating temperature limited by boiling point

Cost

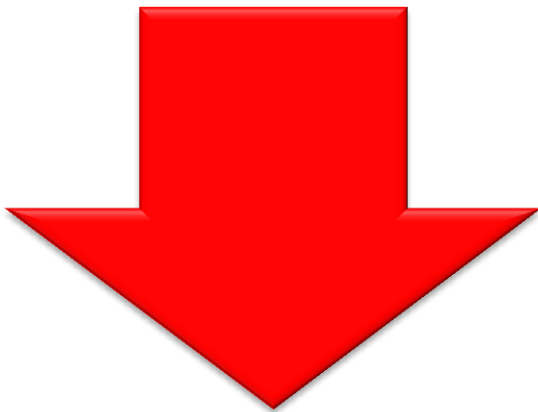
LIGHT WATER COOLING



Cheap

High specific heat capacity

Low power consumption by pumps



Operating temperature limited by boiling point

Absorbs neutrons – results with higher required uranium enrichment level

USED COMBINATIONS

Moderator Coolant	graphite	D2O	H2O	None
CO ₂	GCR, AGR	—	—	—
He	THTR GT-MHR, PBMR	—	—	—
H2O	RBMK	ACR	PWR, VVER BWR	—
D2O	—	CANDU PHWR	—	—
Liquid metal	—	—	—	FBR

CLASSIFICATION ACCORDING TO DESIGN

Loop-type (with pressure vessel)

- PWR, VVER
- BWR
- GCR, AGR
- GT-MHR, PBMR

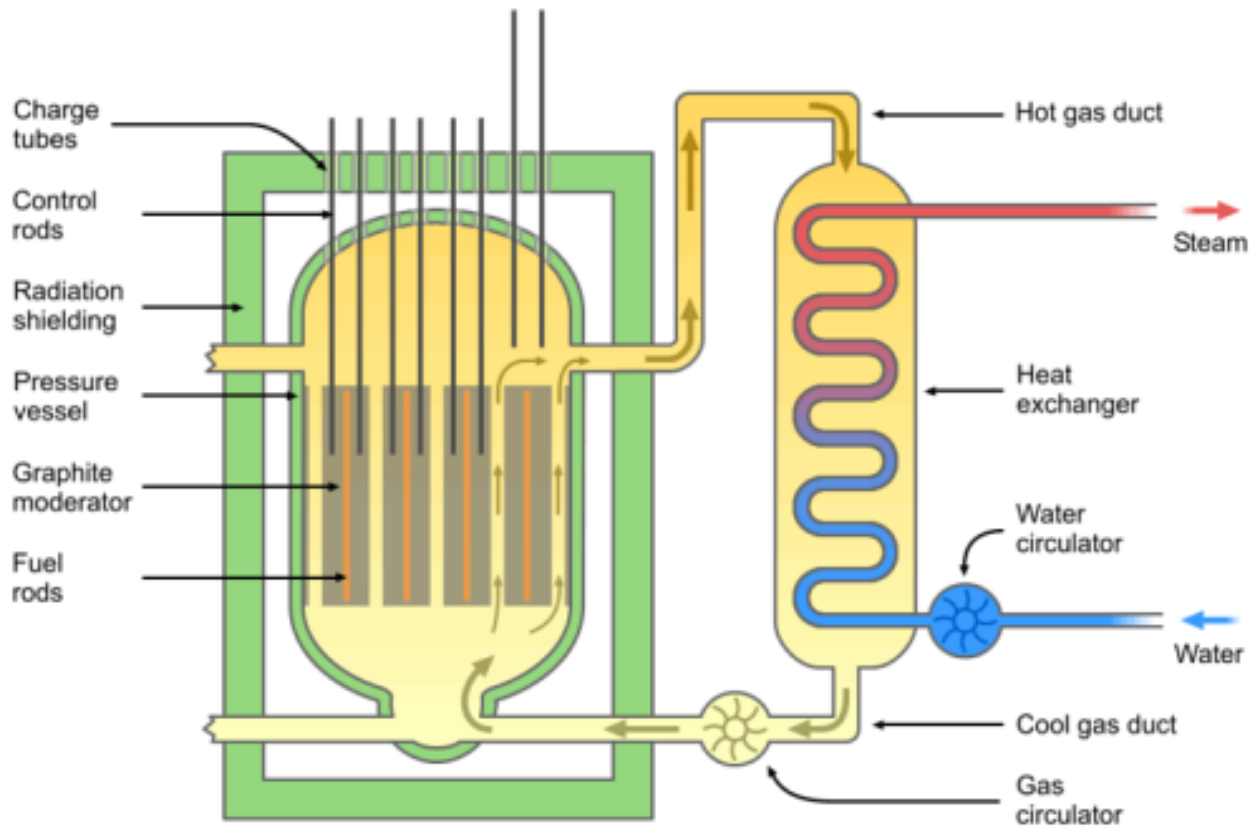
Channel-type

- RBMK
- CANDU

Pool-type

- FBR

GAS-COOLED REACTOR (GCR)



GAS-COOLED REACTOR (GCR)

- Pressure vessel (steel or concrete)
- Coolant: CO₂
- Moderator: graphite
- Fuel: natural uranium, cladding: Magnox or Mg-Zr
- Two-circuit design:
 - Gas primary circuit, ca. 400°C, 7-27 bar
 - Water-steam secondary circuit with a steam turbine
- Unit efficiency:
- Manufacturers: GBR (Magnox), FRA (UNGG)
- Operators: GBR, ITA, JPN, FRA, ESP, PRK
- Units 60-550 MWe

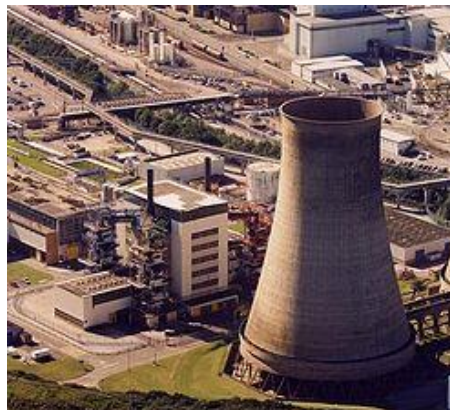
GAS-COOLED REACTOR (GCR)



Magnox fuel
element



Sizewell A (GBR)
 2×245 MWe gross
 2×210 MWe net
1966-2006



Calder Hall (GBR)
 4×60 MWe gross
 4×50 MWe net
1956-2003

GAS-COOLED REACTOR (GCR)

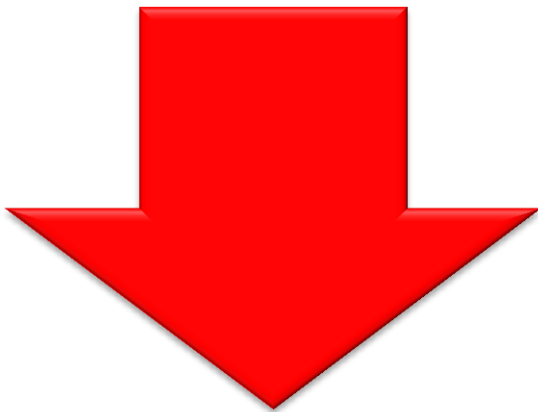


Saint-Laurent A (FRA)
500+530 MWe gross
480+515 MWe net
1969-1992

GAS-COOLED REACTOR (GCR)

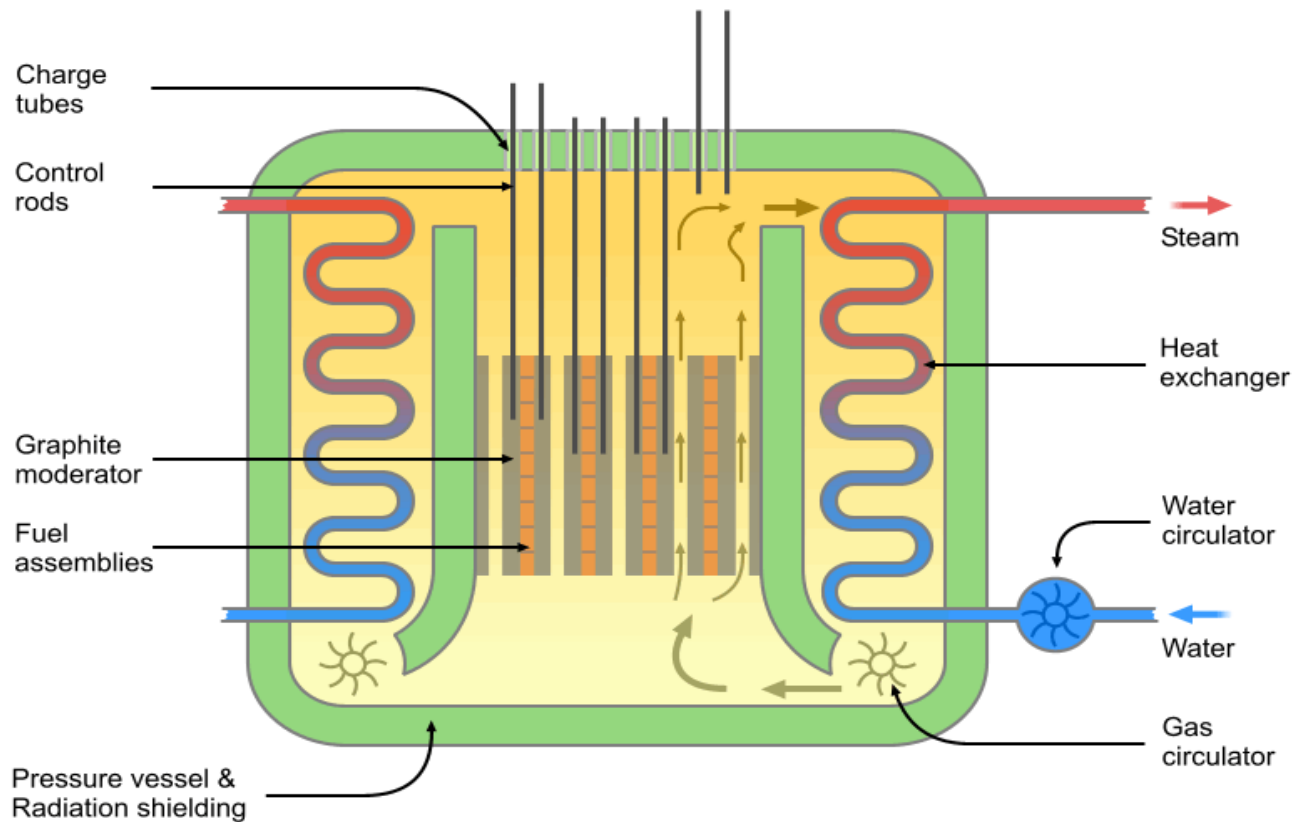


Simple design
Can be cooled down by natural convection
On-line refueling



High own power consumption (blowers)
Temperature restricted by fuel cladding material
No safety containment
Low fuel burnup

ADVANCED GAS-COOLED REACTOR (AGR)

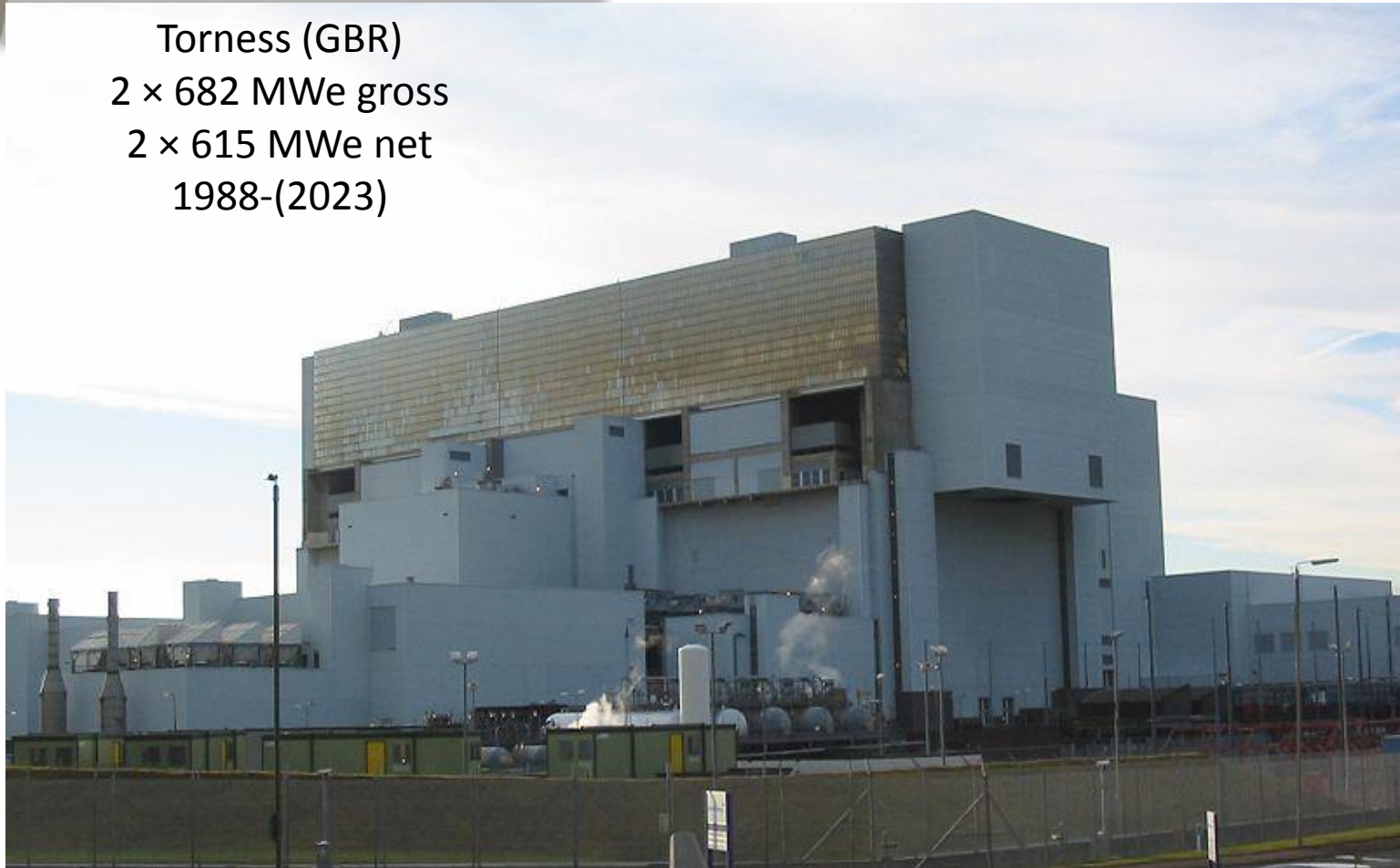


ADVANCED GAS-COOLED REACTOR (AGR)

- Pressure vessel – concrete with steel lining, integrated steam generators
- Coolant: CO₂
- Moderator: graphite
- Fuel: enriched uranium (2-3%), stainless steel cladding
- Two-circuit design:
 - Gas primary circuit, ca. 650/300°C, 40 bar
 - Secondary water-steam circuit with a steam turbine, 196 bar, 543°C
- Unit efficiency: 41% gross
- Manufacturer: GBR
- User: GBR
- Units 550-620 MWe

ADVANCED GAS-COOLED REACTOR (AGR)

Torness (GBR)
2 × 682 MWe gross
2 × 615 MWe net
1988-(2023)



ADVANCED GAS-COOLED REACTOR (AGR)

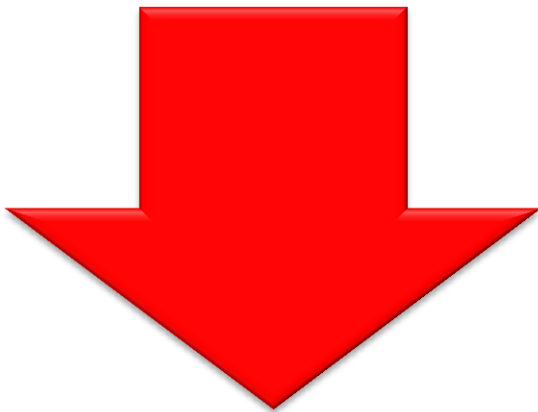


Simple design

Online refuelling

High parameters of live steam
(superheated steam)

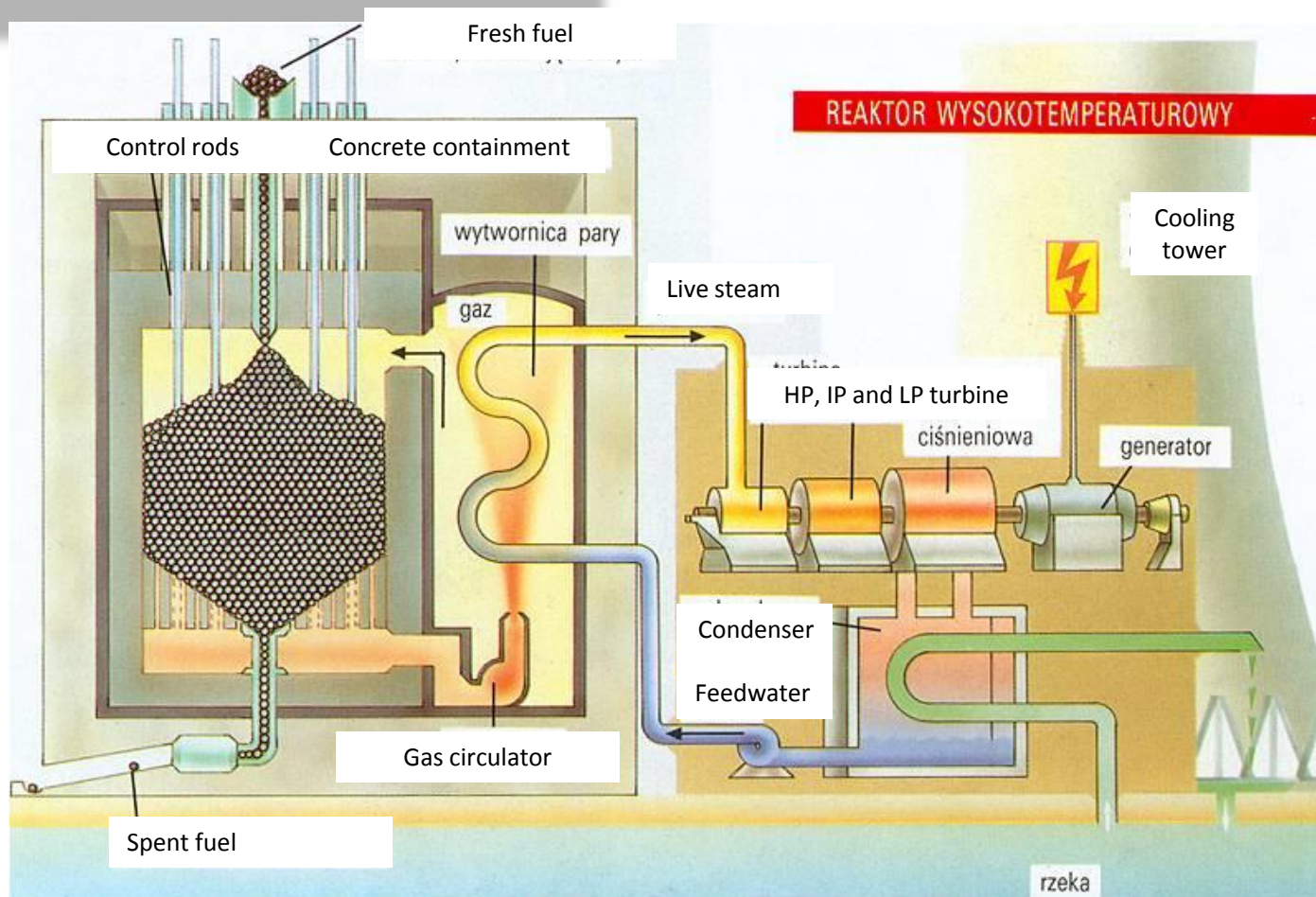
High gross efficiency



Large own energy consumption

Low burnup of fuel

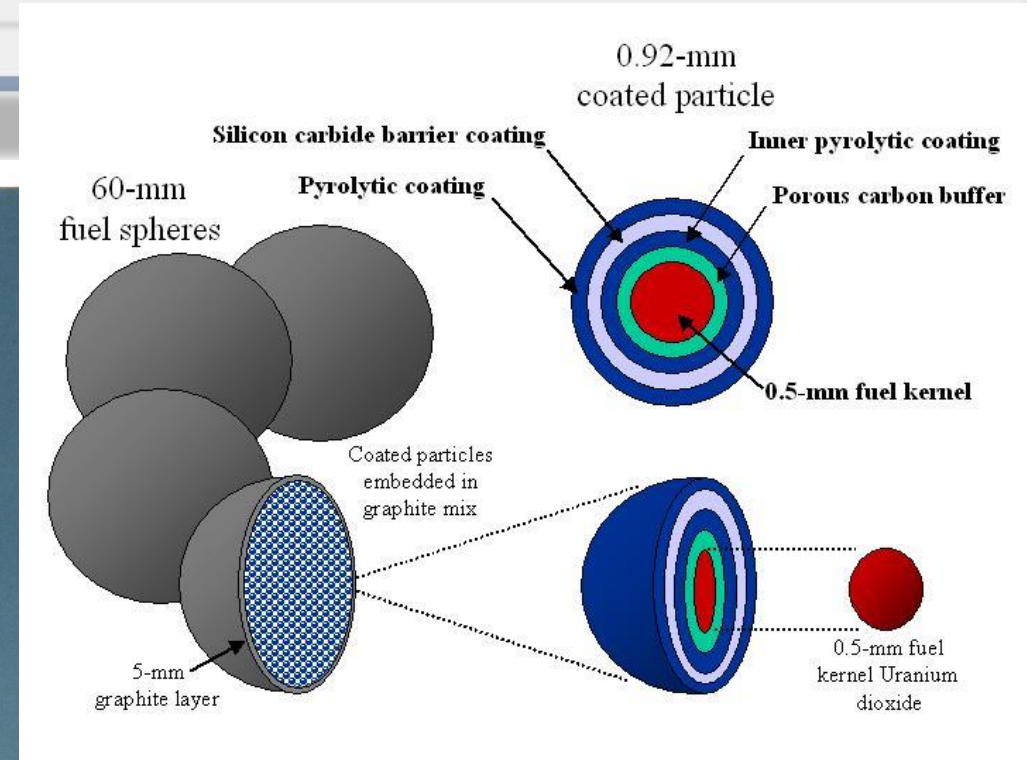
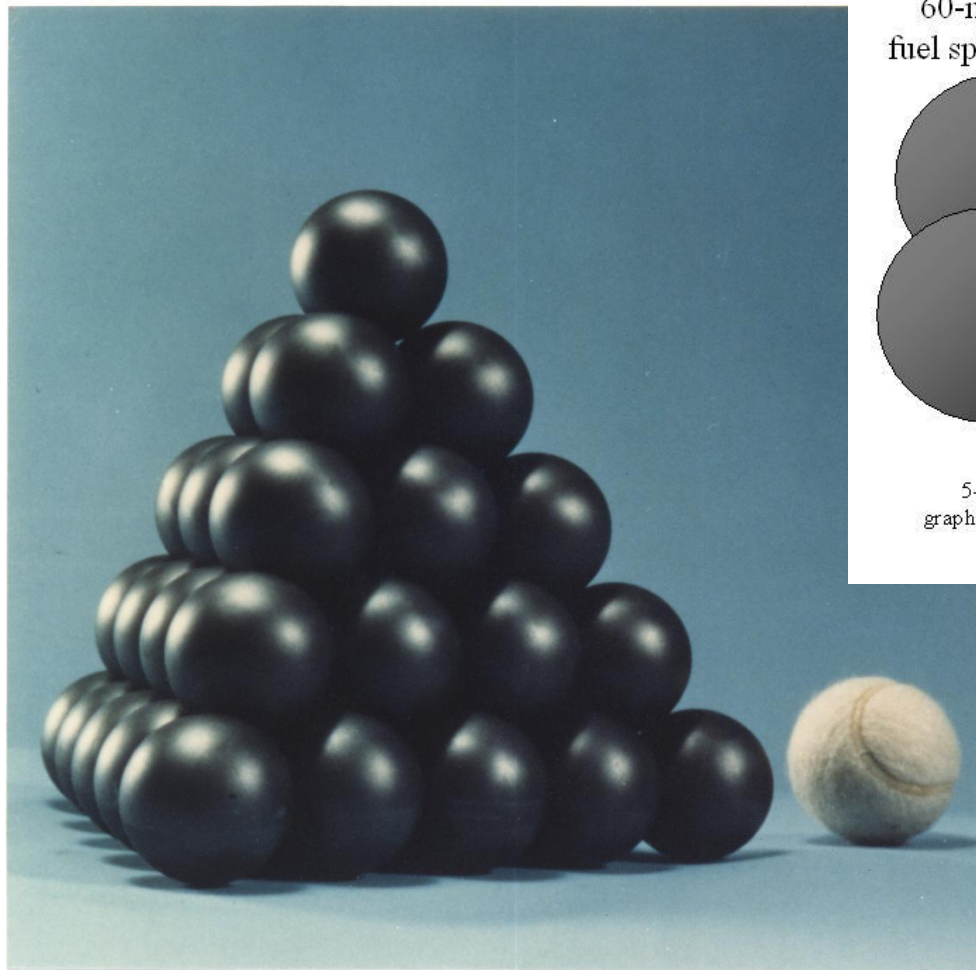
HIGH-TEMPERATURE REACTOR (HTR)



HIGH-TEMPERATURE REACTOR (HTR)

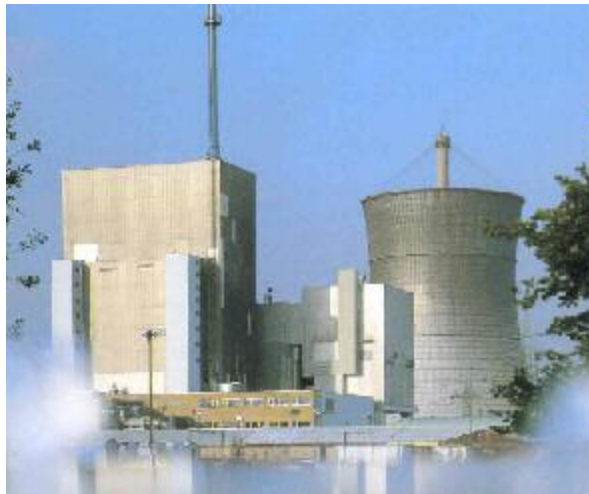
- Pressure vessel (steel or concrete)
- coolant: He
- Moderator: graphite
- Fuel: uranium or thorium in ball form (pebble bed)
- Two-circuit design:
 - Gas primary circuit, ca. 750°C
 - Water-steam secondary circuit, >500°C
- Manufacturers: USA, DEU
- Operators: USA, DEU
- 40 MWe, 300 MWe, 330 MWe

PEBBLE BED - TRISO FUEL

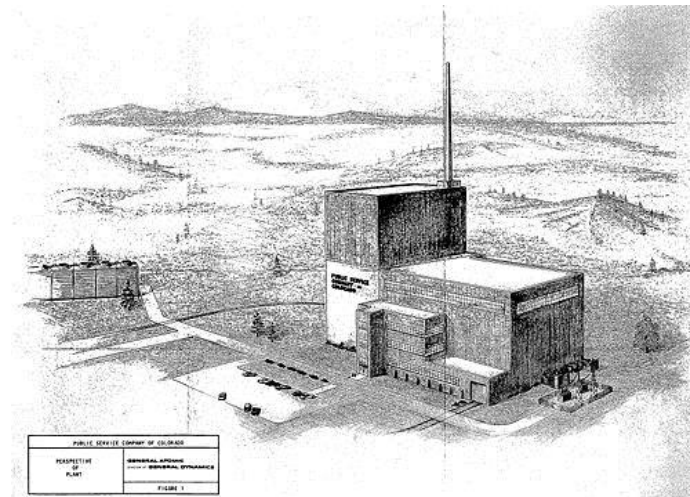


HIGH-TEMPERATURE REACTOR (HTR)

THTR-300
308 MWe gross
296 MWe net
1985-1987



Fort St. Vrain
342MWe gross
330MWe net
1976-1989



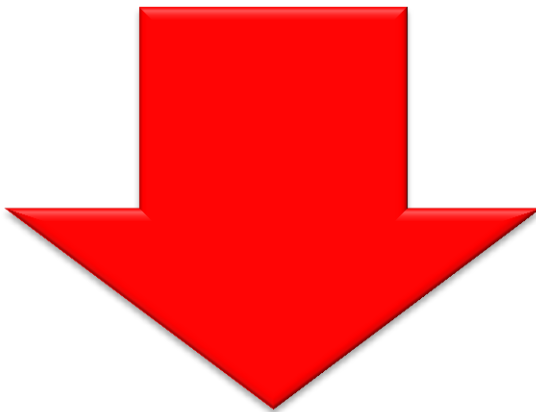
HIGH-TEMPERATURE REACTOR (HTR)



Online refuelling

High efficiency

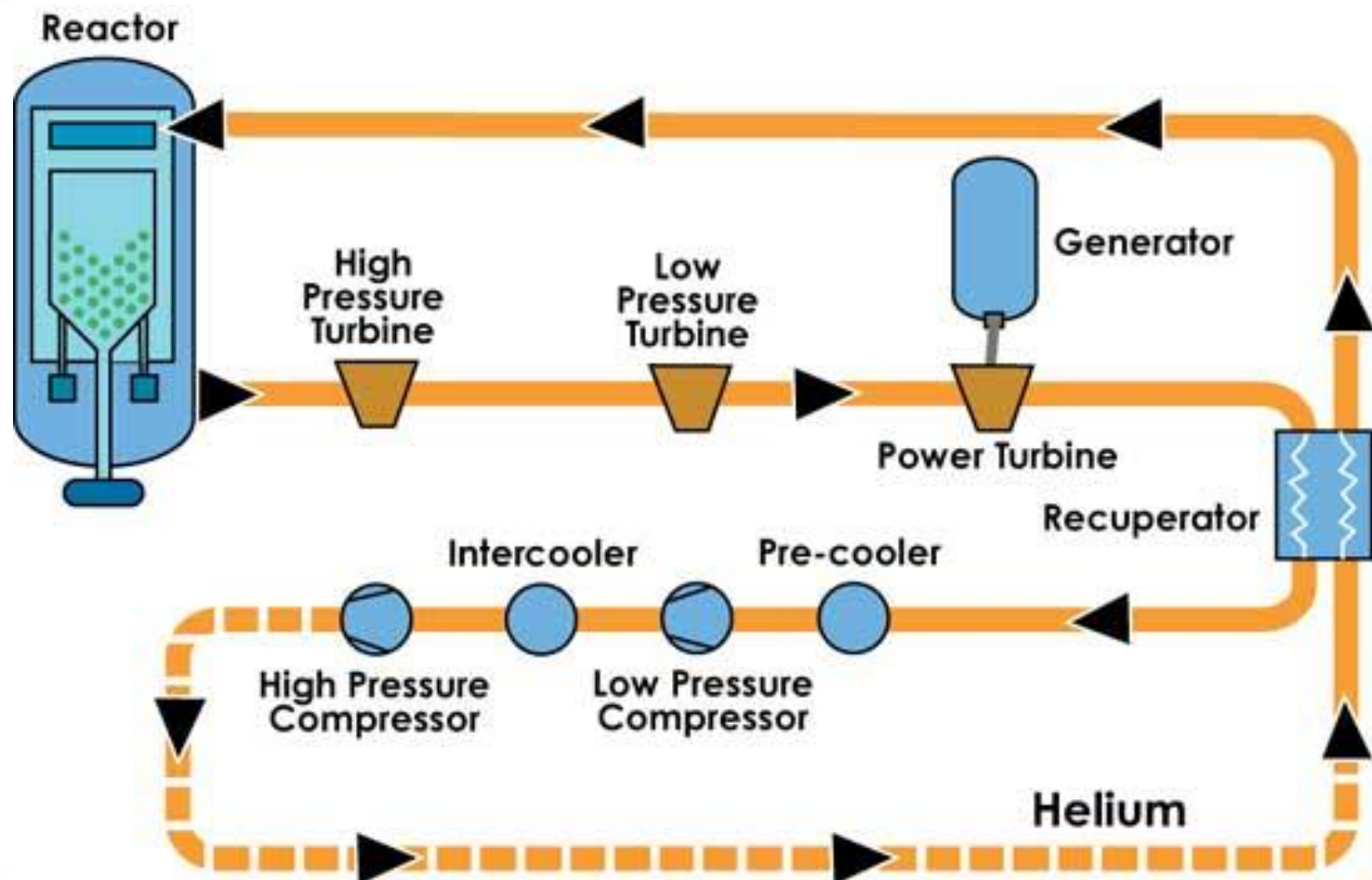
High parameters of live steam
(superheated steam)

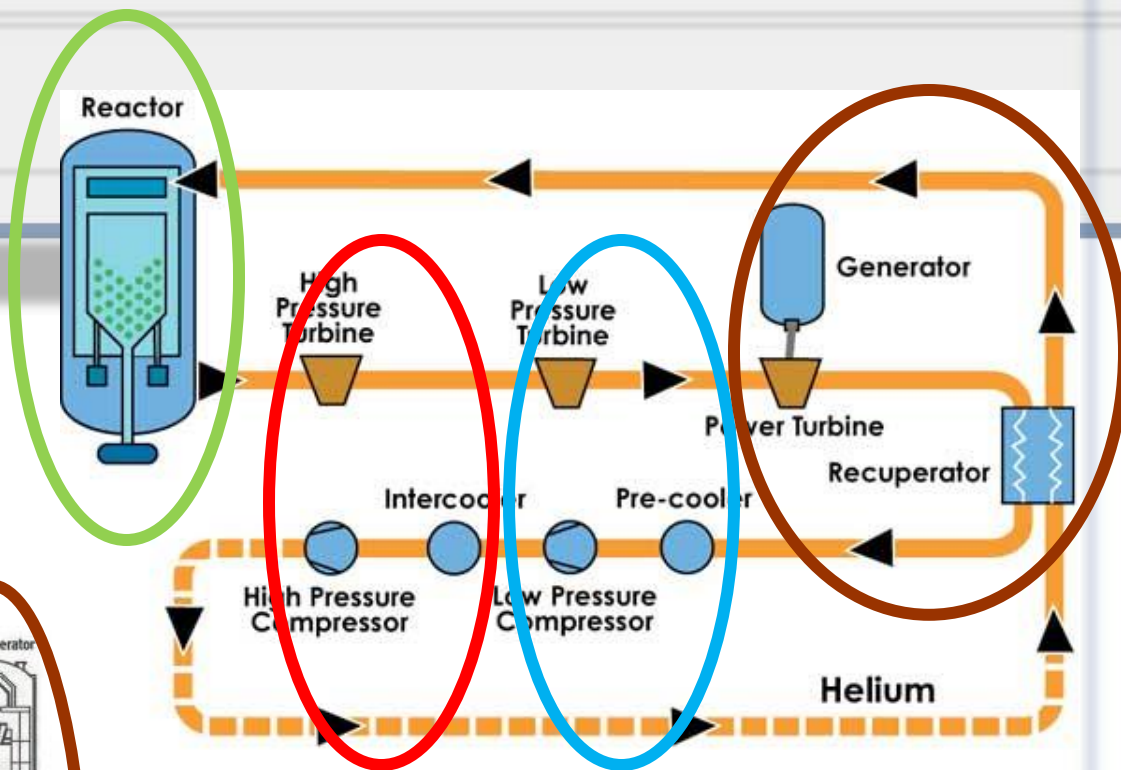
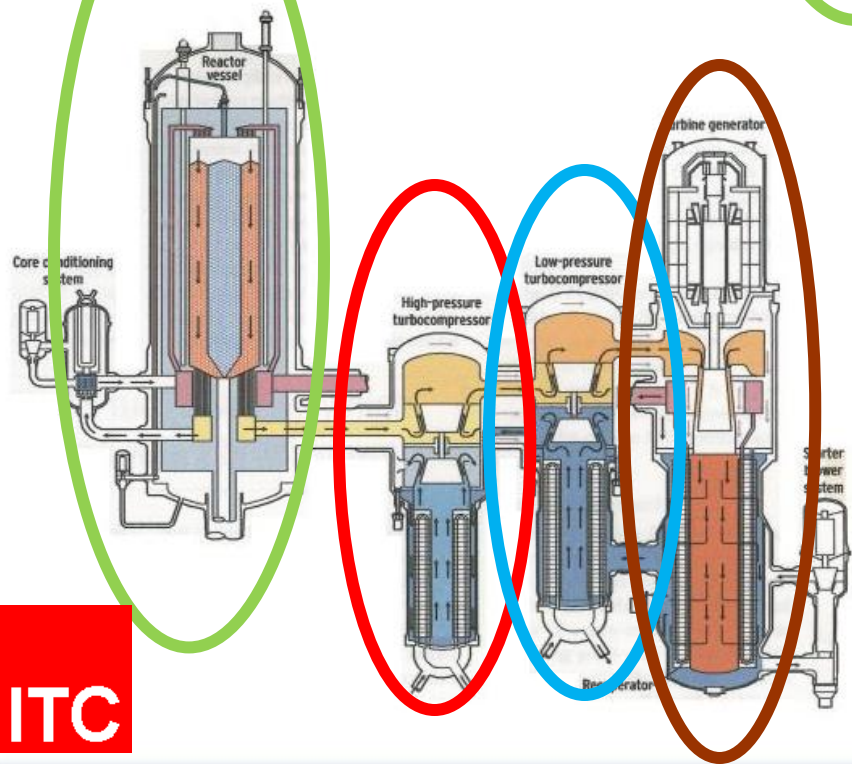


Operational problems: water leaks,
corrosion

Insufficient research, terminated in late
1980s/early 1990s

PEBBLE BED MODULAR REACTOR (PBMR)

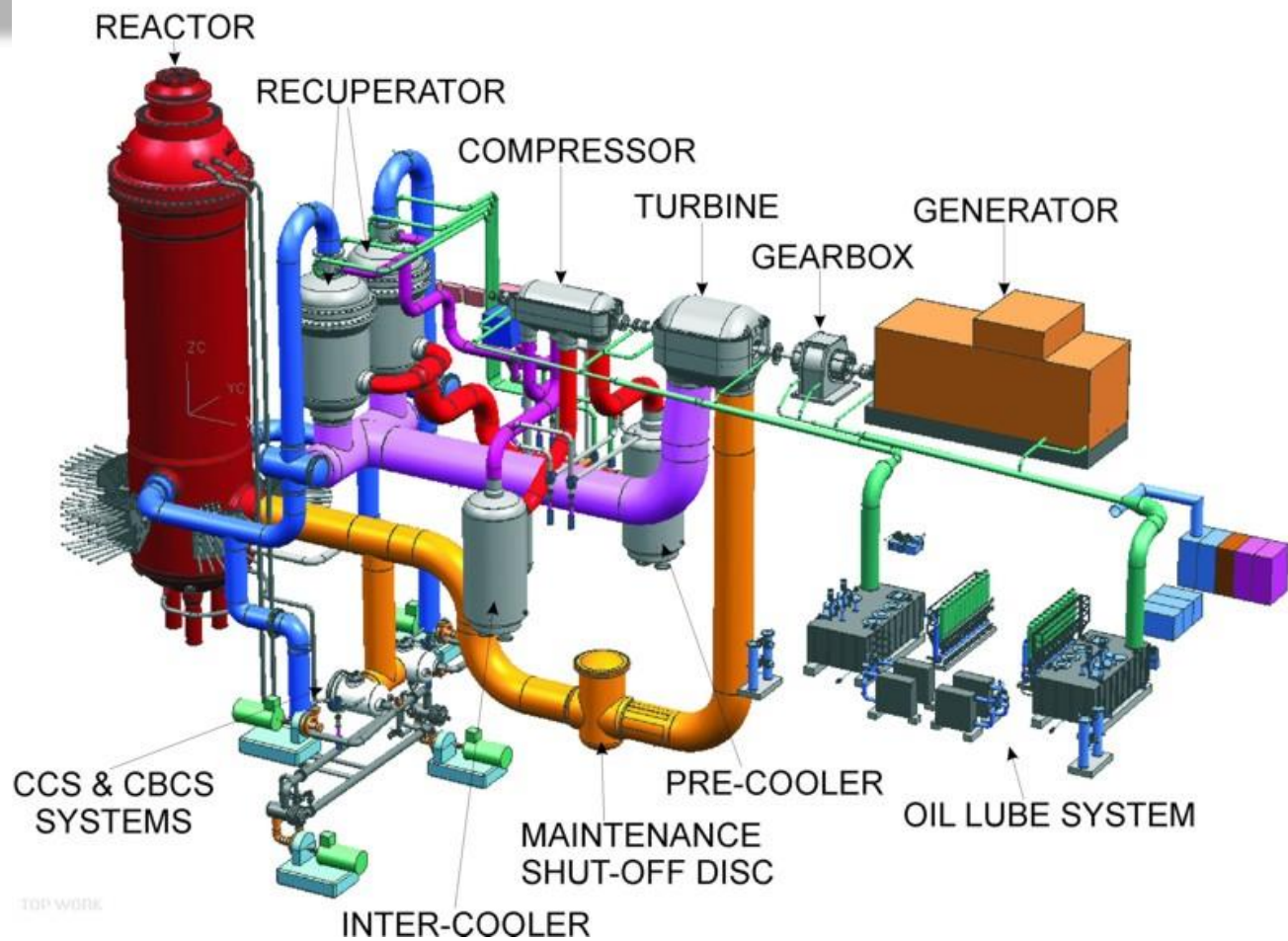




PEBBLE BED MODULAR REACTOR (PBMR)

- Pressure vessel
- Coolant: He
- Moderator: graphite
- Fuel: uranium or thorium in TRISO balls (pebble bed)
- Single-circuit design with a gas turbine (Brayton cycle):
 - 900/500°C
- Efficiency over 45%
- Manufacturers: ZAF, CHN
- Operators: none so far
- 160 MWe (ZAF), ok. 200 MWe (CHN)

PEBBLE BED MODULAR REACTOR (PBMR)



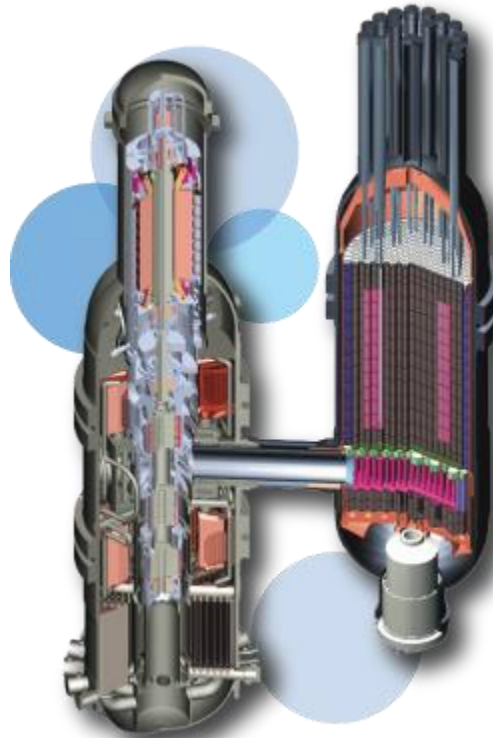
PEBBLE BED MODULAR REACTOR (PBMR)



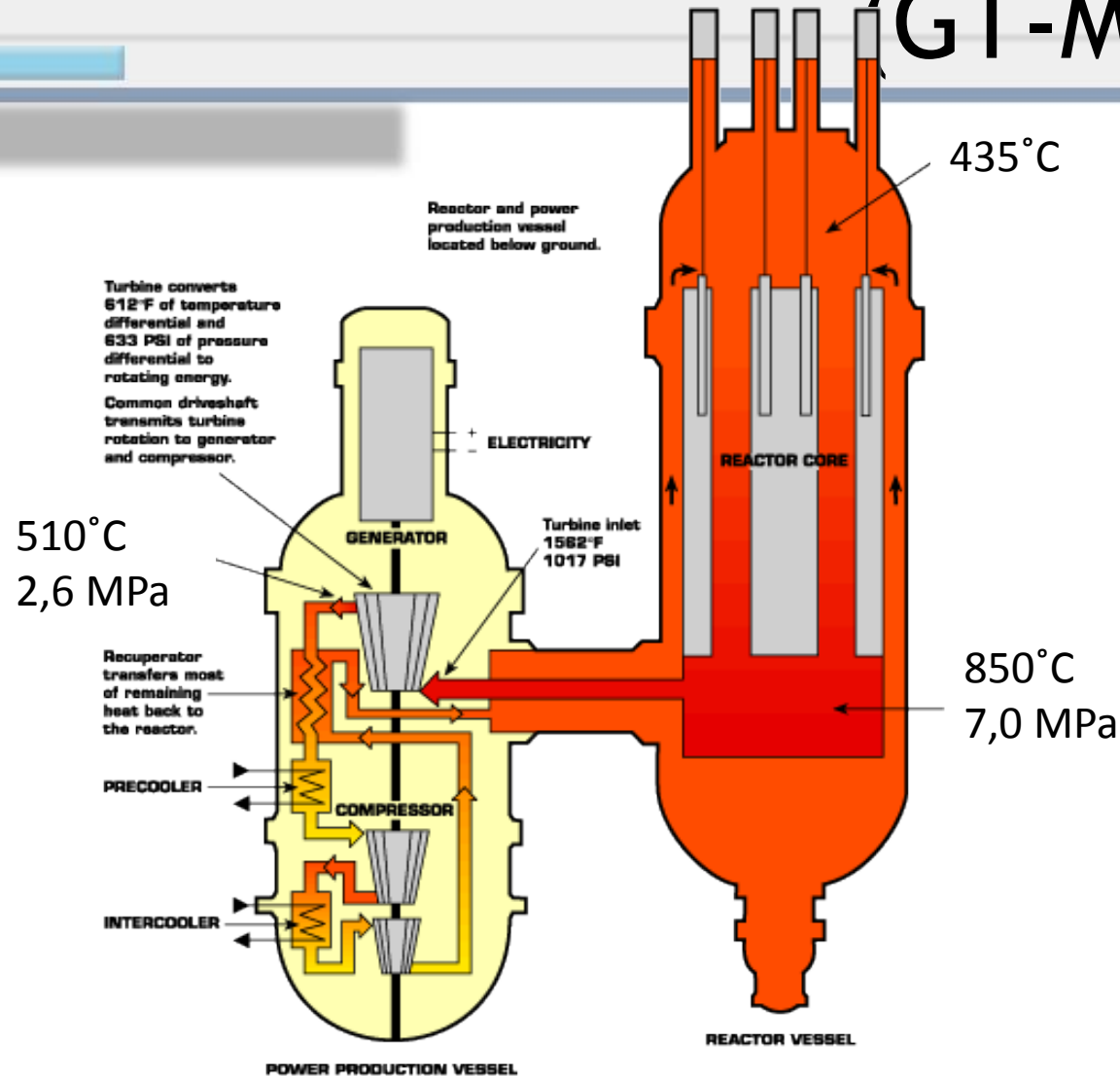
GAS TURBINE MODULAR HELIUM REACTOR (GT-MHR)

- Pressure vessel with coolant channels
- Coolant: He
- Moderator: graphite
- Fuel: uranium elements inside graphite prisms
- Single-circuit design with gas turbine, Brayton cycle
 - 850/435°C
 - 70/26 bar
- Efficiency ca. 48%
- Manufacturers: USA (RUS)
- Operators: (RUS?) none so far
- Units of 285 MWe

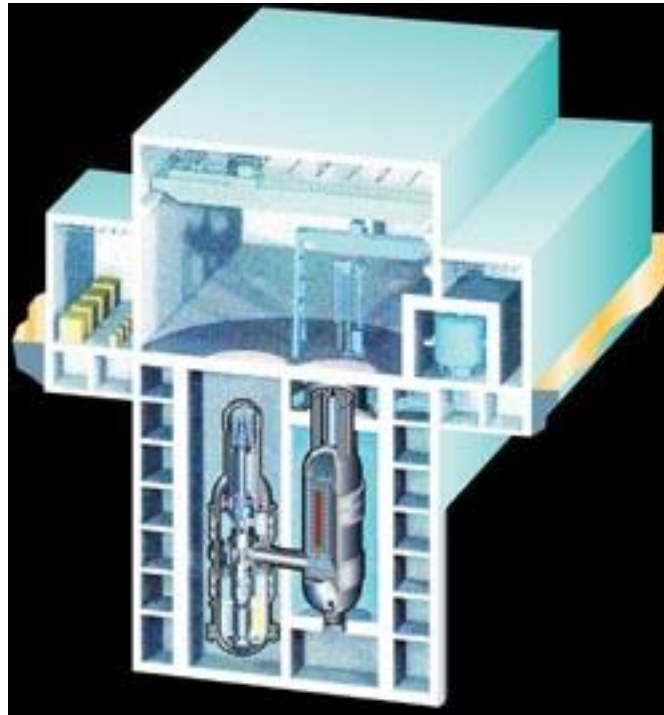
GAS TURBINE MODULAR HELIUM REACTOR (GT-MHR)



GAS TURBINE MODULAR HELIUM REACTOR (GT-MHR)



GAS TURBINE MODULAR HELIUM REACTOR (GT-MHR)



GAS TURBINE MODULAR HELIUM REACTOR (GT-MHR) PEBBLE BED MODULAR REACTOR (PBMR)

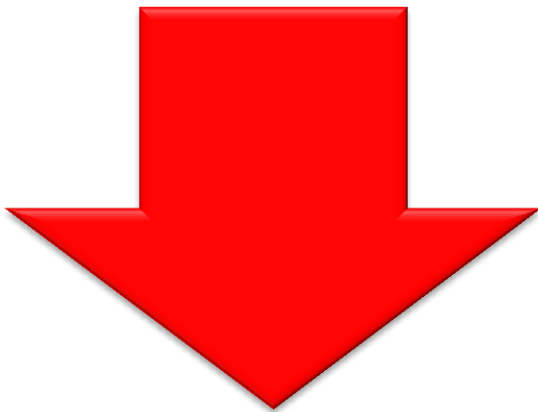


High efficiency

High flexibility + small units – not only
baseload

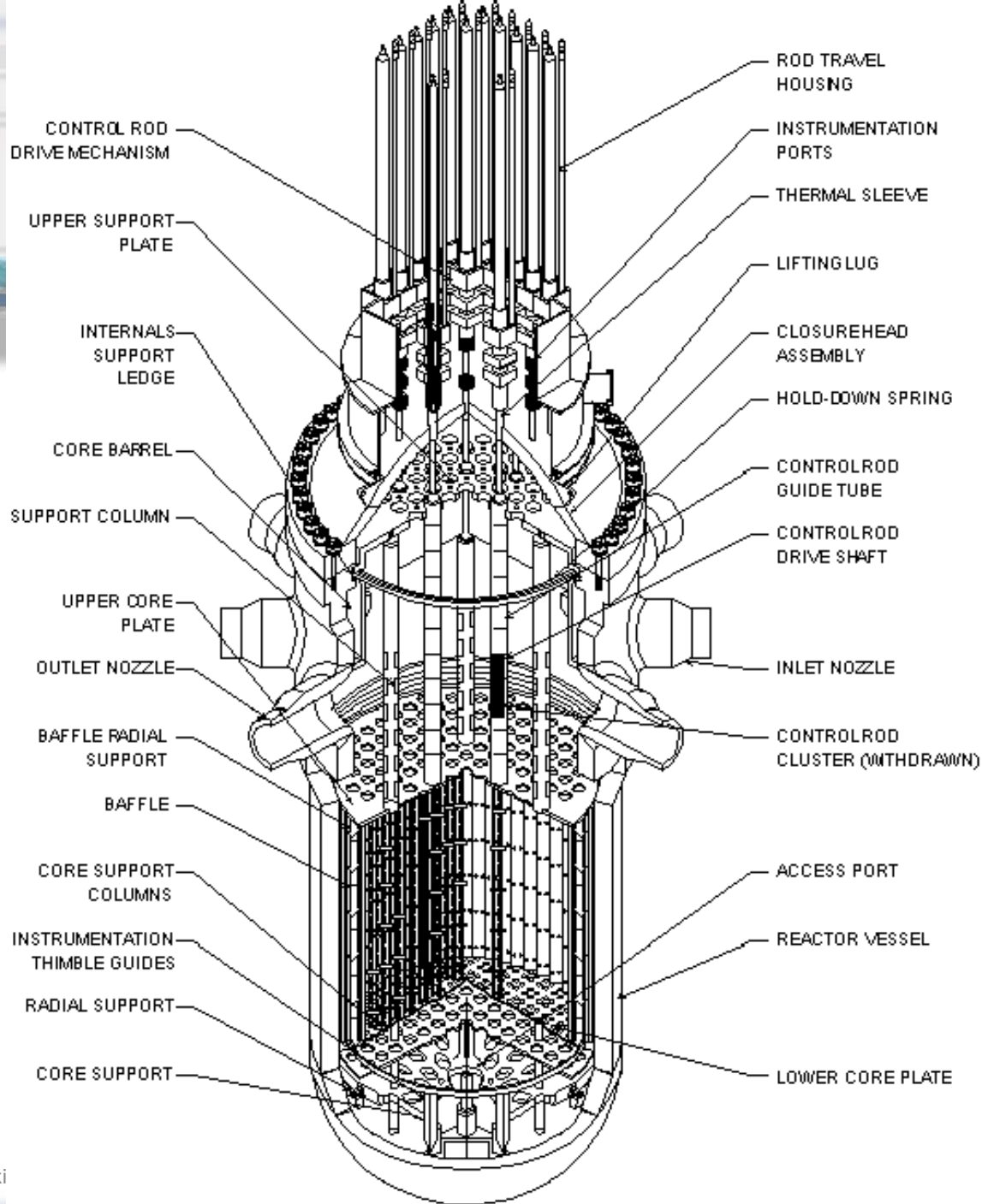
Online refuelling (PBMR only)

No risk of corrosion

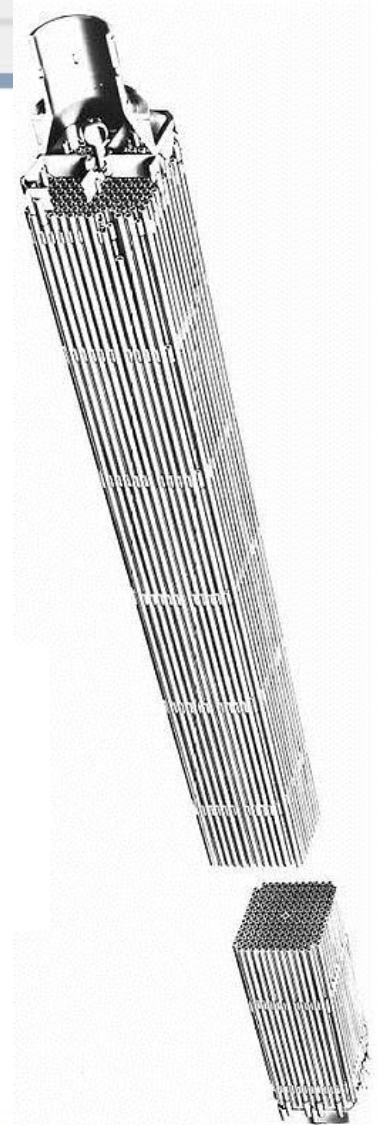


No practical experience

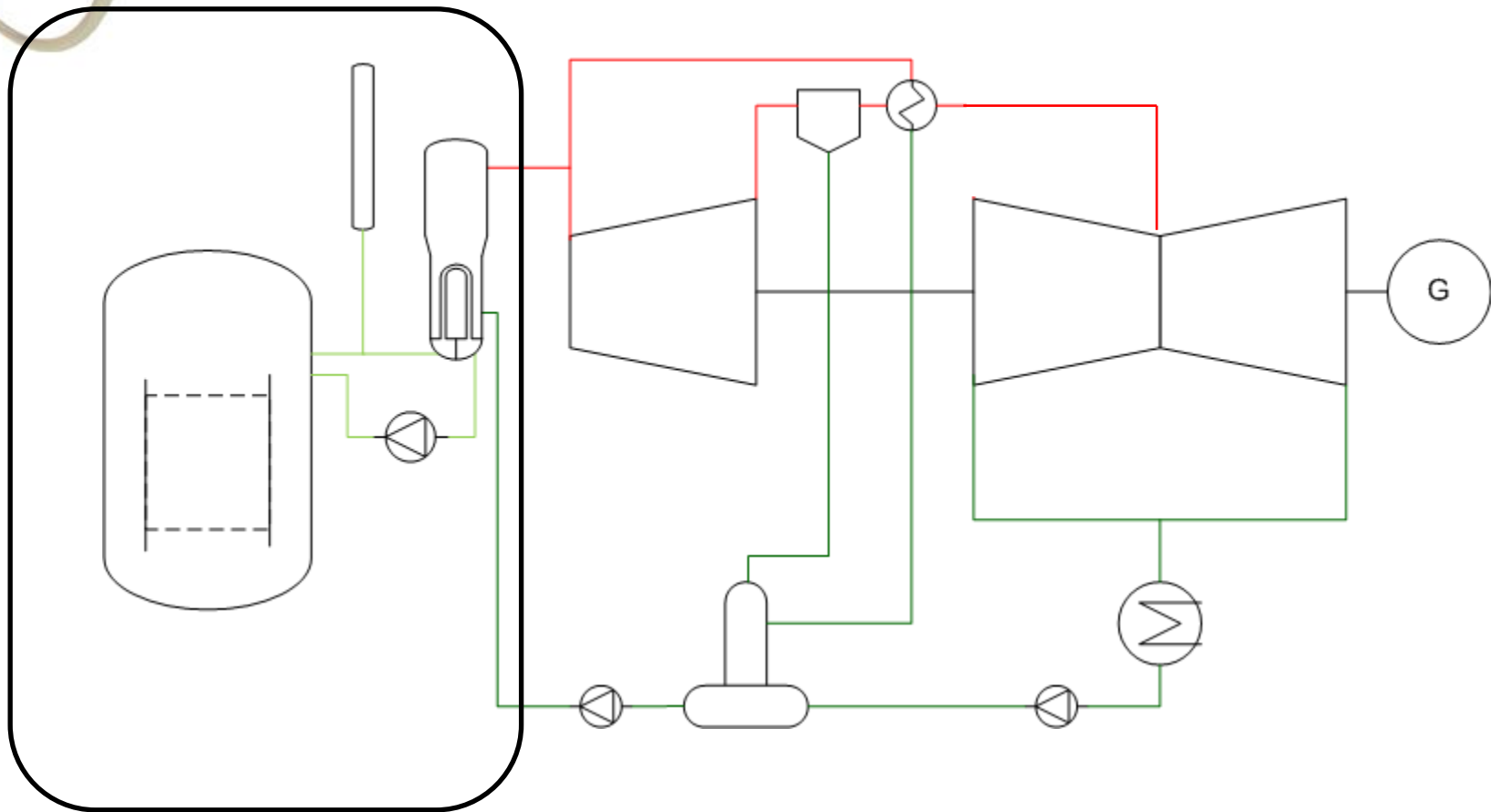
PBMR development suspended due to
lack of funding



PWR



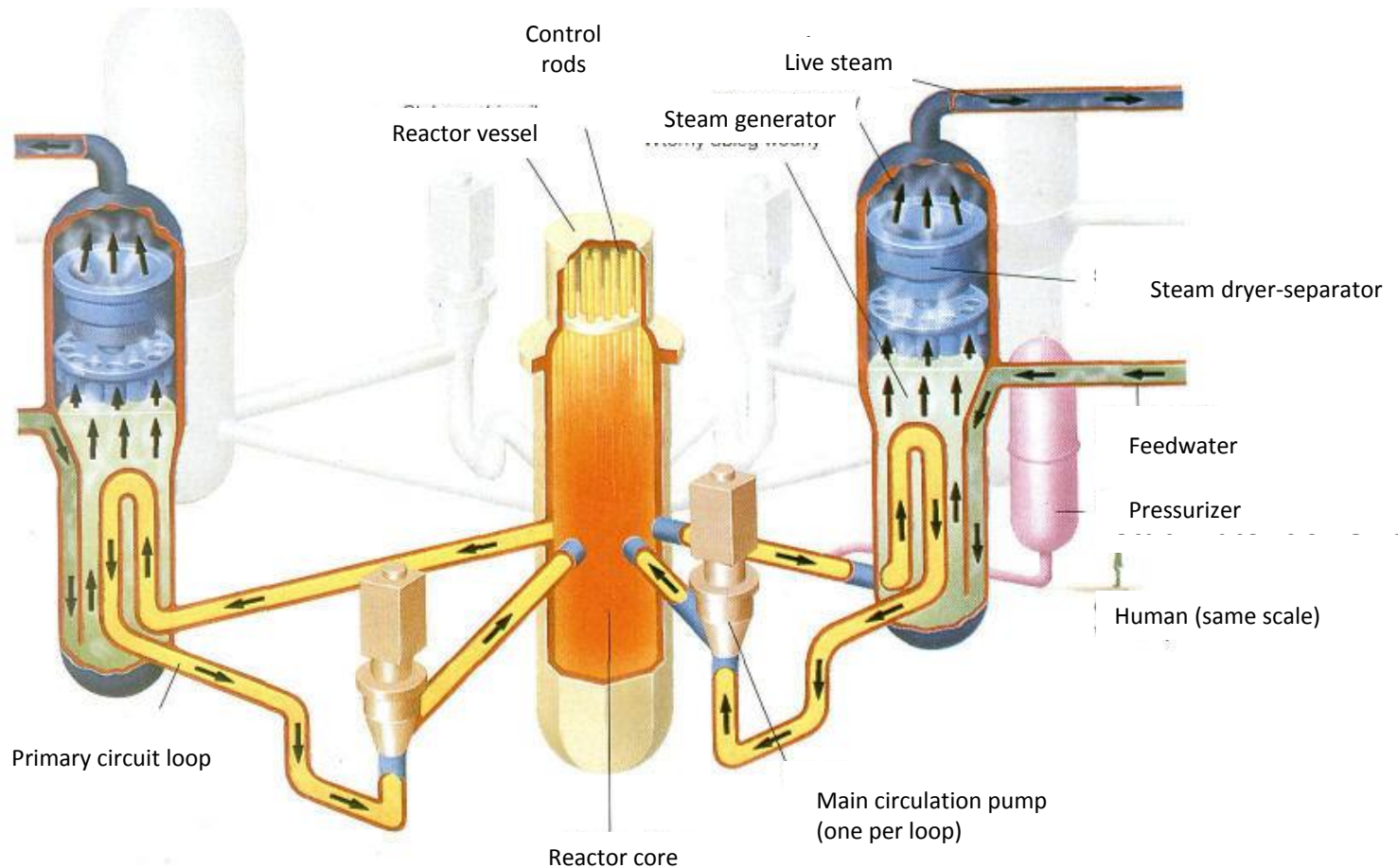
A PWR UNIT



PRESSURIZED WATER REACTOR (PWR)

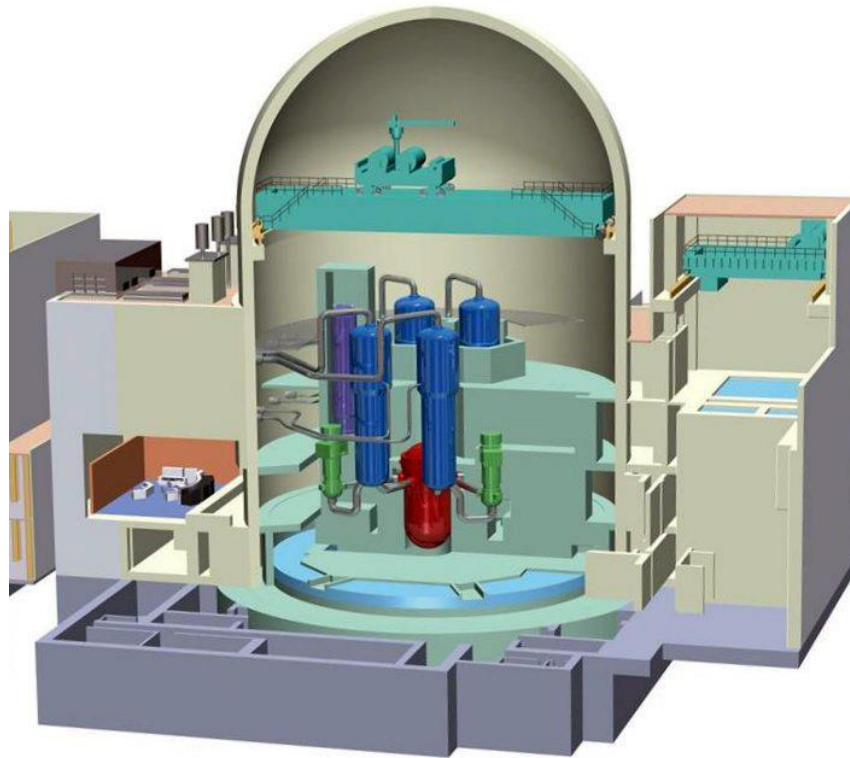
- Steel pressure vessel
- Coolant: H_2O
- Moderator: H_2O (same volume as coolant)
- Fuel: enriched uranium (4÷5%)
- Two-circuit design
 - Pressurized water primary circuit, 150÷200 bar, 300÷350°C
 - Rankine –cycle secondary circuit, 260÷320°C
- Efficiency: traditionally ca 32%, newest EPR up to 37%
- Power control: control rods
- Reactivity control: boric acid in primary circuit
- Manufacturers: USA, DEU, FRA, KOR, JPN, SWE
- Operators: ...
- Up to 1600 MWe per unit

PRESSURIZED WATER REACTOR (PWR)



PRESSURIZED WATER REACTOR (PWR)

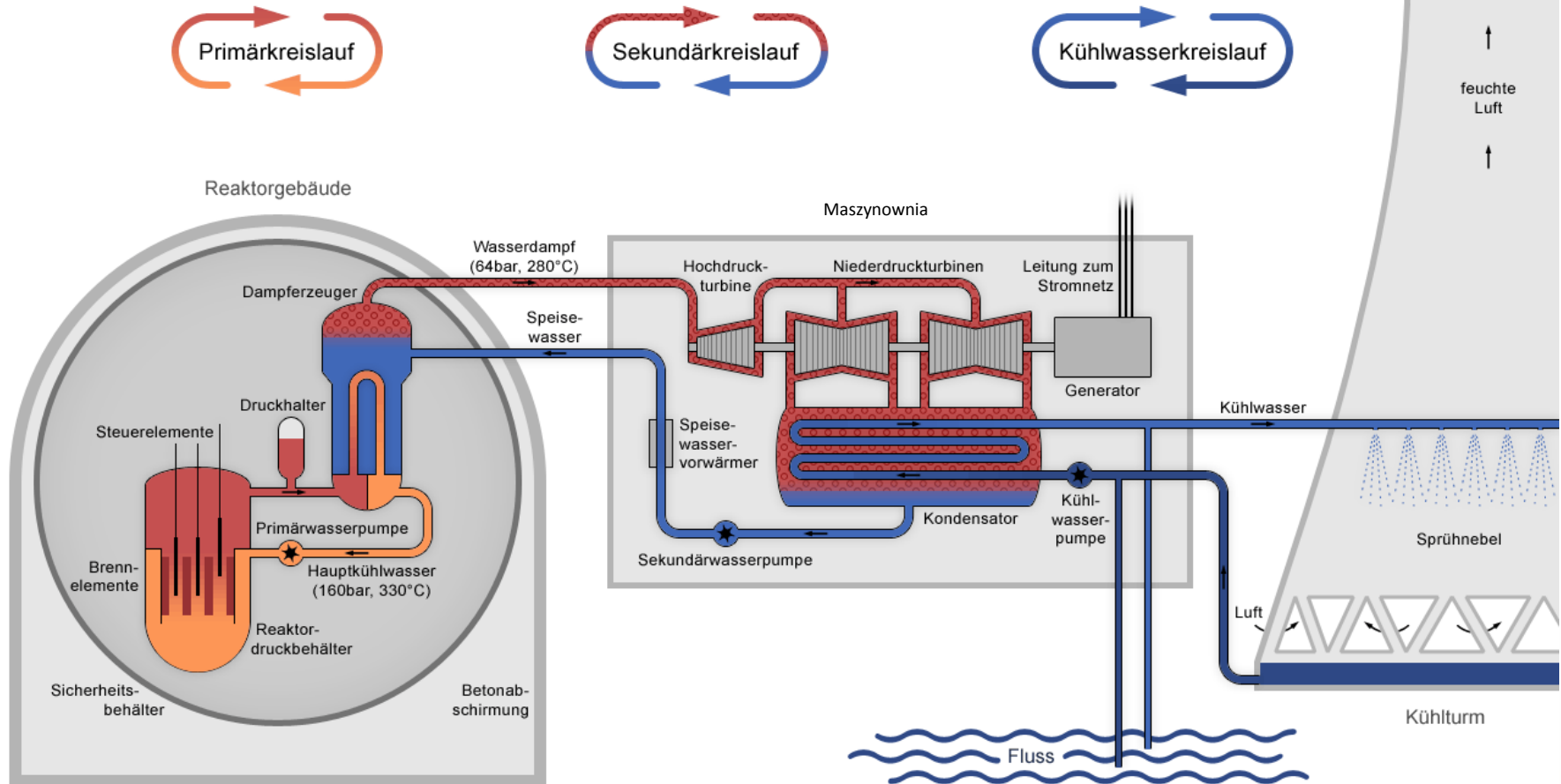
Typical Pressurized Water Reactor



Source: U.S. Nuclear Regulatory Commission

PWR PLANT DESIGN (KWU)

Kernkraftwerk mit Druckwasserreaktor



Das Kernkraftwerk Grohnde

A Reaktorgebäude

- 1 Betonkule
- 2 Reaktorsicherheitsbehälter
- 3 Rundlaufkan
- 4 Reaktordruckgefäß
- 5 Dampferzeuger
- 6 Hauptkühlmittelpumpe
- 7 Personenschleuse
- 8 Lademaschine
- 9 Wasserbecken für gebrauchte Brennelemente
- 10 Nuklearer Zwischenkühler
- 11 Flutbehälter
- 12 Frischdampf-Armatur
- 13 Halbportalgerüst

B Hilfsanlagengebäude

- 14 Abwasserndampfer
- 15 Zuluftanlage
- 16 Kontrollbehälter für radioaktive Abwässer
- 17 Wäscherei
- 18 Duschräume

C Büro- und Sozialgebäude

D Schaltanlagengebäude

- 19 Kraftwerkskantine
- 20 Rechnerraum
- 21 Warten-Nebenraum

E Maschinenhaus

- 22 Wasserabscheider/Zwischenüberhitzer
- 23 Turbine
- 24 Generator
- 25 Erregermaschine
- 26 Generatorableitung
- 27 Kondensator
- 28 Speisewasserbehälter
- 29 Speisewasserpumpe
- 30 Rohrbrücke
- 31 Maschinentrailo-Anlage

F Kondensatreinigungsanlage

G Notspeisegebäude

- 32 Notspesiediesel
- 33 Schaltanlage
- 34 Deionatbecken

H Bedarfsfilteranlage

I Abluftkamin

J Notstromdiesel- und Kaltwasserzentrale

- 35 Notstromdiesel
- 36 Kaltmaschine

K Kühlwasserpumpenbauwerk

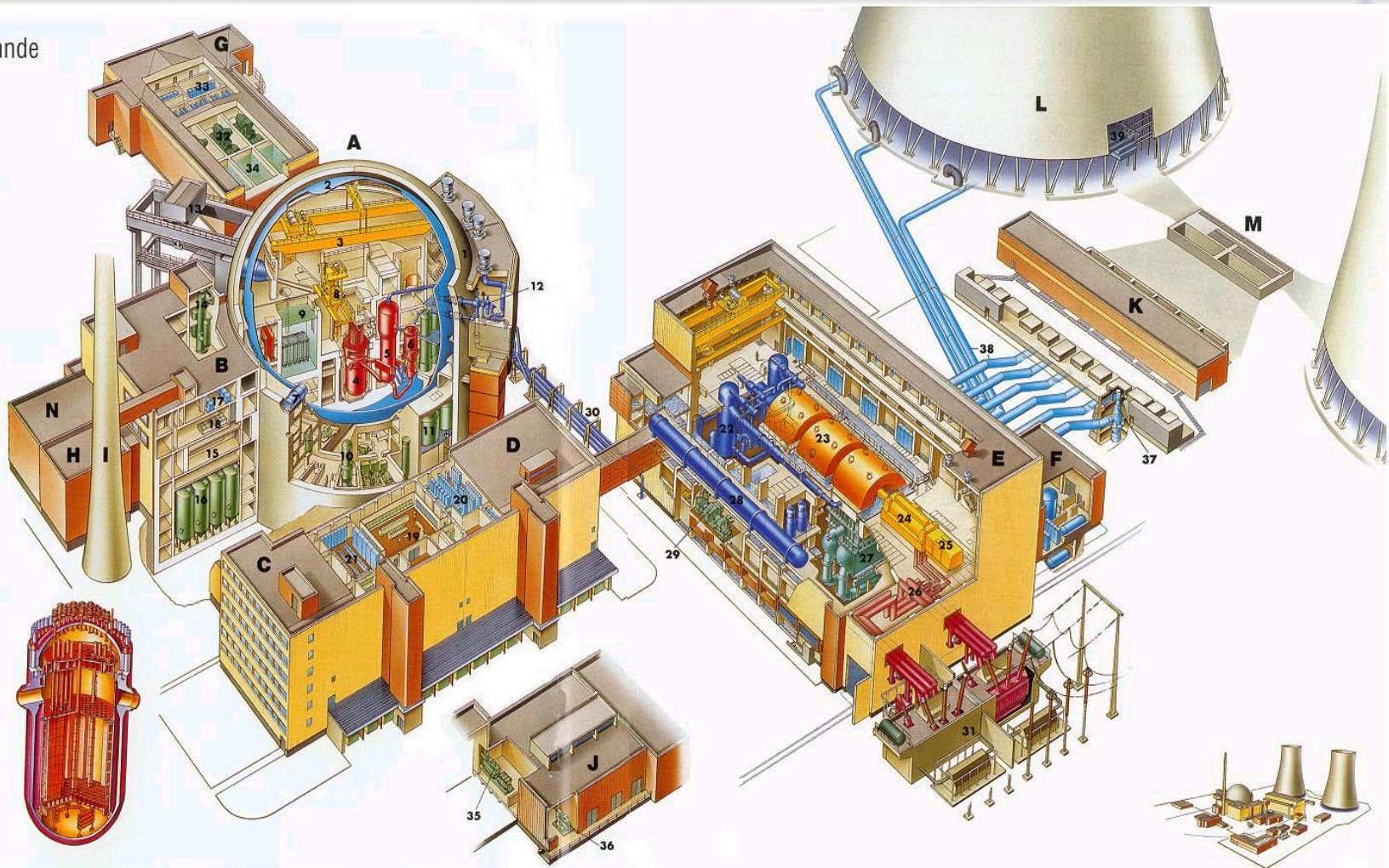
- 37 Hauptkühlwasserpumpe
- 38 Hauptkühlwasserleitungen

L Kühlturm

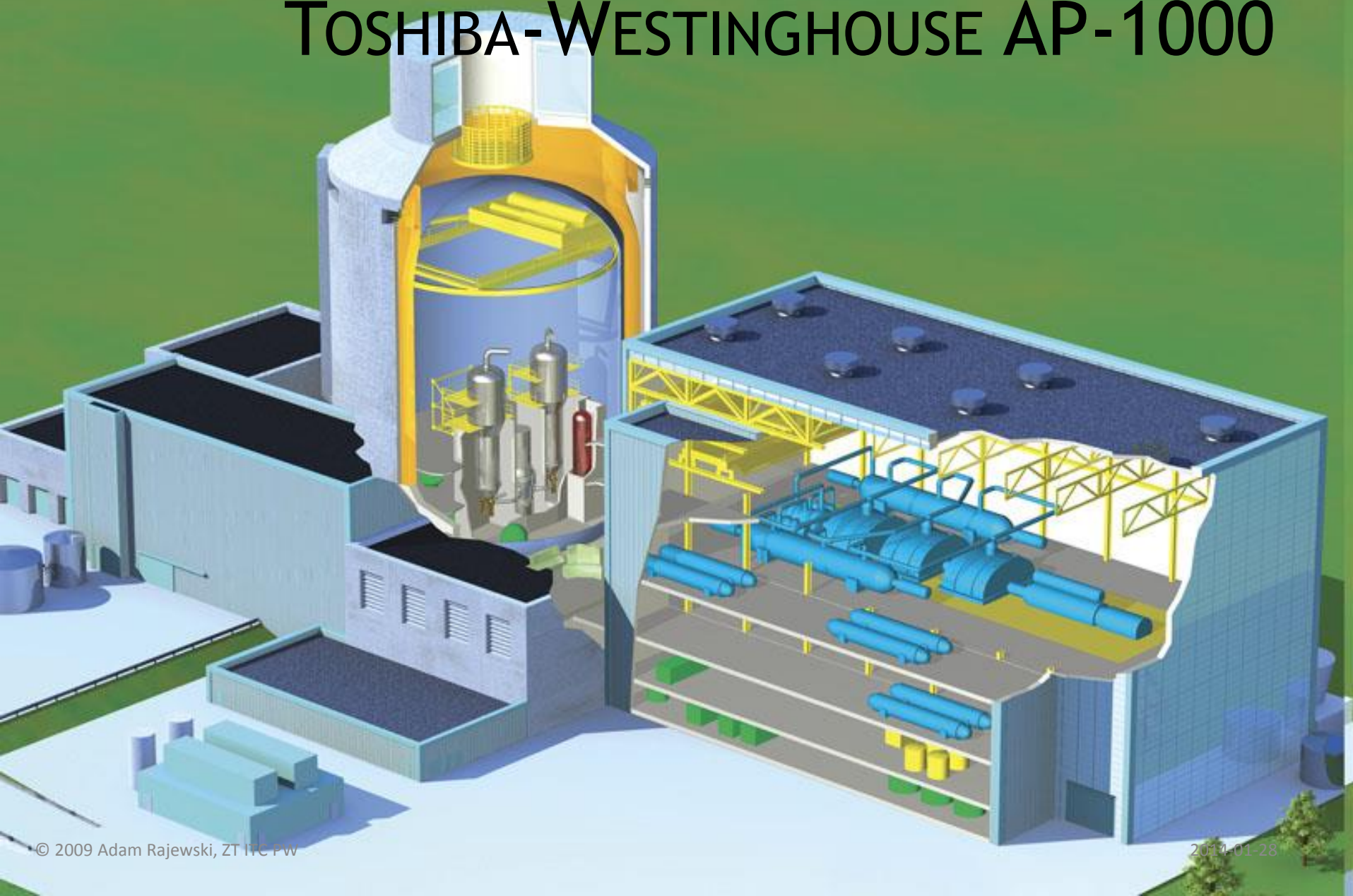
- 39 Kühlturmeinbauten

M Kühlwassermischbauwerk

N Abfallbehandlung



TOSHIBA-WESTINGHOUSE AP-1000



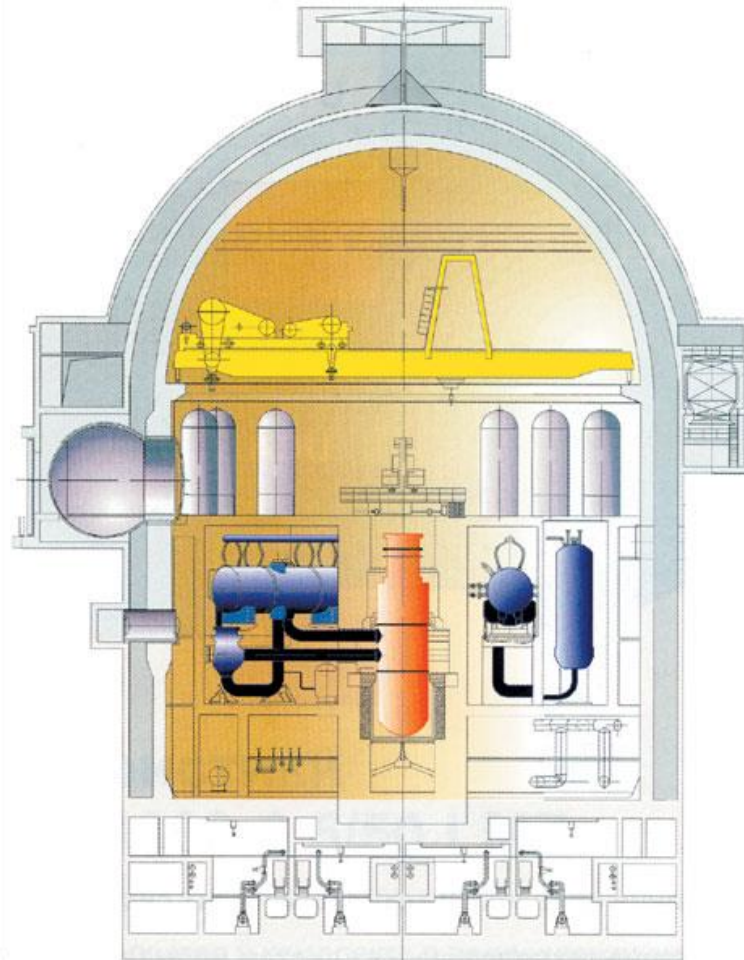
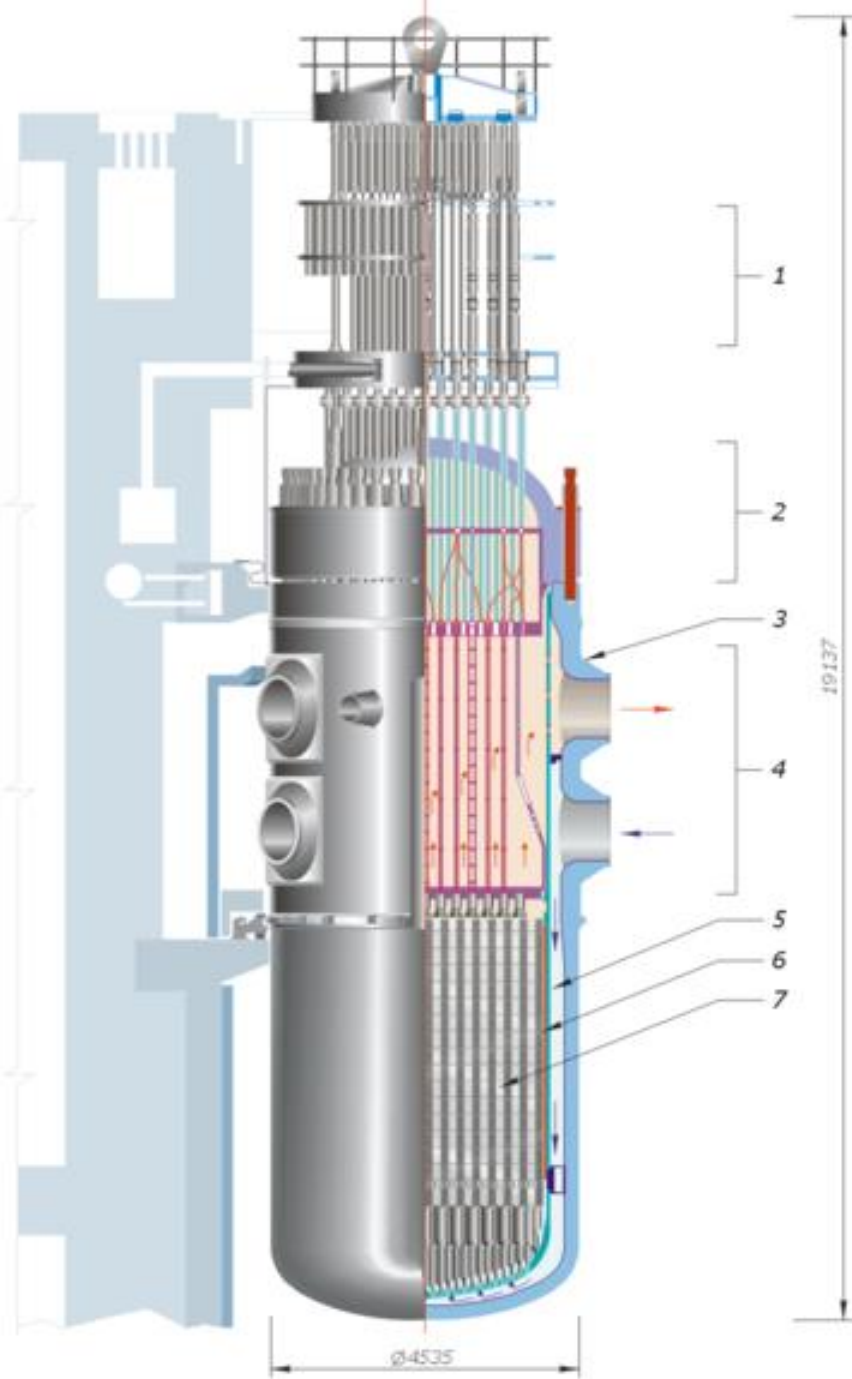
AREVA EPR



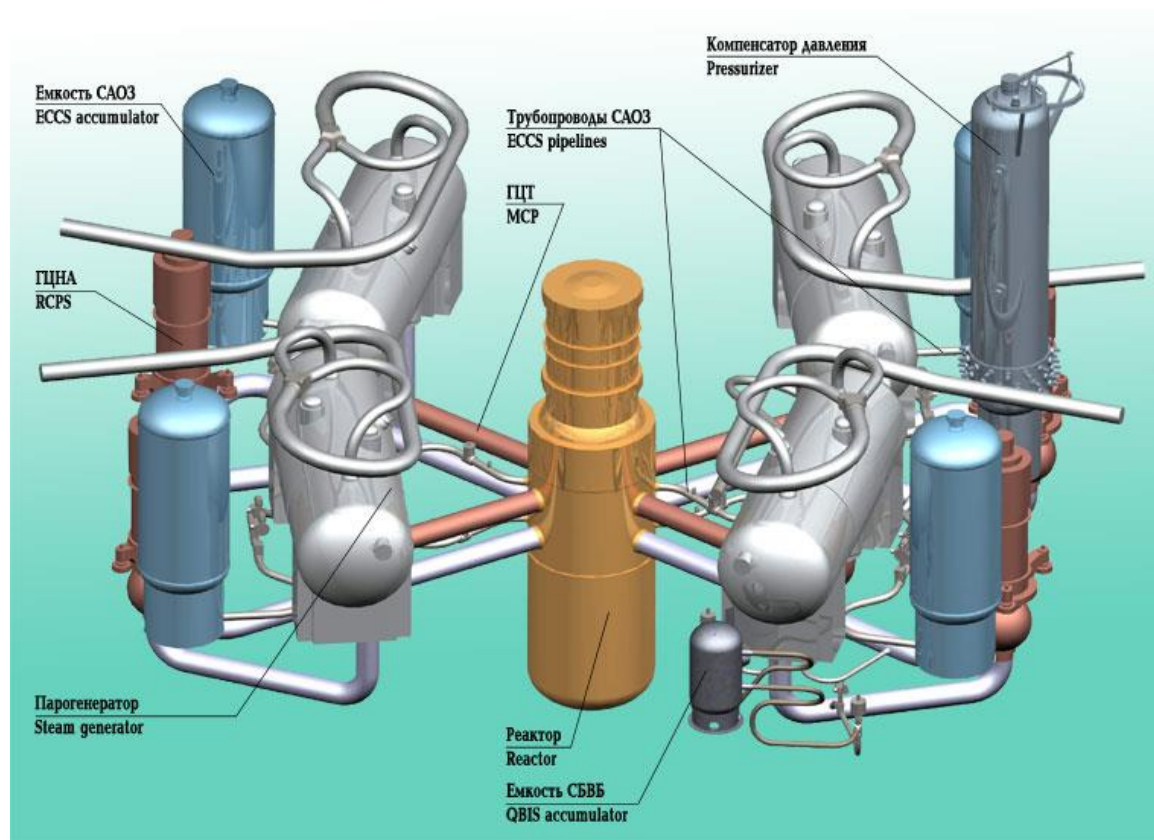
ВОДО-ВОДЯНОЙ ЭНЕРГЕТИЧЕСКИЙ РЕАКТОР(VVER)

- Soviet/Russian version of PWR technology
 - Horizontal steam generators
- Manufacturers: SUN/RUS
- Operators: RUS, UKR, BGR, HUN, SVK, CZE, DDR, IRN, FIN, IND, CHN
- Types:
 - VVER-440, 440 MWe
 - VVER-1000, 1000 MWe
 - Planned: VVER-1200, VVER-1500

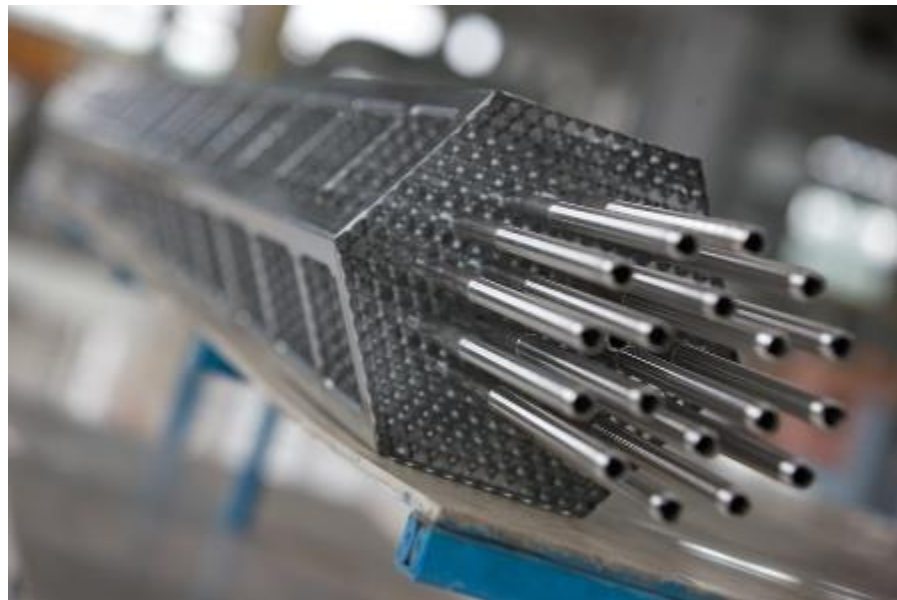
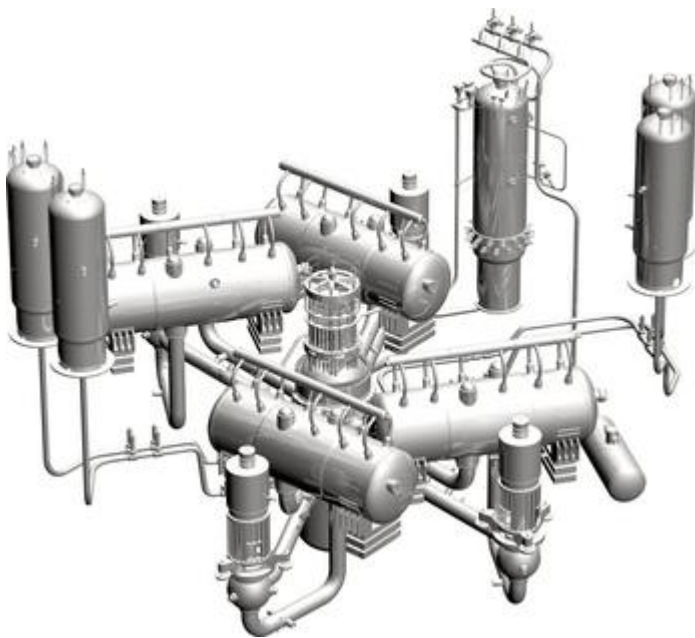
VVER



VVER-1500



VVER REACTORS (1000/1200)





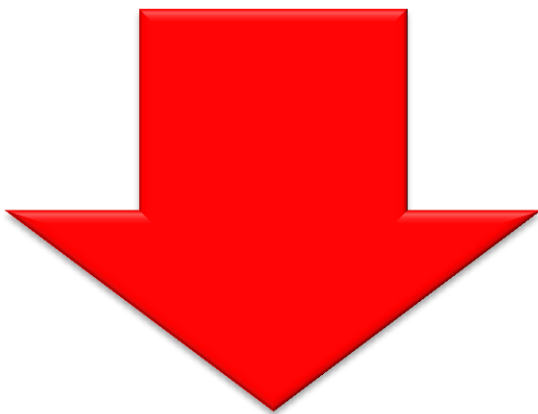
PRESSURIZED WATER REACTORS PWR/VVER



High reliability

Common technology – well proven

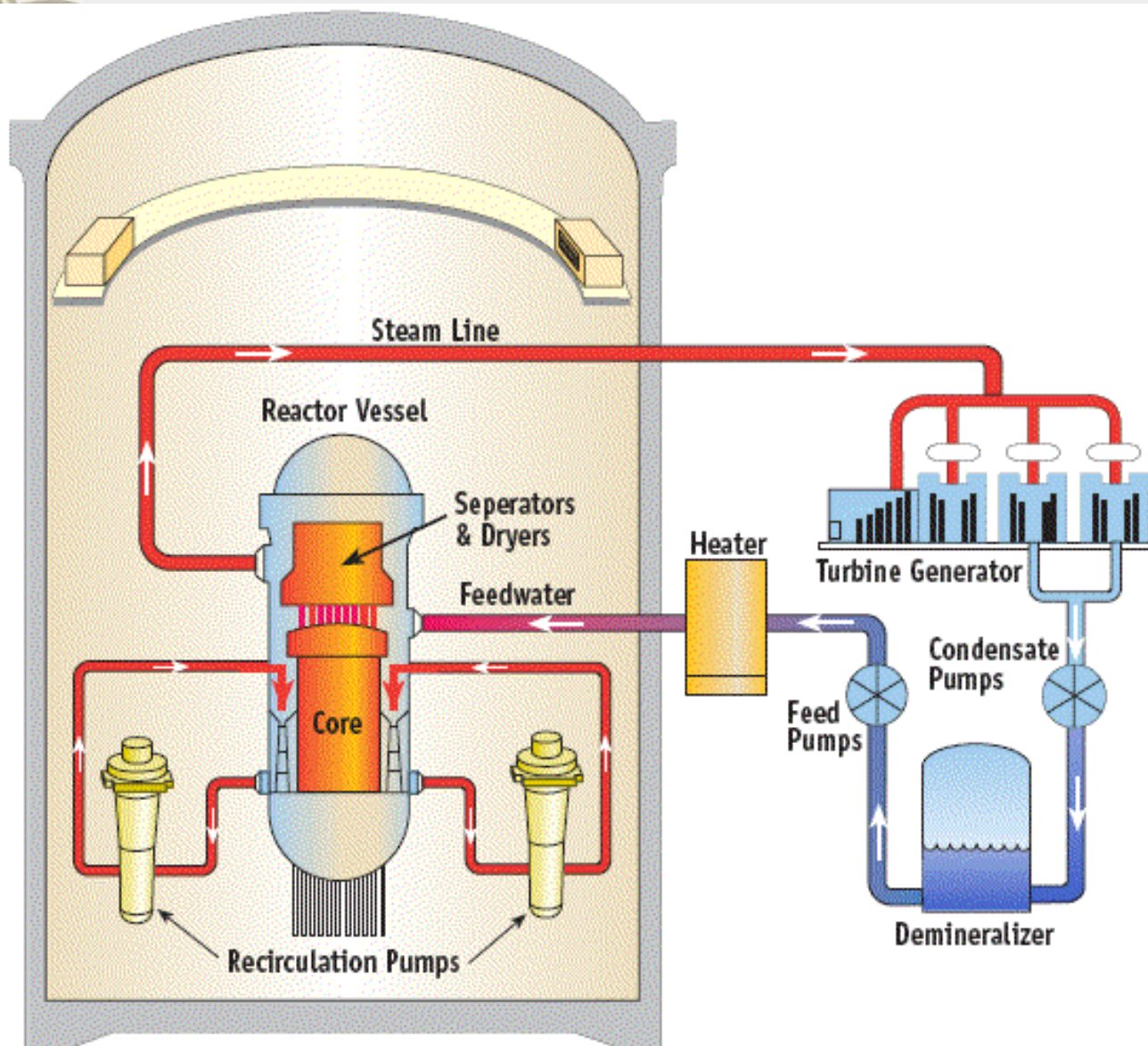
Reaction shuts down at LOCA



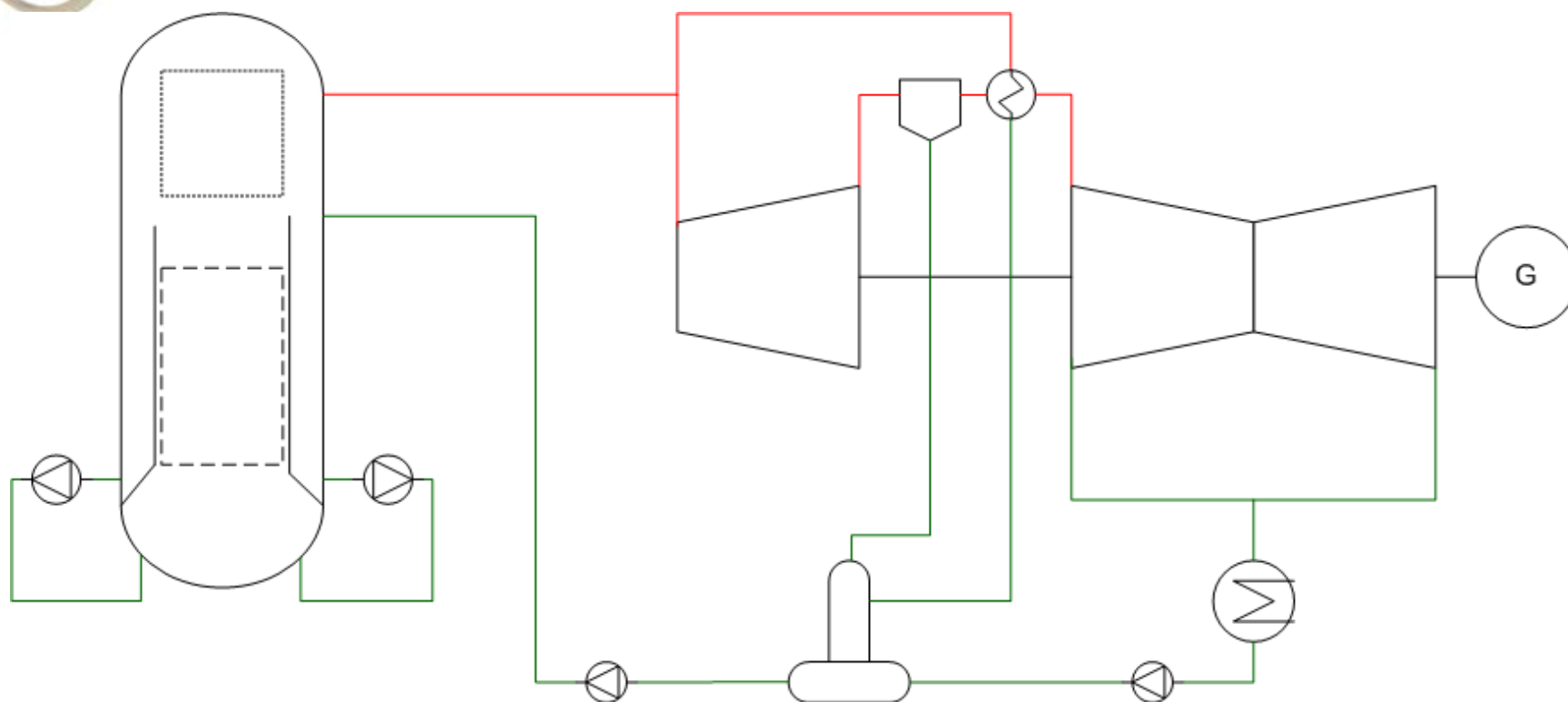
Low efficiency

Possibility of corrosion due to boric acid use

BWR



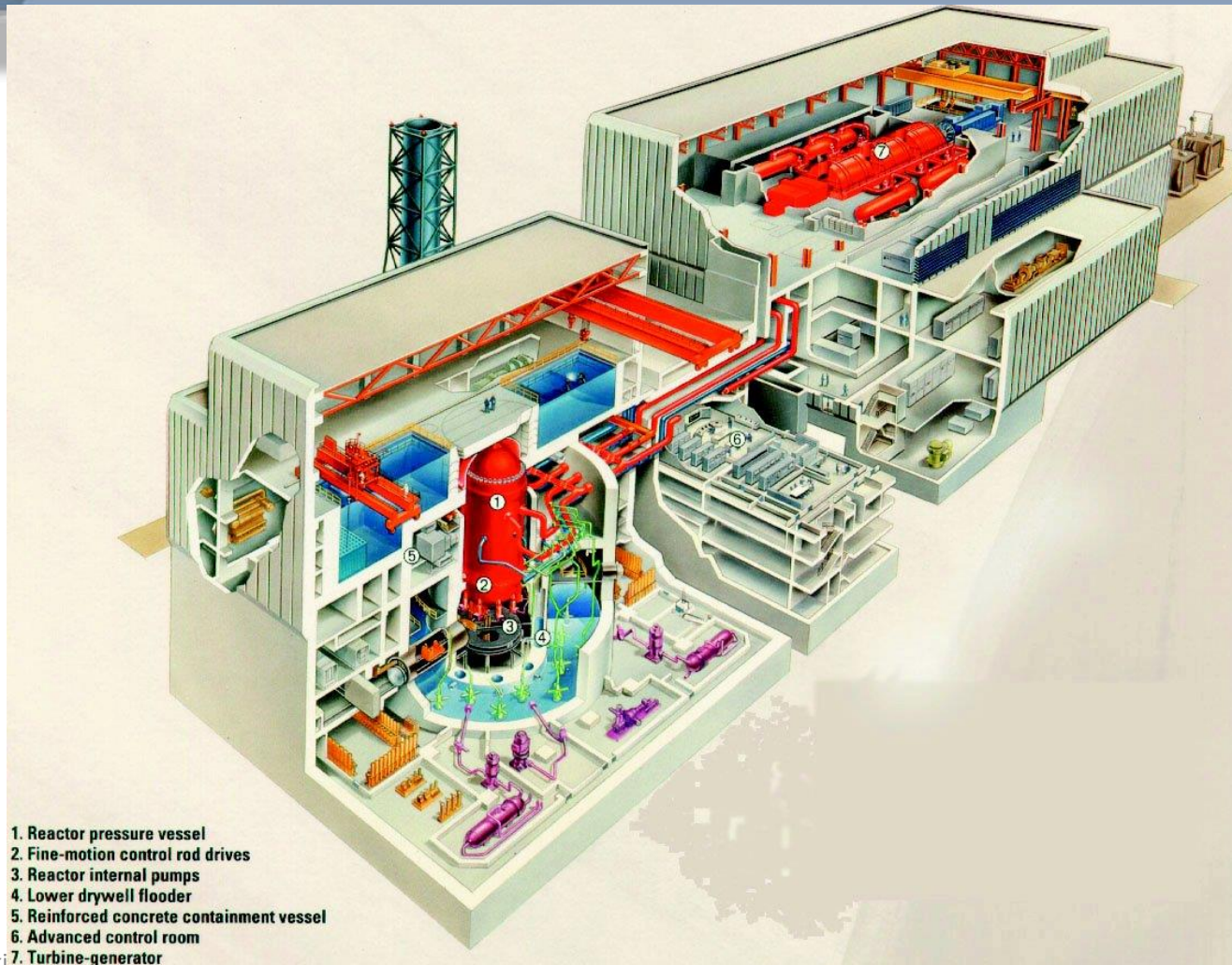
BWR UNIT



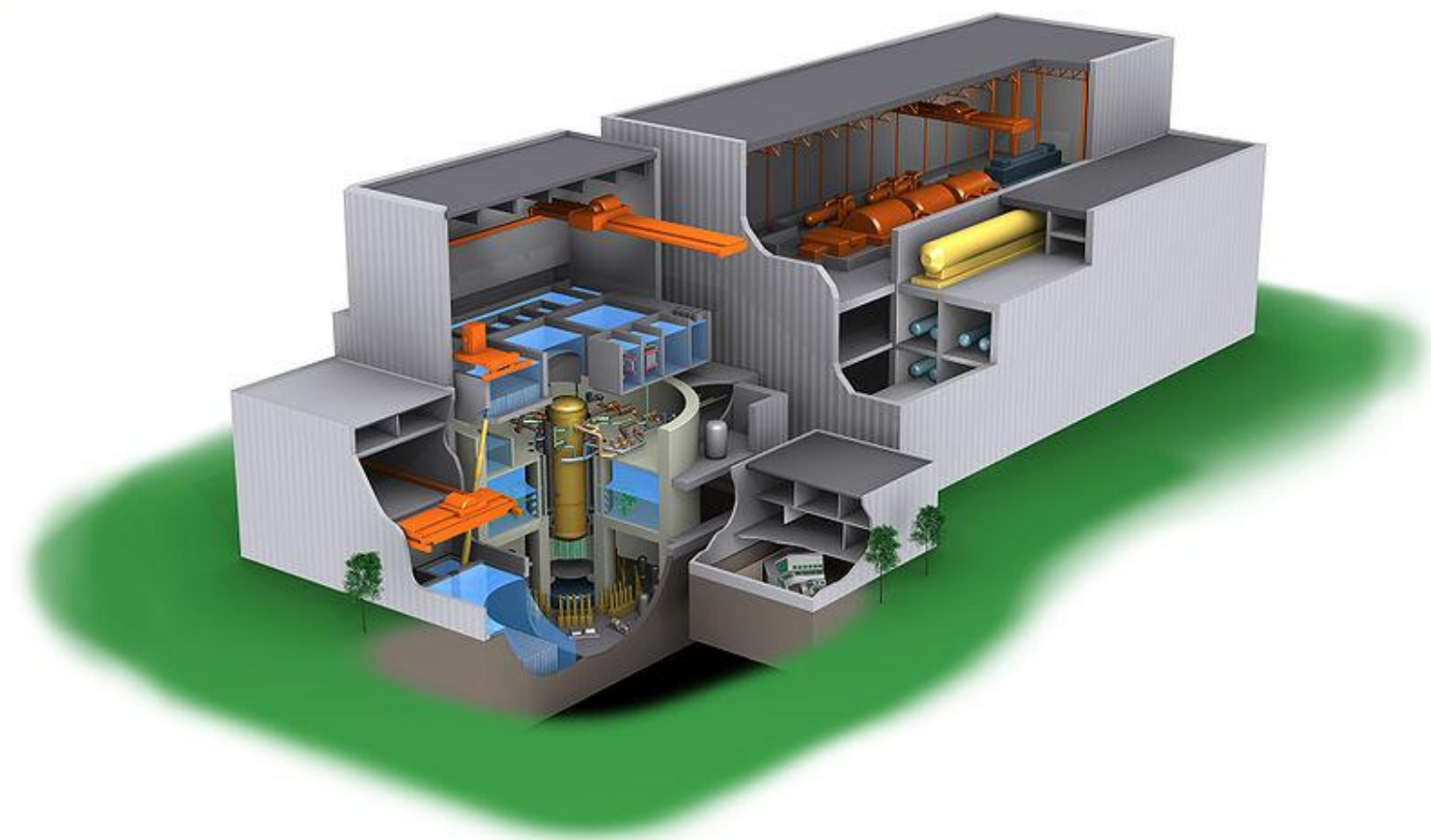
BOILING WATER REACTOR (BWR)

- Steel pressure vessel
- Coolant: H₂O (water-steam mixture)
- Moderator: H₂O (same flow as coolant)
- Fuel: enriched uranium(4÷5%)
- Single-circuit design: water boiling within the core
 - Saturated steam production
- Efficiency ca. 33%
- Start-up, shut-down, rough power control: control rods (from the bottom)
- Fine power control: recirculation pumps (moderator flow)
- Reactivity control: cruciform control rods (from the bottom)
- Manufacturers: USA, DEU, SWE
- Operators: USA, DEU, SWE, FIN, CHE, JPN, ESP, ITA, MEX
- Up to 1400 MWe per unit

GE-HITACHI ABWR



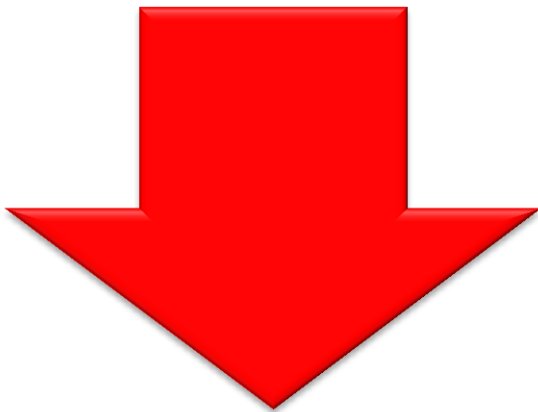
GE-HITACHI ESBWR



BOILING WATER REACTOR



- High reliability
- Simple design
- No risk of corrosion (no boric acid)
- Common and well-proven technology
- Chain reaction ends at LOCA
- Lower reactor pressure than in PWR

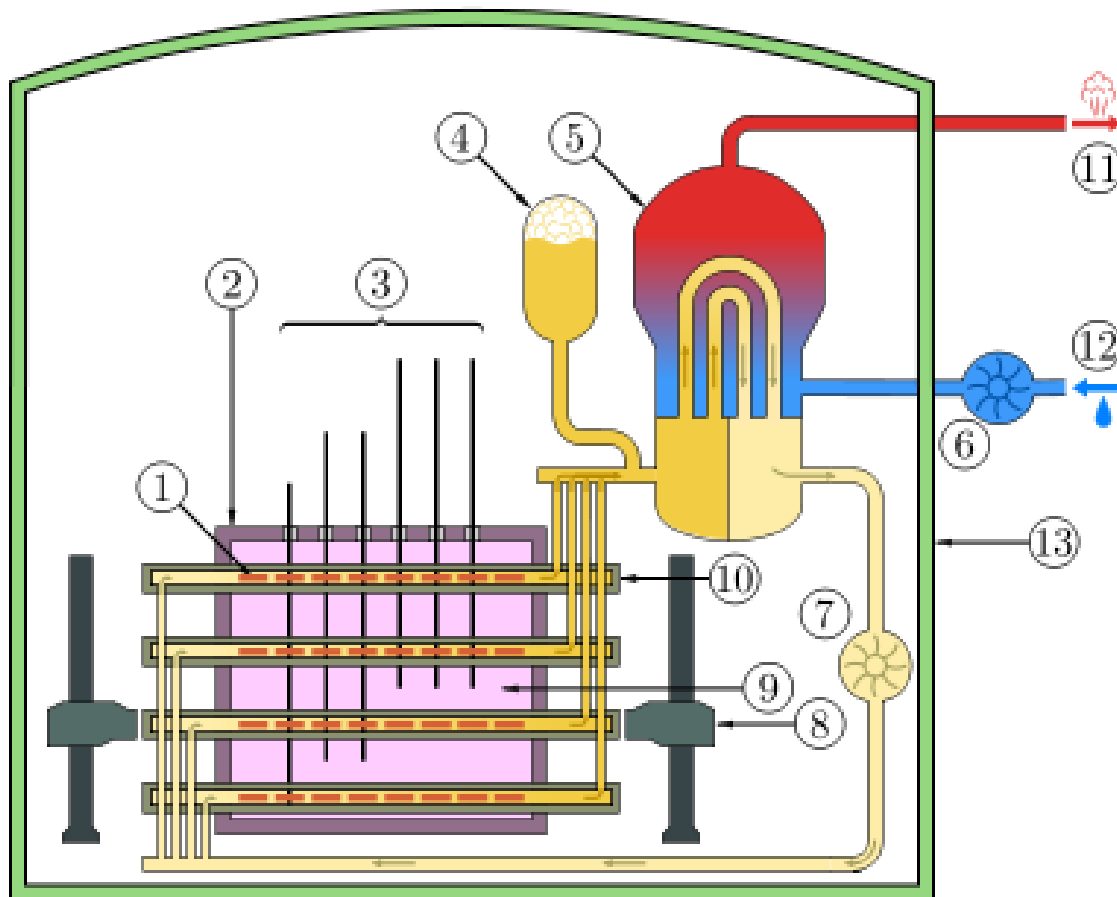


- Low efficiency
- Contaminated steam in the turbine
- Lower power density than in PWR – larger pressure vessel
- Steam separator inside – larger pressure vessel

PRESSURIZED HEAVY WATER REACTOR CANDU, PHWR, ACR

- Low-pressure vessel & high-pressure cooling channels
- Coolant: D₂O (H₂O in planned ACR)
- Moderator: D₂O
- Fuel: Natural or slightly enriched (0.9÷1.2%) uranium
- Two-circuit design:
 - Pressurized heavy water primary circuit, ca. 100 bar (ACL 130 bar)
 - Secondary Rankine-cycle circuit, 50 bar, 260°C (ACL 70 bar)
- Efficiency: ca. 30%
- Manufacturers: CAN, IND
- Operators: CAN, IND, ARG, KOR, PAK, ROU, CHN
- Up to 935 MWe per unit (1200 MWe for ACL-1200)

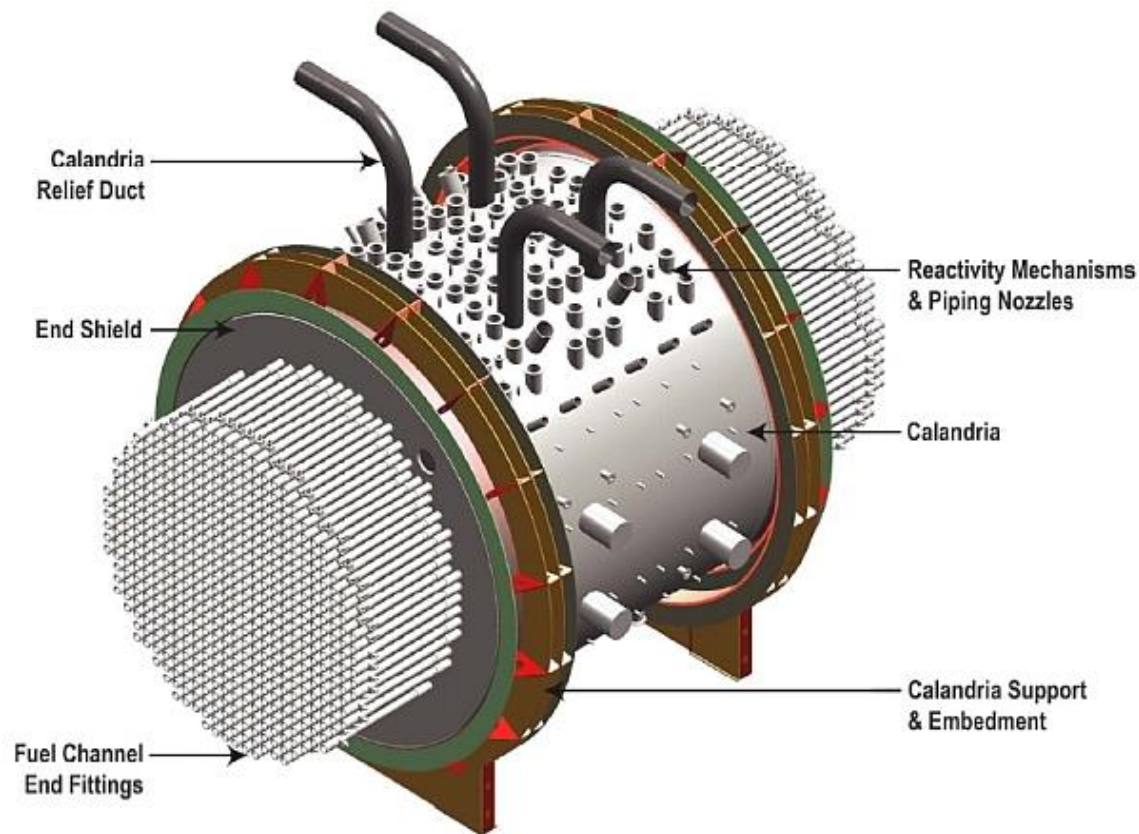
PRESSURIZED HEAVY-WATER REACTOR CANDU (CANADIAN DEUTERIUM URANIUM)



1. Fuel bundle
2. Calandria
3. Control rods
4. Pressurizer
5. Steam generator ($\times 2$)
6. Feedwater pump
7. Main circulation pump
8. Refuelling device
9. Heavy water moderator
10. Pressurized cooling channel
11. Live steam
12. Feedwater
13. Containment



ACR - ADVANCED CANDU REACTOR



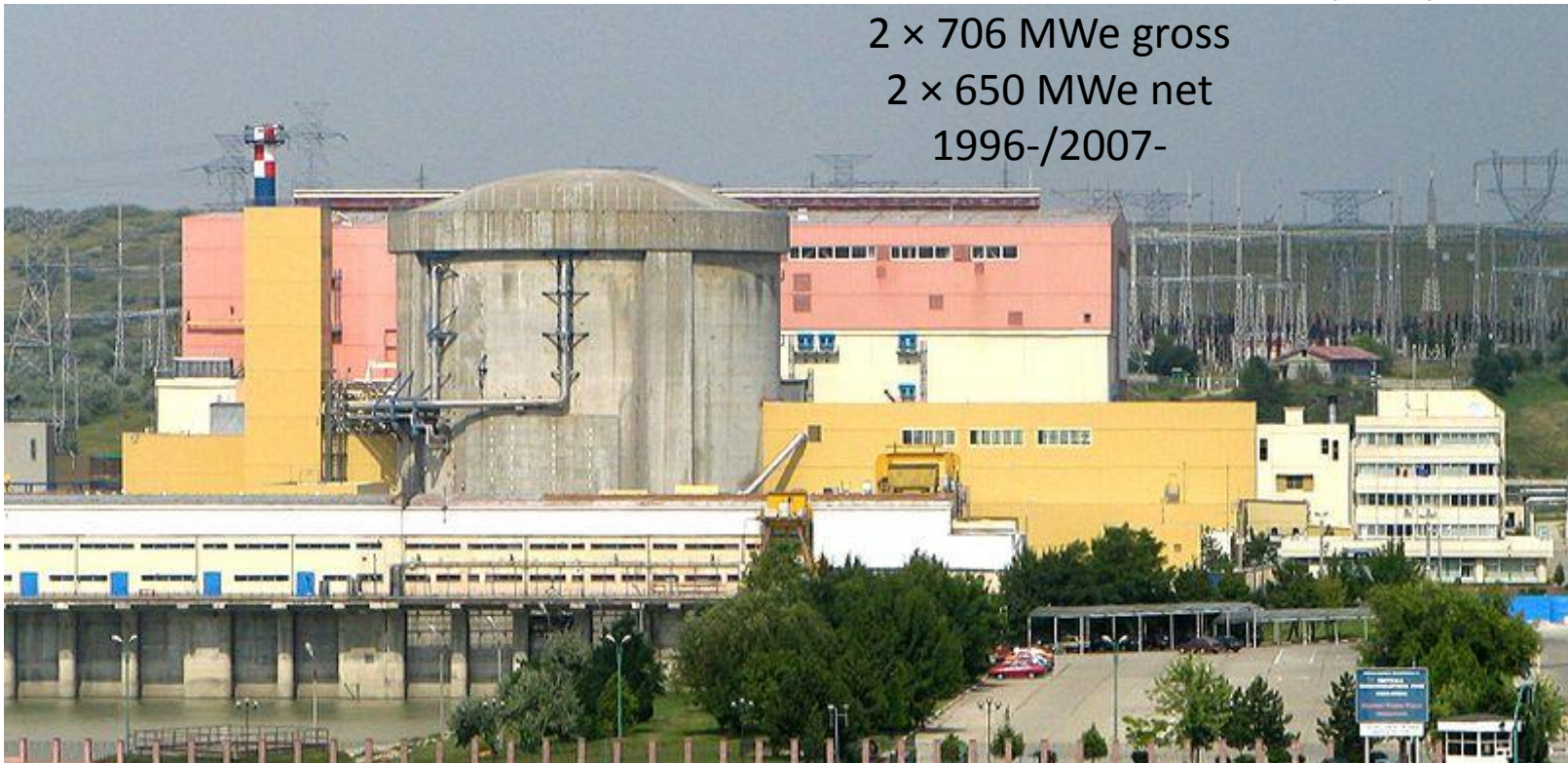
CANDU REACTOR

Centrala Nucleară de la Cernavodă (ROU)

2 × 706 MWe gross

2 × 650 MWe net

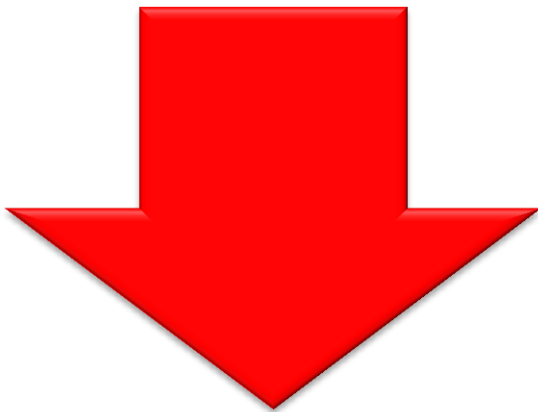
1996-/2007-



PRESSURIZED HEAVY WATER REACTOR (PHWR)



- Low pressure & temperature in calandria
- Radioactive isotope production capability
- Online refuelling
- Low fuel enrichment

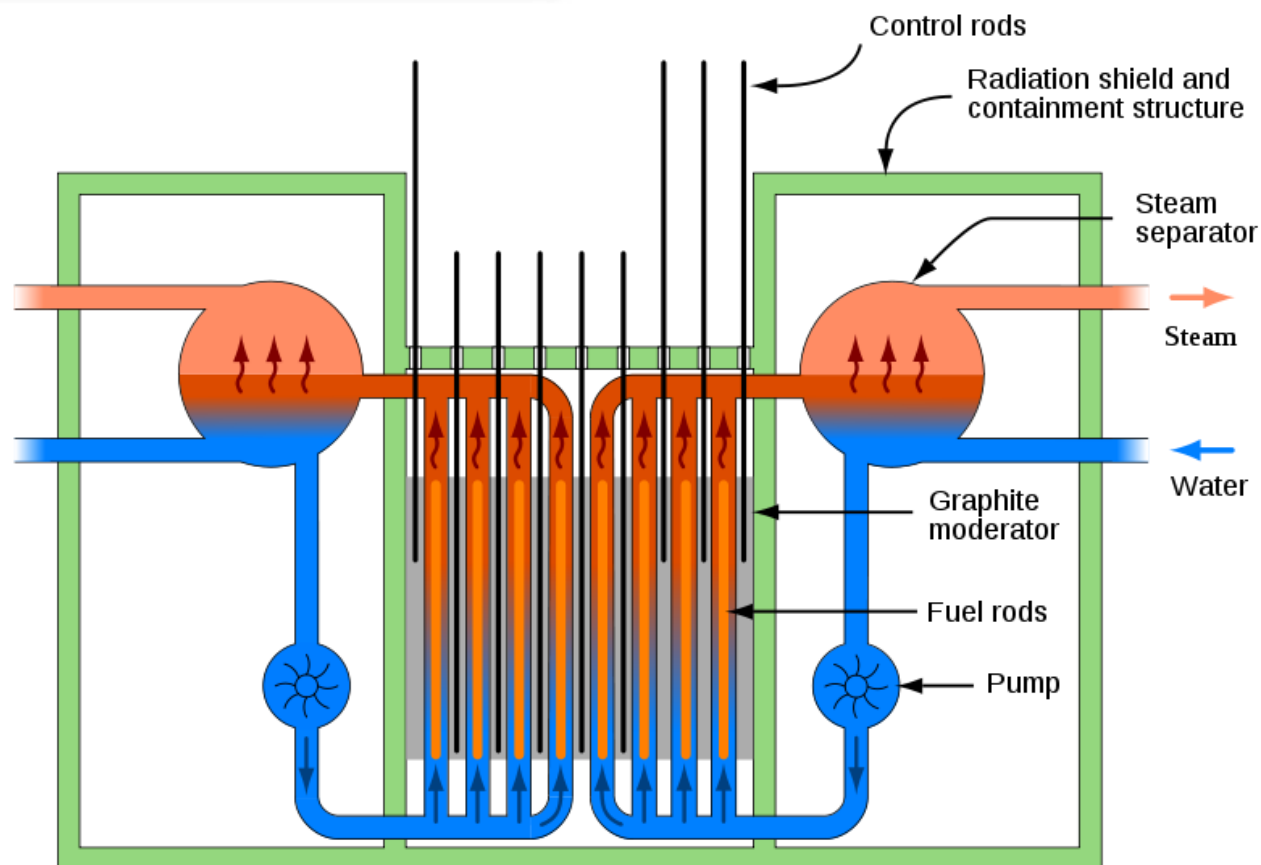


- Low efficiency
- Large core volume
- High number of pressurized connections - leaks
- Necessity to produce heavy water

LIGHT WATER GRAPHITE REACTOR (LWGR) РЕАКТОР БОЛЬШОЙ МОЩНОСТИ КАНАЛЬНЫЙ (RBMK)

- Channel-type reactor
- Coolant: H₂O
- Moderator: graphite
- Fuel: enriched uranium, 2%
- Single-circuit design (except the Obninsk prototype unit)
 - Live steam parameters: 70 bar, 285°C
- Efficiency ca. 32%
- Manufacturer: SUN
- Operators: SUN → LTU, RUS
- Units of 1000 or 1500 MWe (RBMK-1000, RBMK-1500)

LIGHT WATER GRAPHITE REACTOR (LWGR) Реактор Большой Мощности Канальный (РБМК)



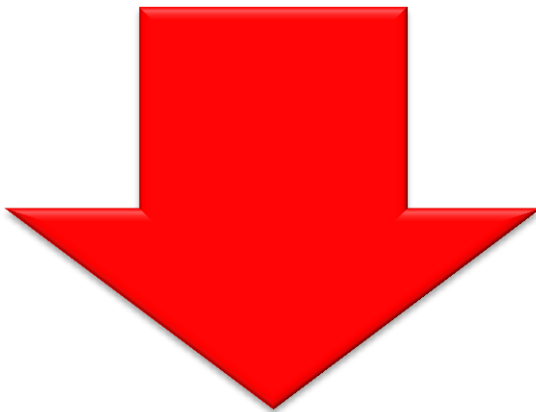
LIGHT WATER GRAPHITE REACTOR (LWGR) РЕАКТОР БОЛЬШОЙ МОЩНОСТИ КАНАЛЬНЫЙ (RBMK)



Easy to build

Theoretical possibility of producing superheated steam in single-circuit
(never implemented)

Online refuelling



High positive void coefficient!!!

Graphite operating temperature above its flash point in the air

Low efficiency (could be corrected by superheated steam generation)

Large core volume

No containment

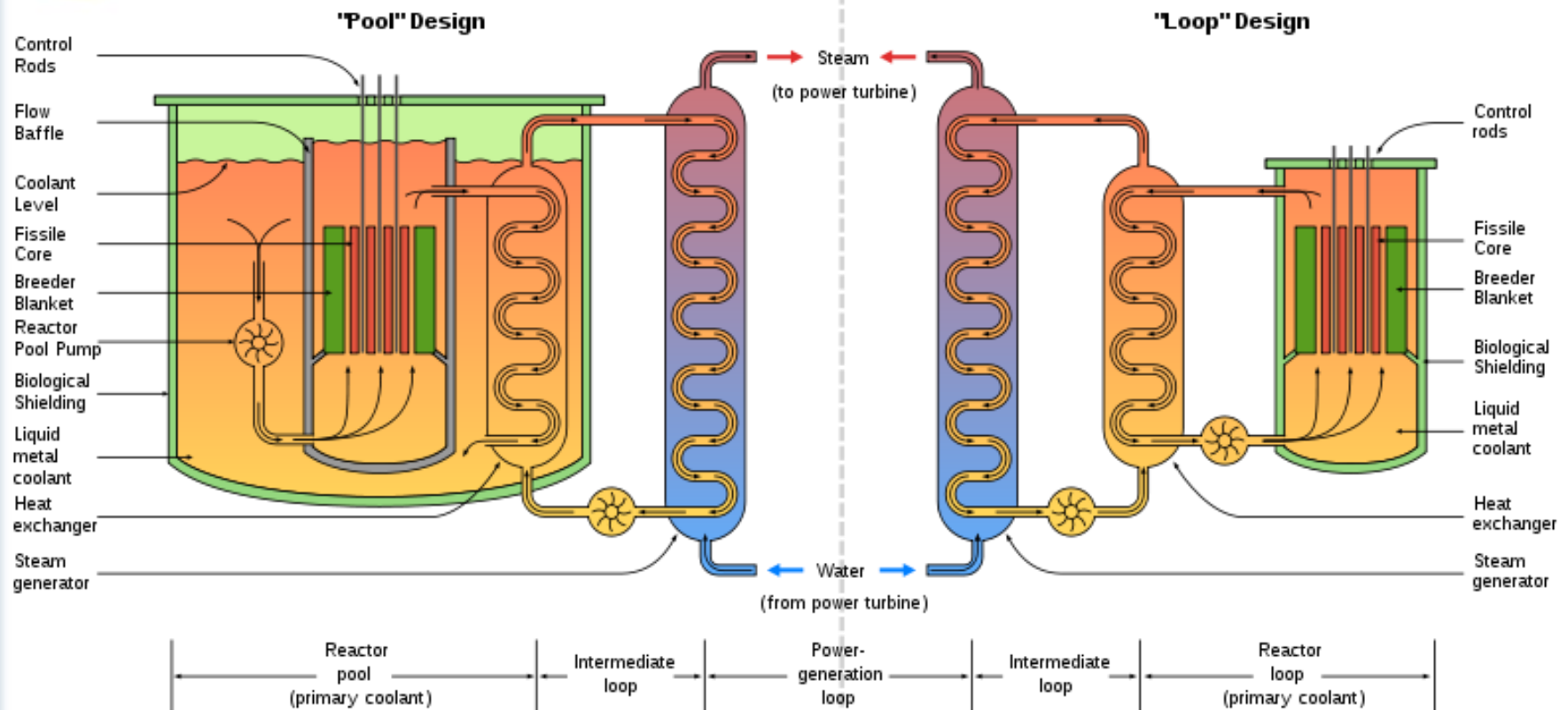
Insufficient safety systems (could be improved)

FAST BREEDER REACTOR (FBR)

- Pool-type or loop-type
- Coolant: liquid Na (possibly Bi-Pb)
- Moderator: none needed
- Fuel: MOX – $\text{PuO}_2 + \text{UO}_2$
- Three-circuit design
 - Primary circuit, liquid metal, active, $400 \div 600^\circ\text{C}$
 - Intermediate circuit, liquid metal, inactive
 - Secondary circuit, Rankine cycle, 550°C , 160 bar
- Very high power density in the core
- Fuel breeding (conversion of fertile isotopes into fissile isotopes), fuel output > fuel input

FAST BREEDER REACTOR (FBR)

Liquid Metal cooled Fast Breeder Reactors (LMFBR)



FAST BREEDER REACTOR (FBR)

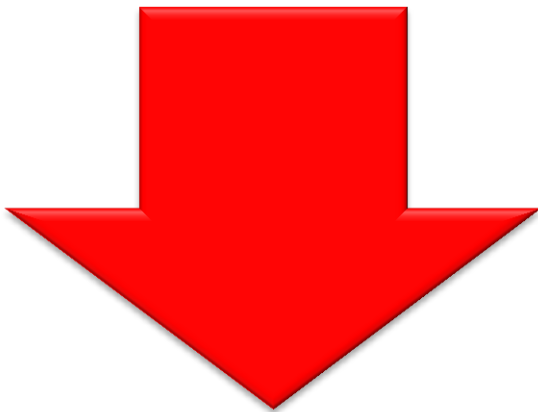
Beloyarsk-3 – BN-600
600 MWe gross
560 MWe net
1980-



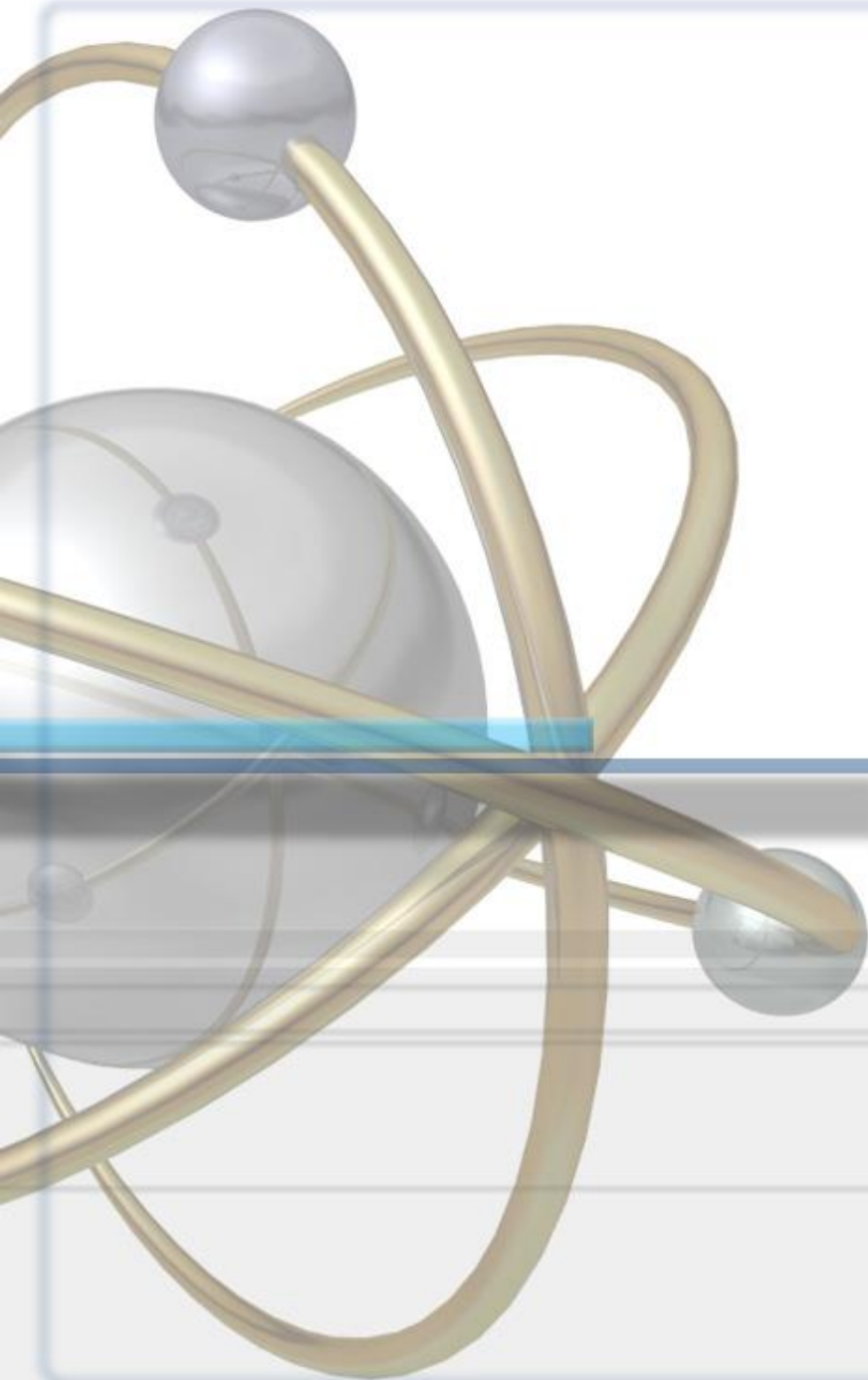
FAST BREEDER REACTOR (FBR)



Fuel breeding
High steam parameters
High efficiency



High melting point of coolant
Na-H₂O heat exchanger
Insufficiently researched

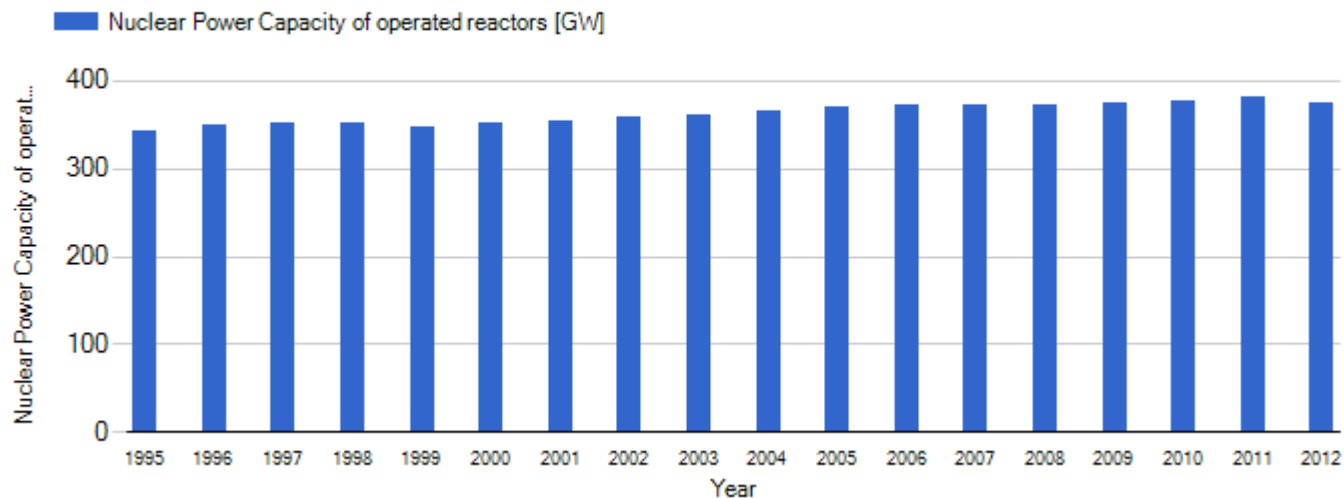


NUCLEAR POWER TODAY & TOMORROW

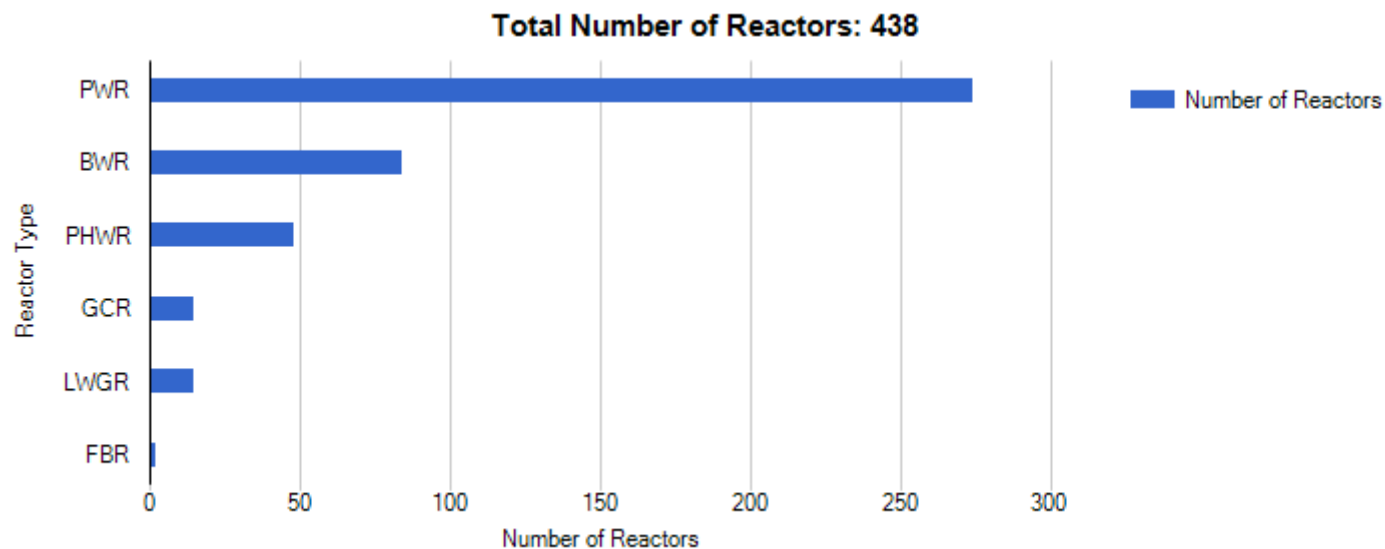
NUCLEAR POWER TODAY (JAN 2014)

- 438 operational units in 31 countries
- Total installed capacity 374 GWe (net)
- 1 unit in long-term shutdown (in Japan, 0.246 GWe)
- 71 units under construction

Source: Power Reactor Information System, IAEA

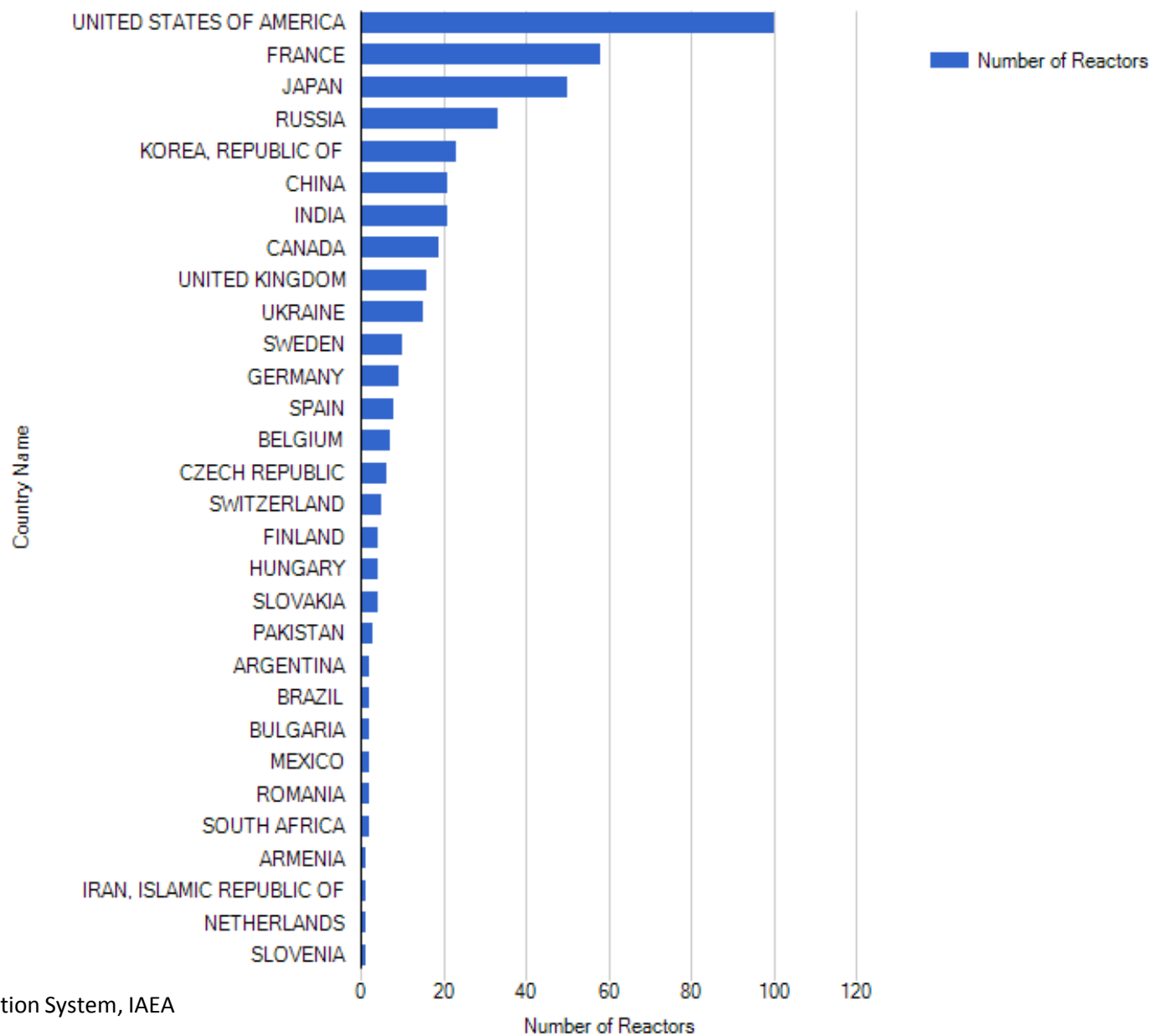


NUCLEAR POWER TODAY (1.2014)



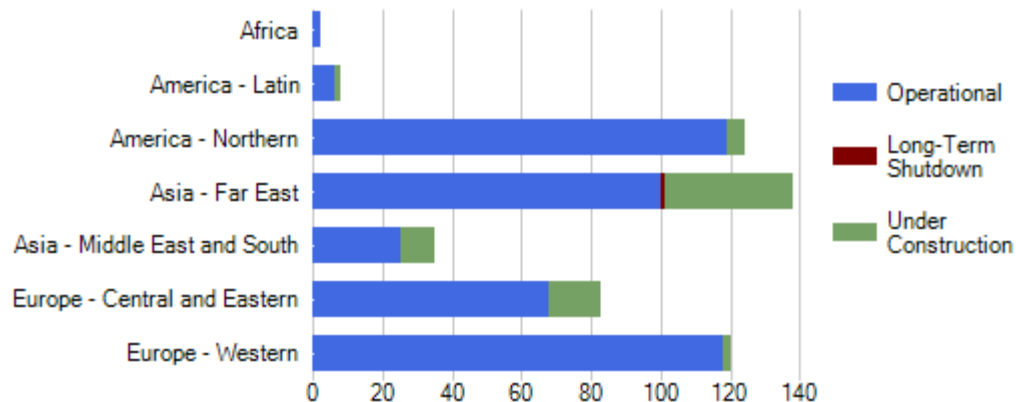
Source: Power Reactor Information System, IAEA

Total Number of Reactors: 438



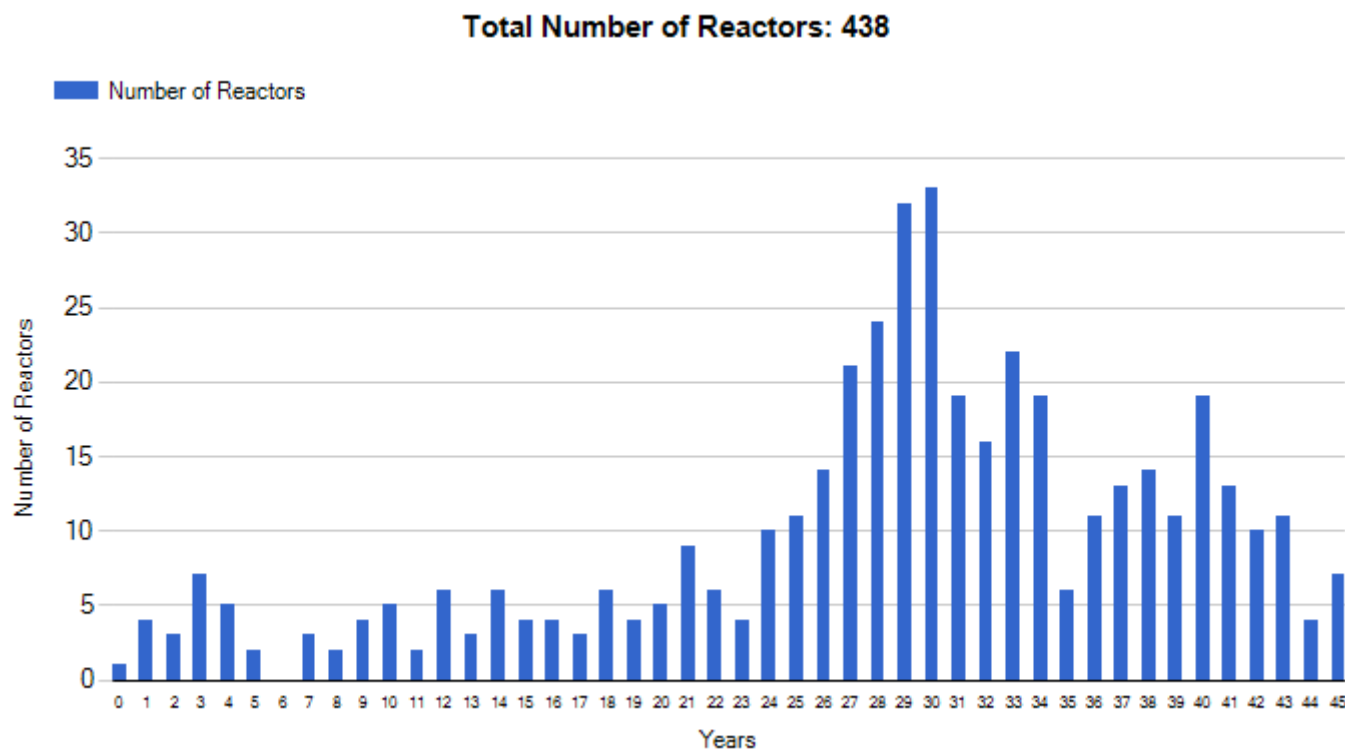
Source: Power Reactor Information System, IAEA

NUCLEAR POWER AROUND THE WORLD



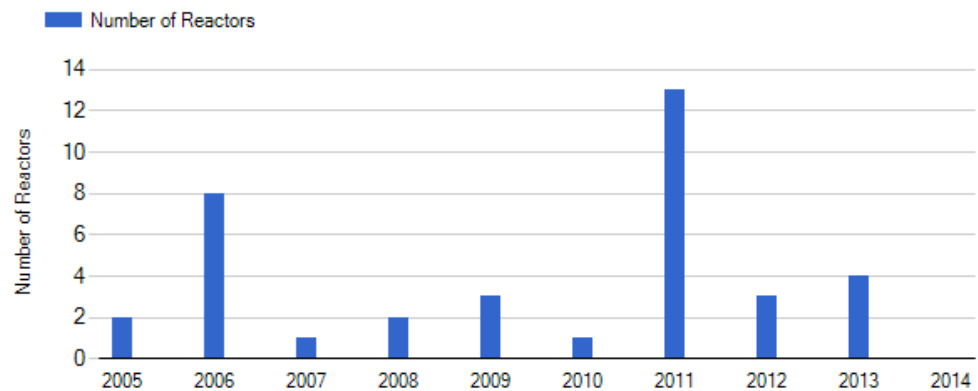
Source: Power Reactor Information System, IAEA

AGE OF NUCLEAR POWER REACTORS

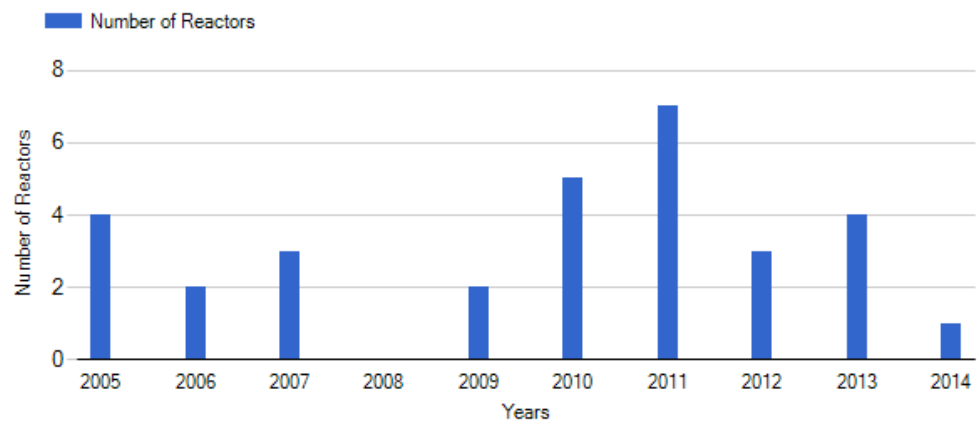
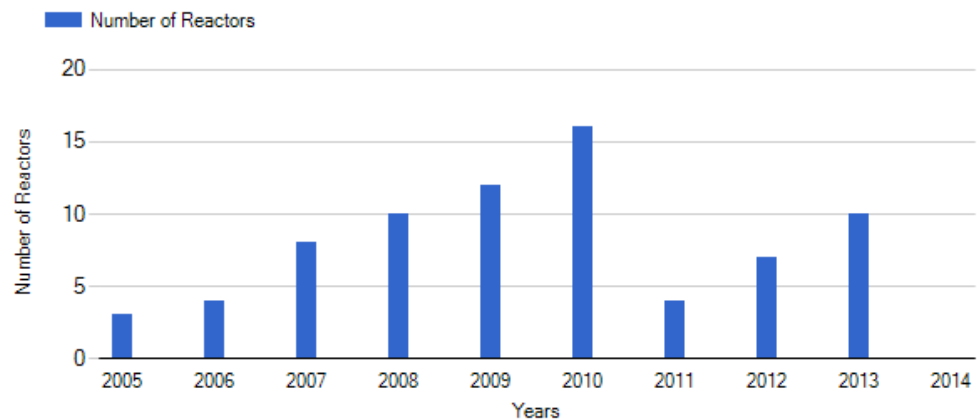


Source: Power Reactor Information System, IAEA

Trend of Permanent Shutdowns

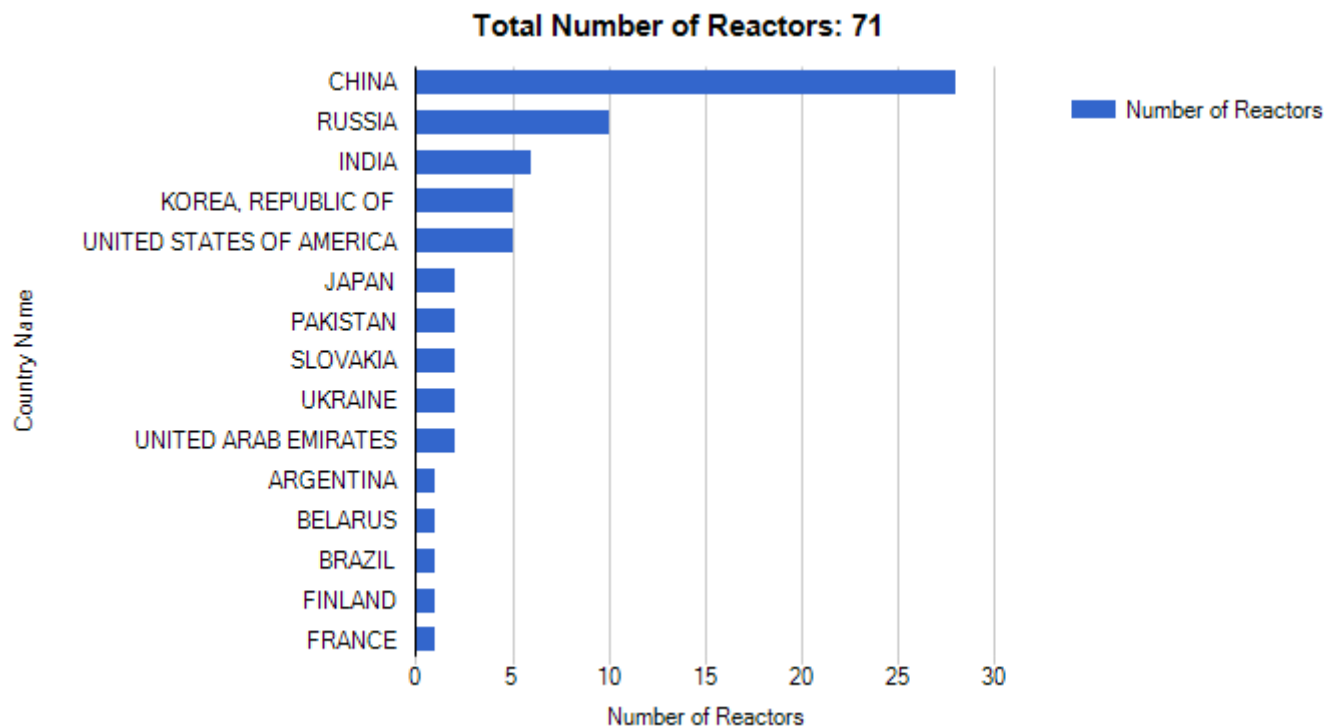


Trend of Construction Starts



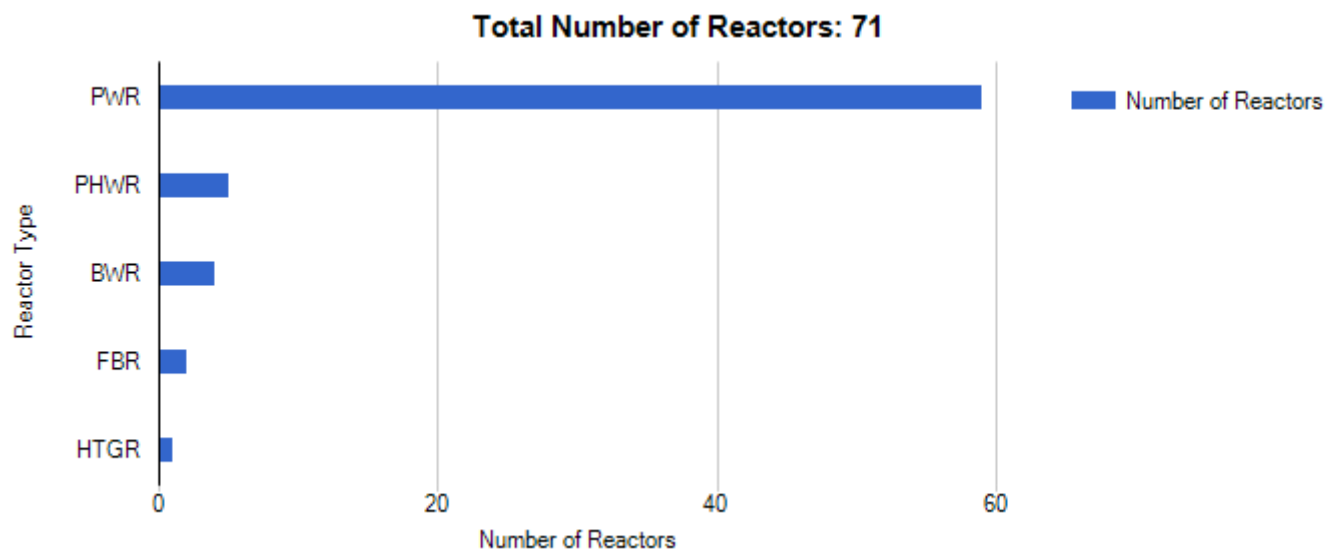
Source: Power Reactor Information System, I/A

UNITS UNDER CONSTRUCTION



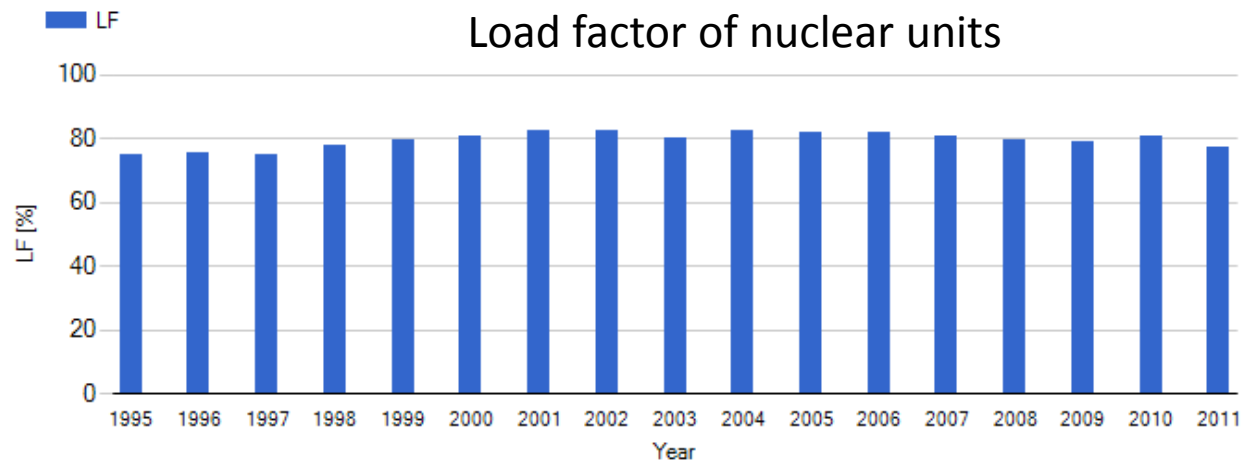
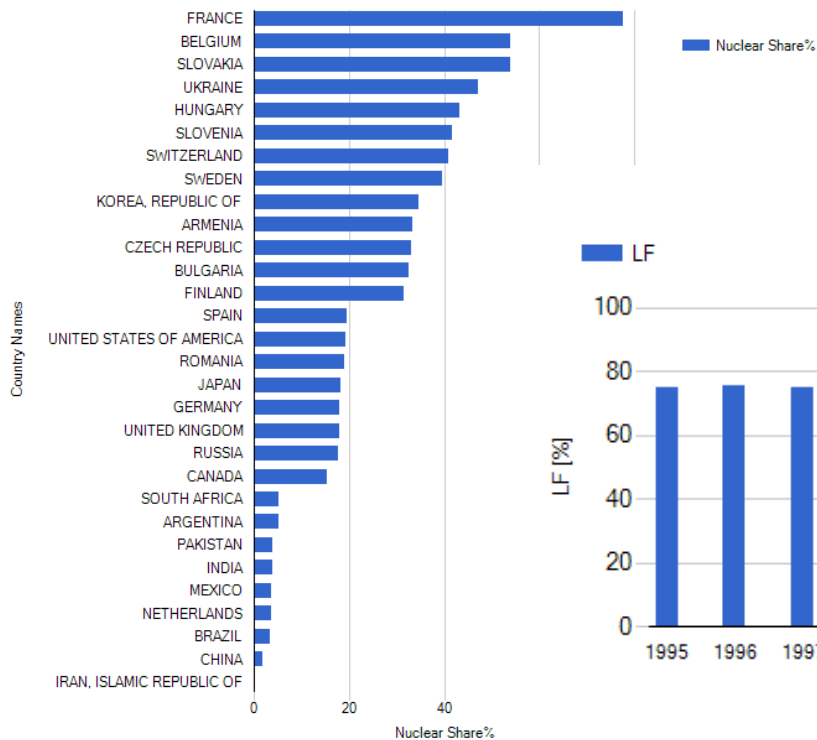
Source: Power Reactor Information System, IAEA

UNITS UNDER CONSTRUCTION



Source: Power Reactor Information System, IAEA

ROLE OF NUCLEAR POWER (2011)



Source: Power Reactor Information System, IAEA

PWR

AREVA
(EPR,
Atmea)

ROSATOM
(VVER-1200,
MIR-1200)

Toshiba-
Westinghouse
(AP-1000)

KEPCO
(OPR-1000,
APR-1400)

CGNPC
(CPR-1000)

Mitsubishi
(APWR,
Atmea)

BWR

GE-Hitachi
(ABWR,
ABWR II, ESBWR)

Toshiba
(ABWR)

Areva
(Kerena)

Atomenergo-
proekt
(VK-300)

PHWR

AECL
(CANDU-6,
ACR)

NPCIL, Bhavini
(AHWR)

FBR

OKBM
Afrikantowa
(BN-800, BN-1200
BREST)

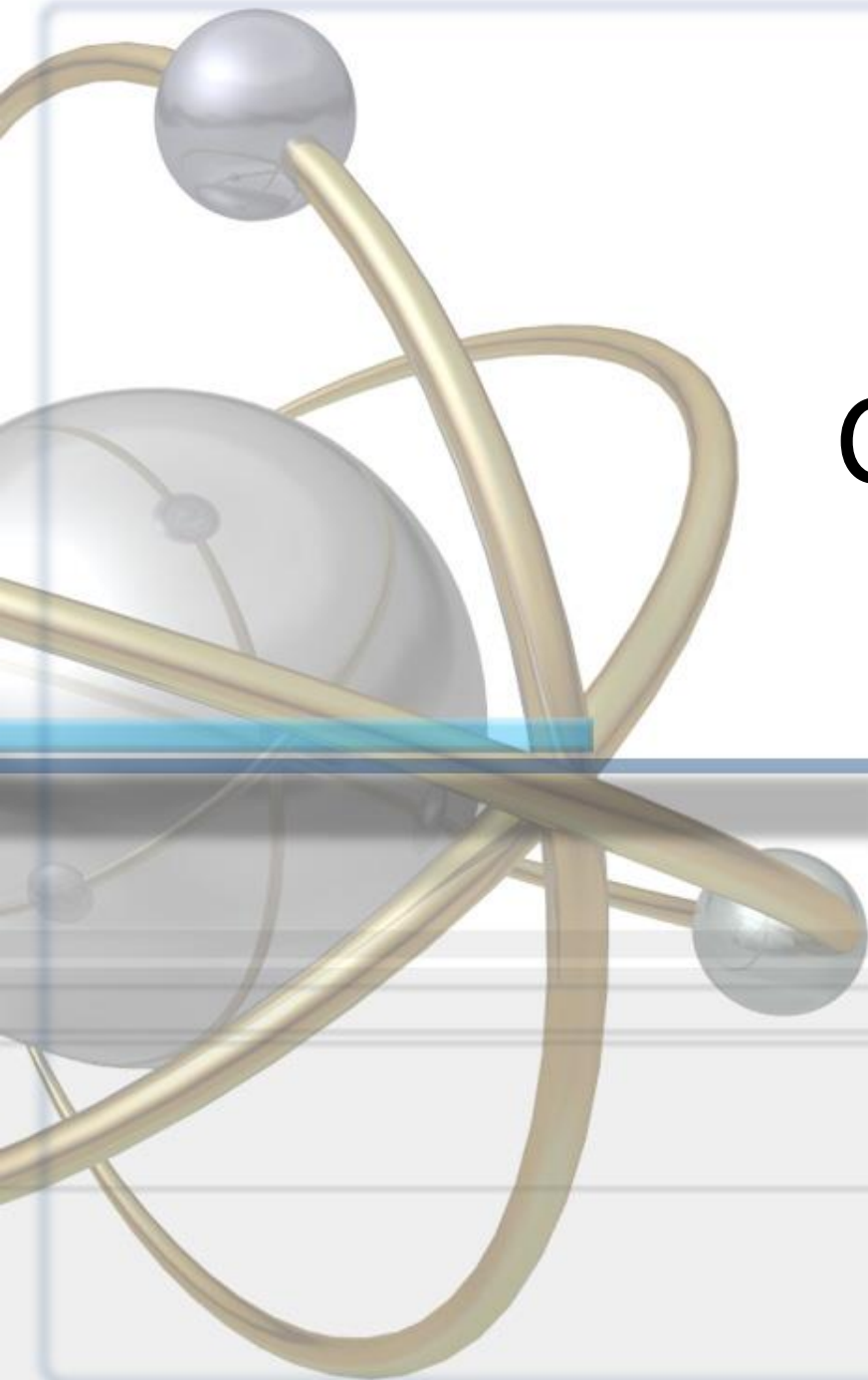
Bhavini

China
(CEFR)

HTR

Tsinghua Univ.
(HTR-PM)

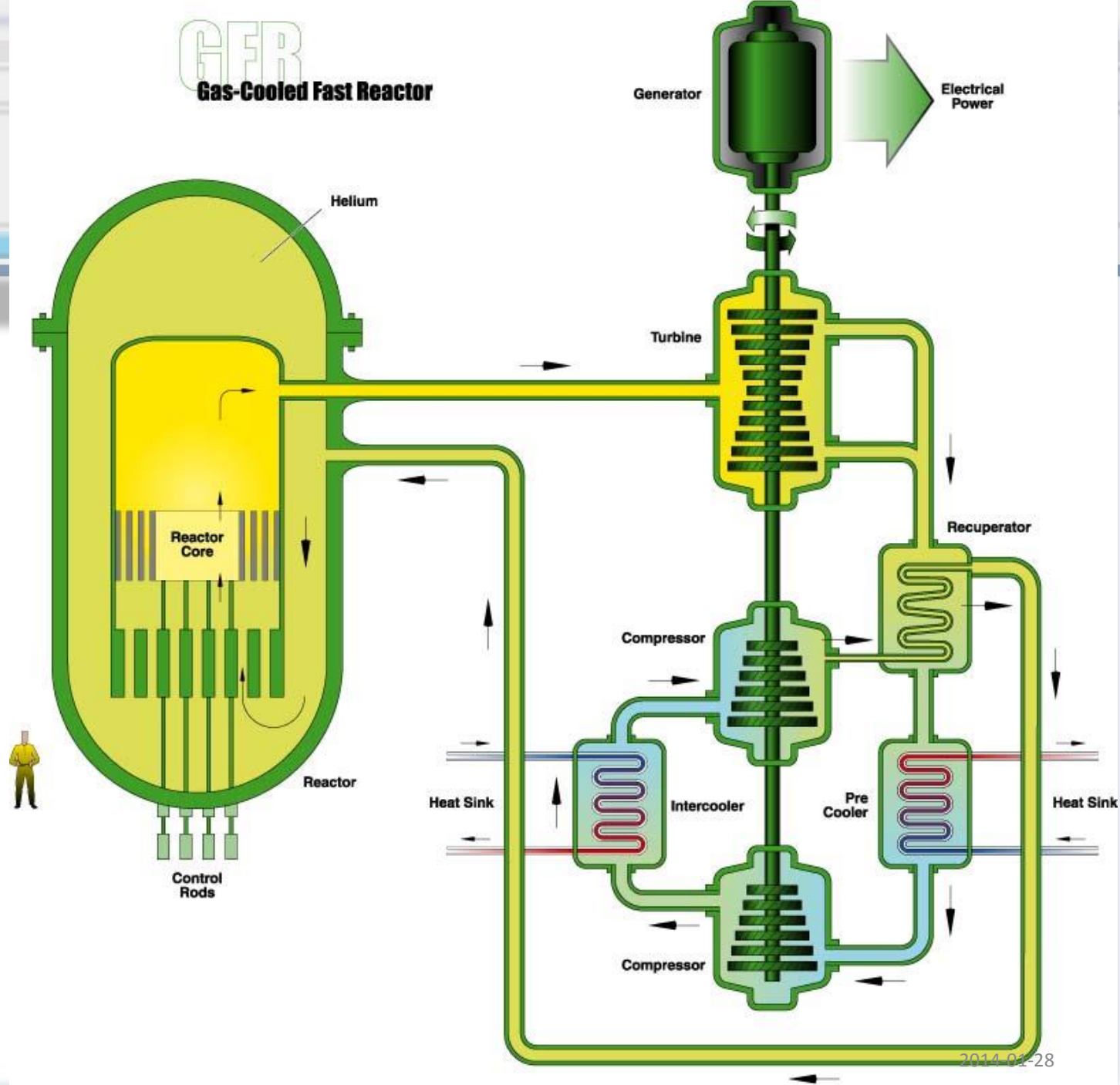
Global market offer
& prototype designs



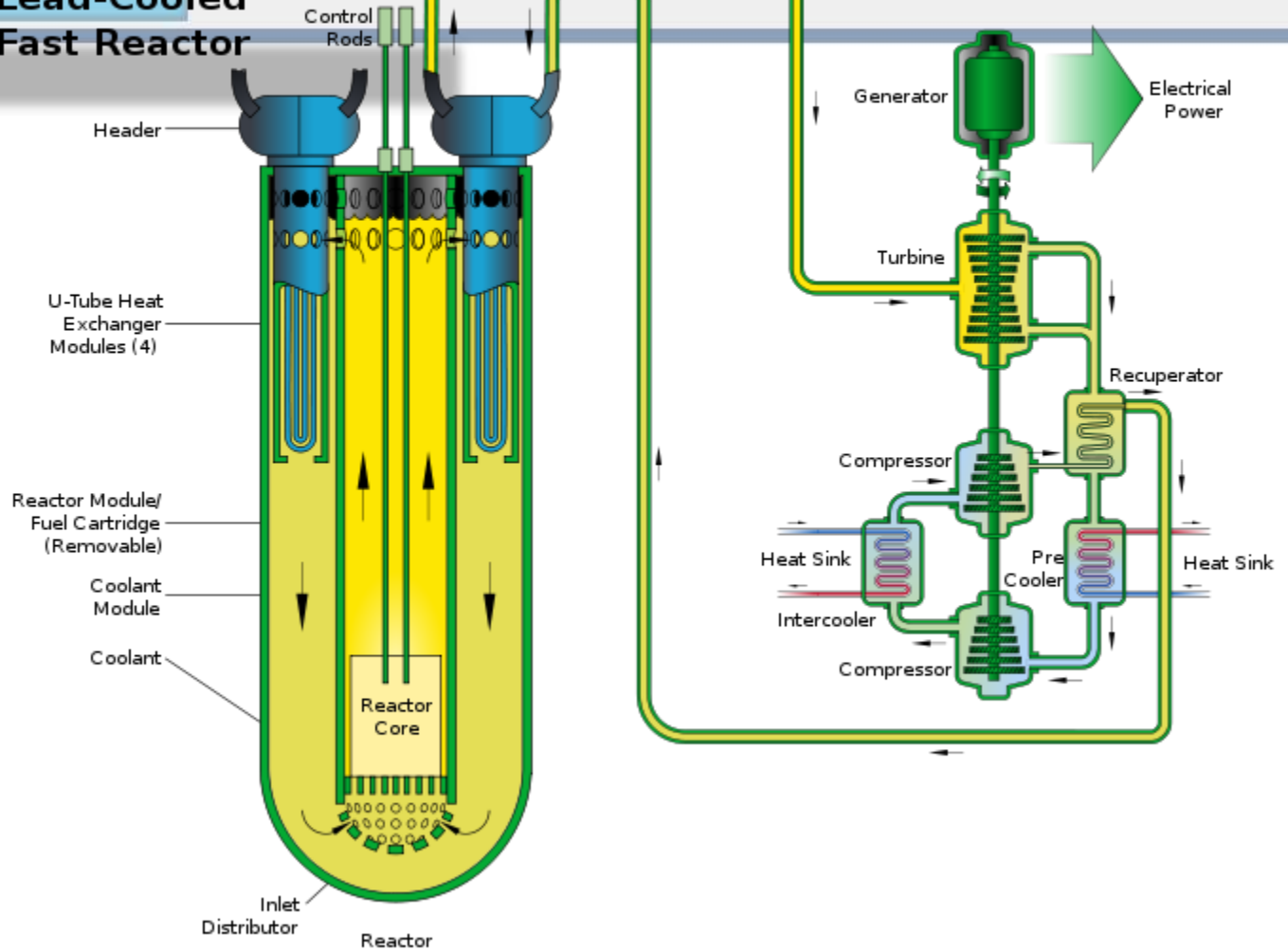
CONCEPTS FOR FUTURE IV GENERATION REACTORS

GFR

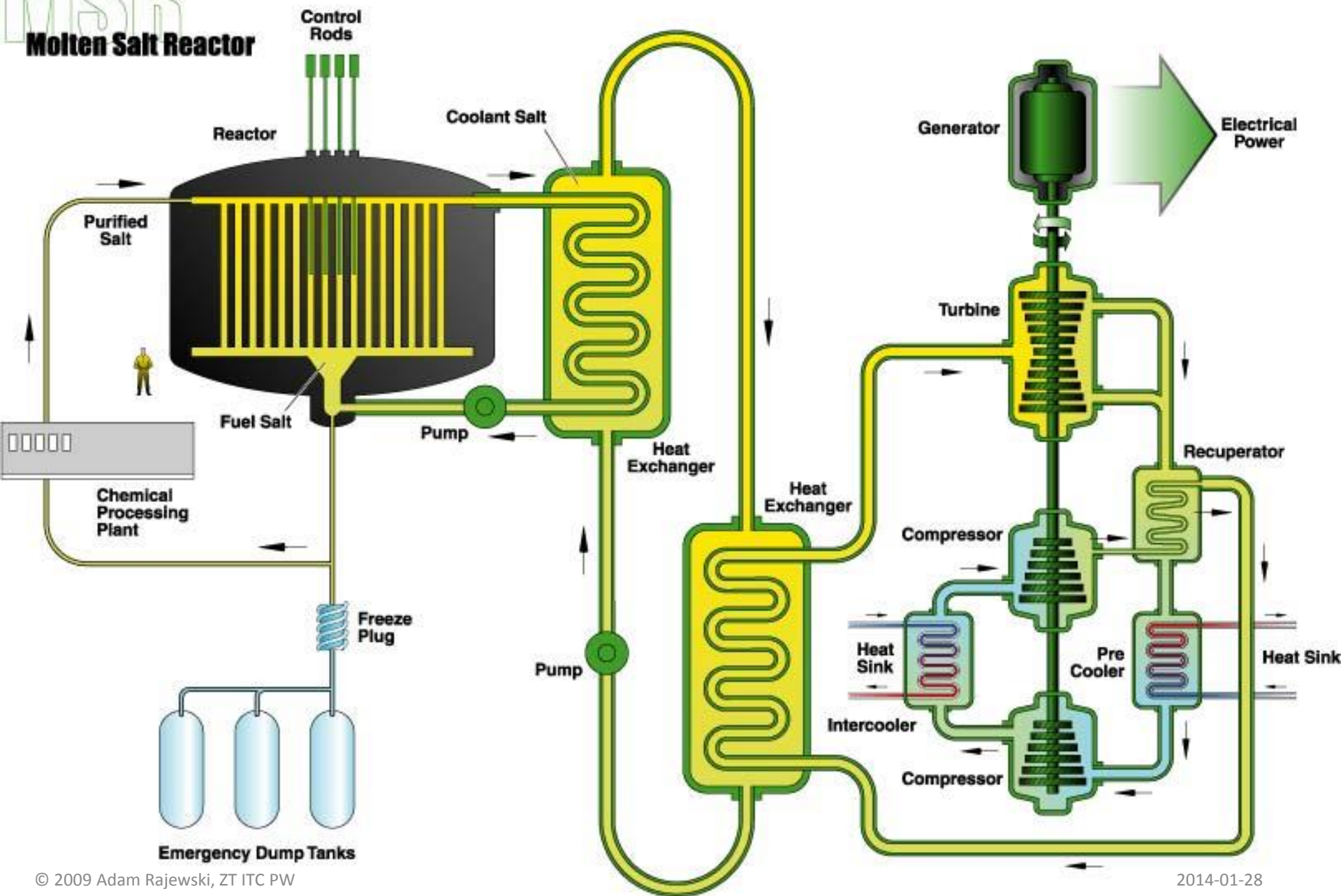
Gas-Cooled Fast Reactor

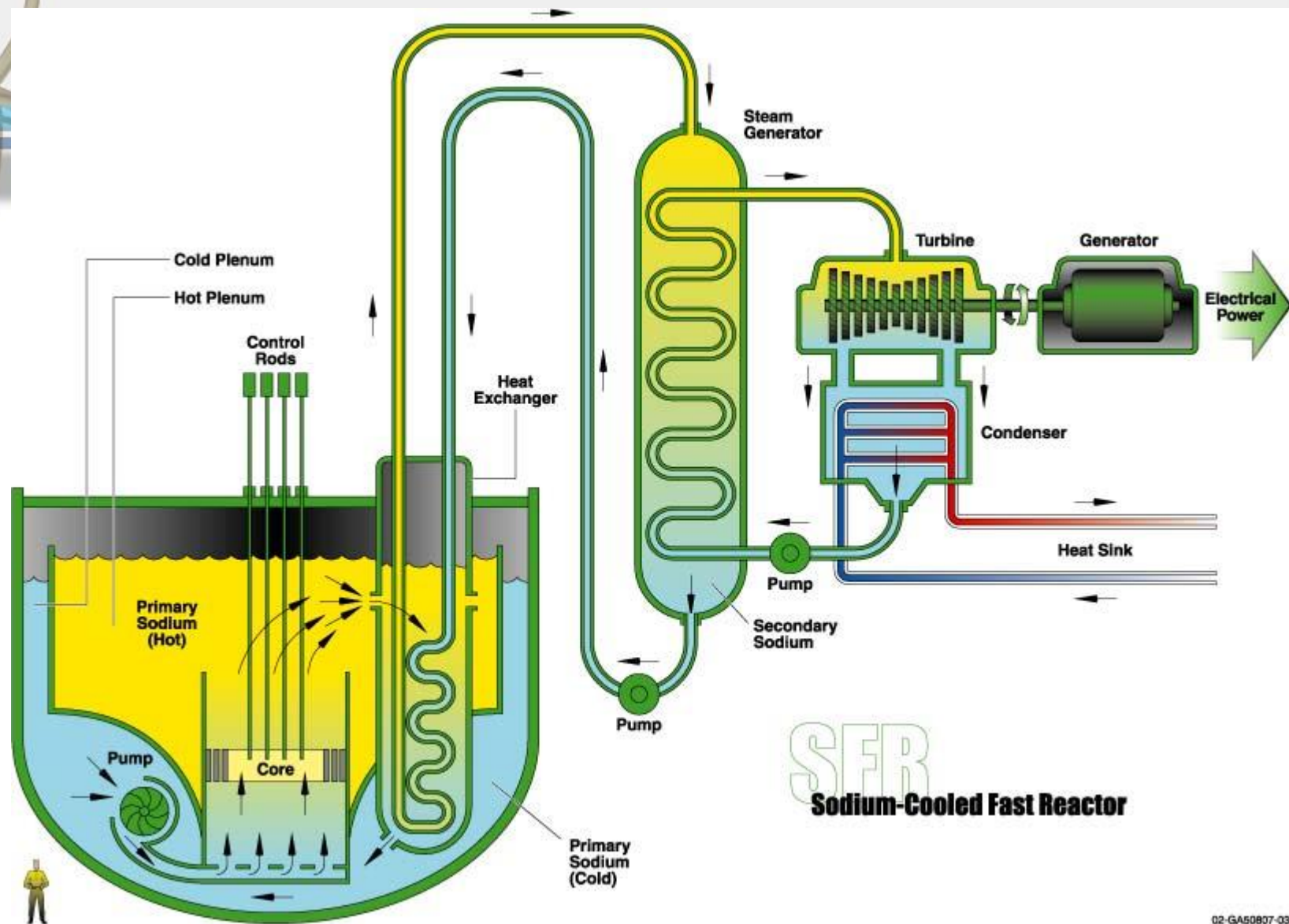


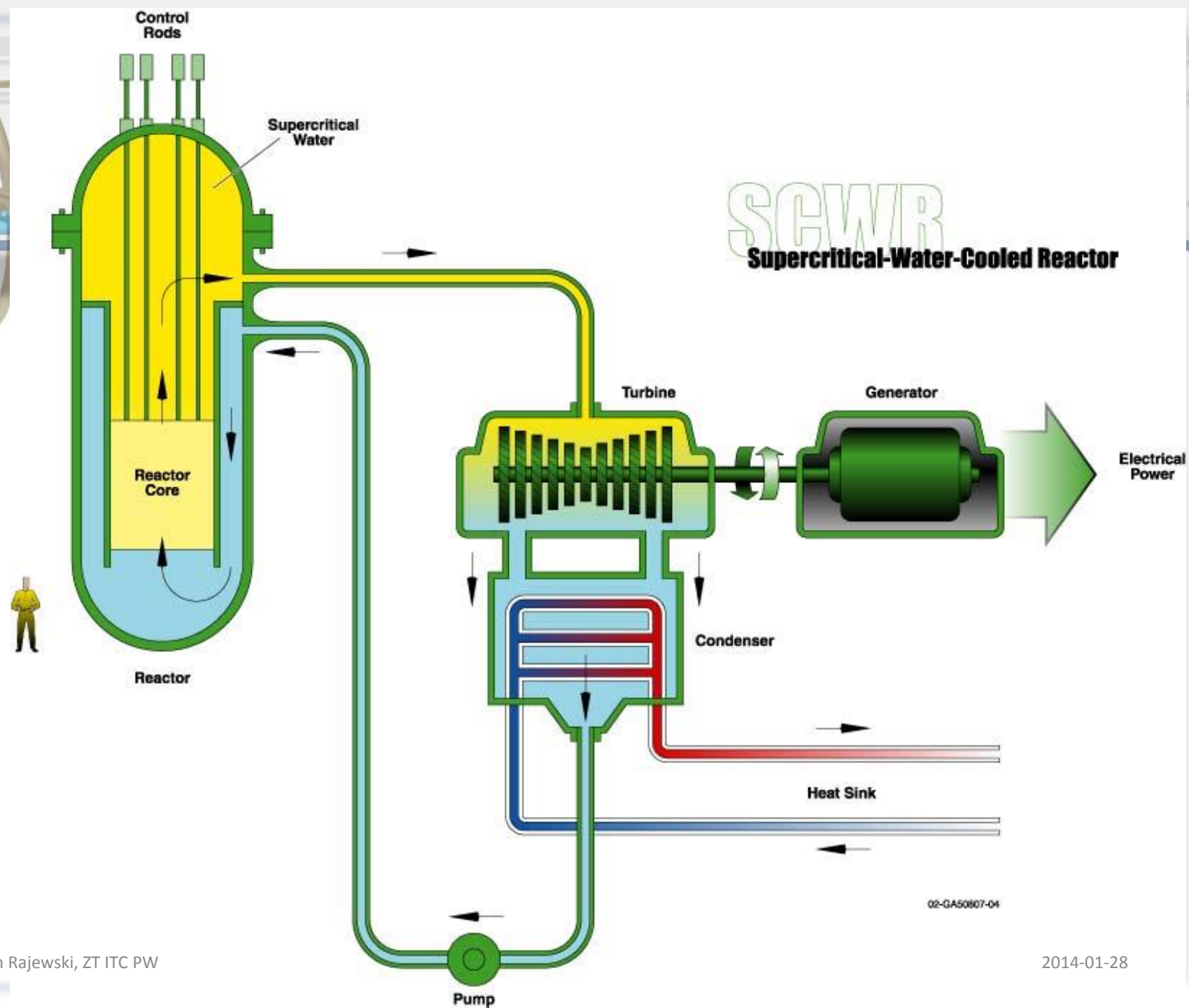
Lead-Cooled Fast Reactor

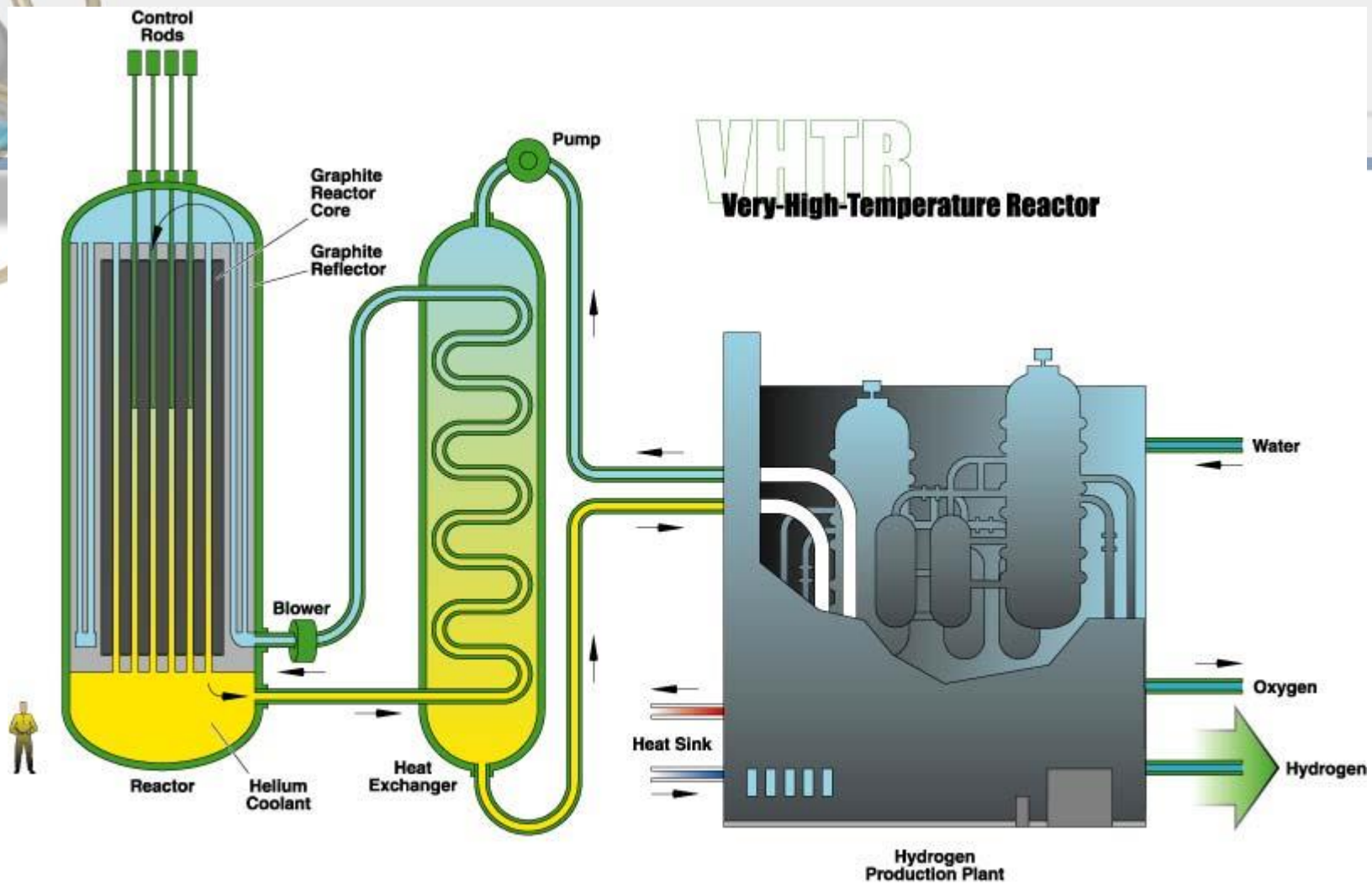


Molten Salt Reactor

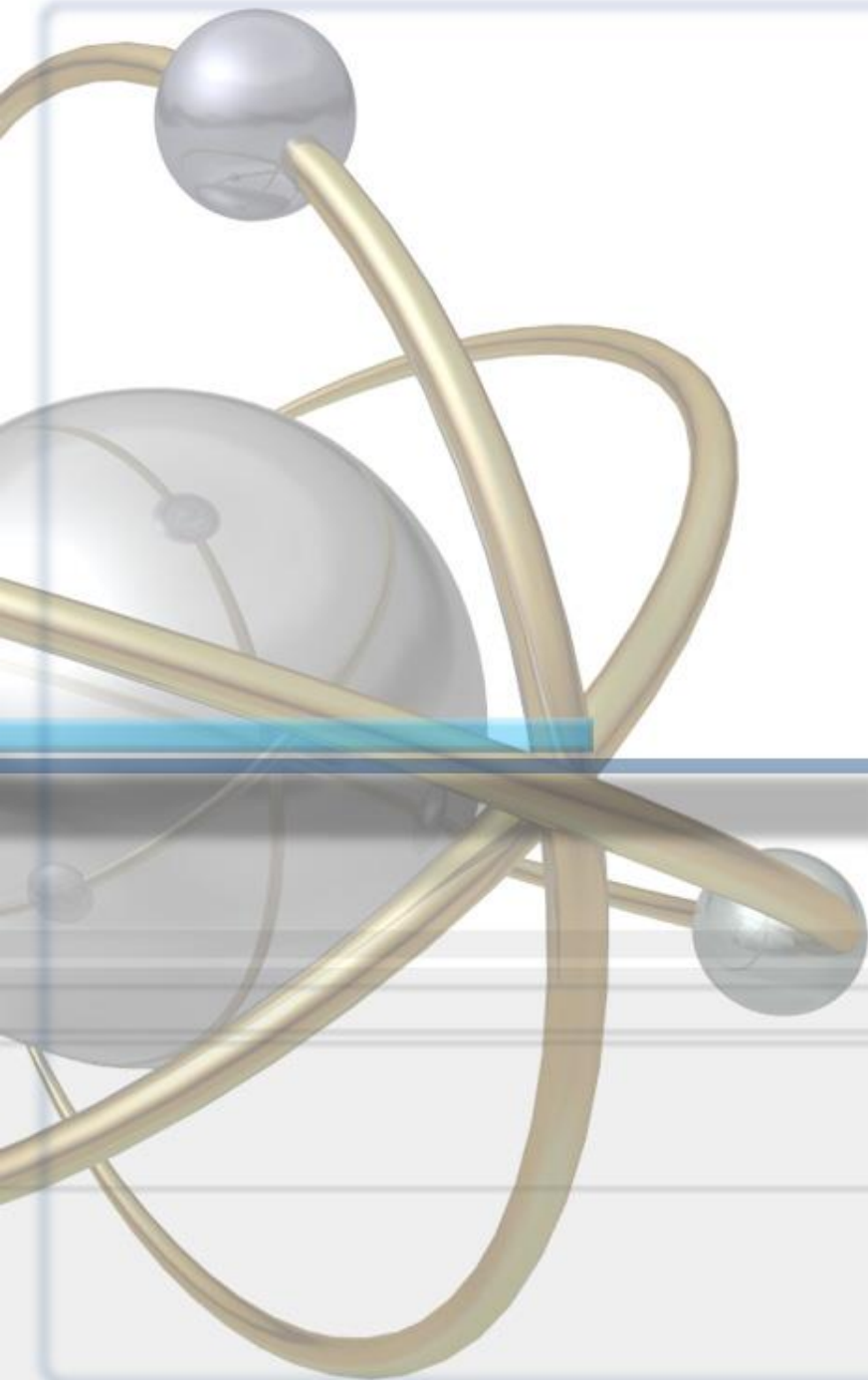








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THANK YOU!