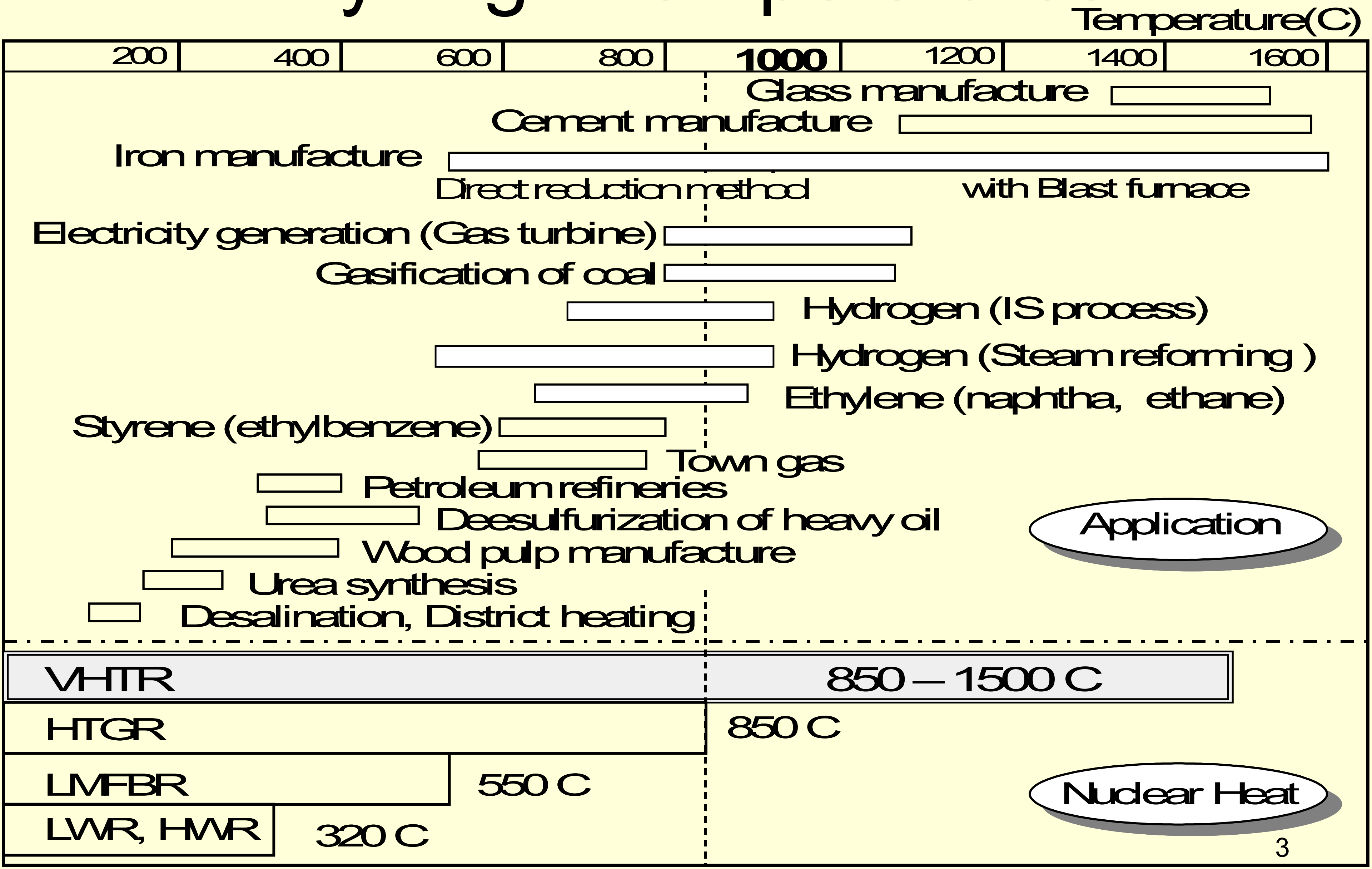
Graphite Moderated

Gas Cooled

Graphite = High Temperatures

- Reactor accident
  - Melting/sublimation point well above 3000; accident temperatures peak around 1600 C
  - Graphite cores are very large leading to large heat capacity to slow temperature rises in an accident
- Graphite will not burn in air even if heated
- Graphite will react with water/steam at elevated temperatures
- Irradiation produces a lot of ^{14}C
- Need to operate to avoid Wigner energy buildup

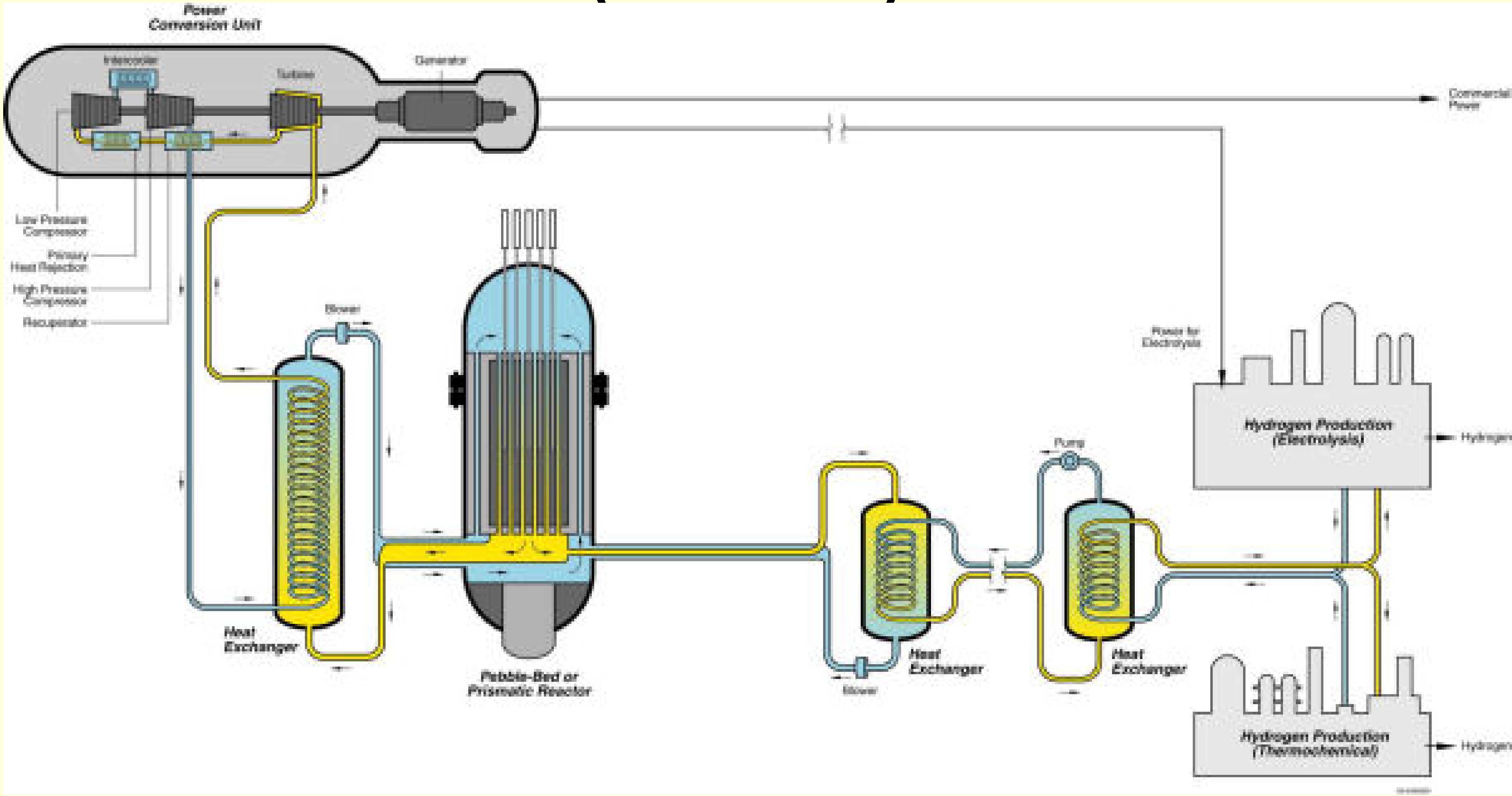
Why High Temperatures?



Gas Cooled

- Helium is the coolant of choice
  - Good thermal conductivity
  - Inert
  - Volume is large: energy and equipment size penalty
- Some legacy designs use CO_2

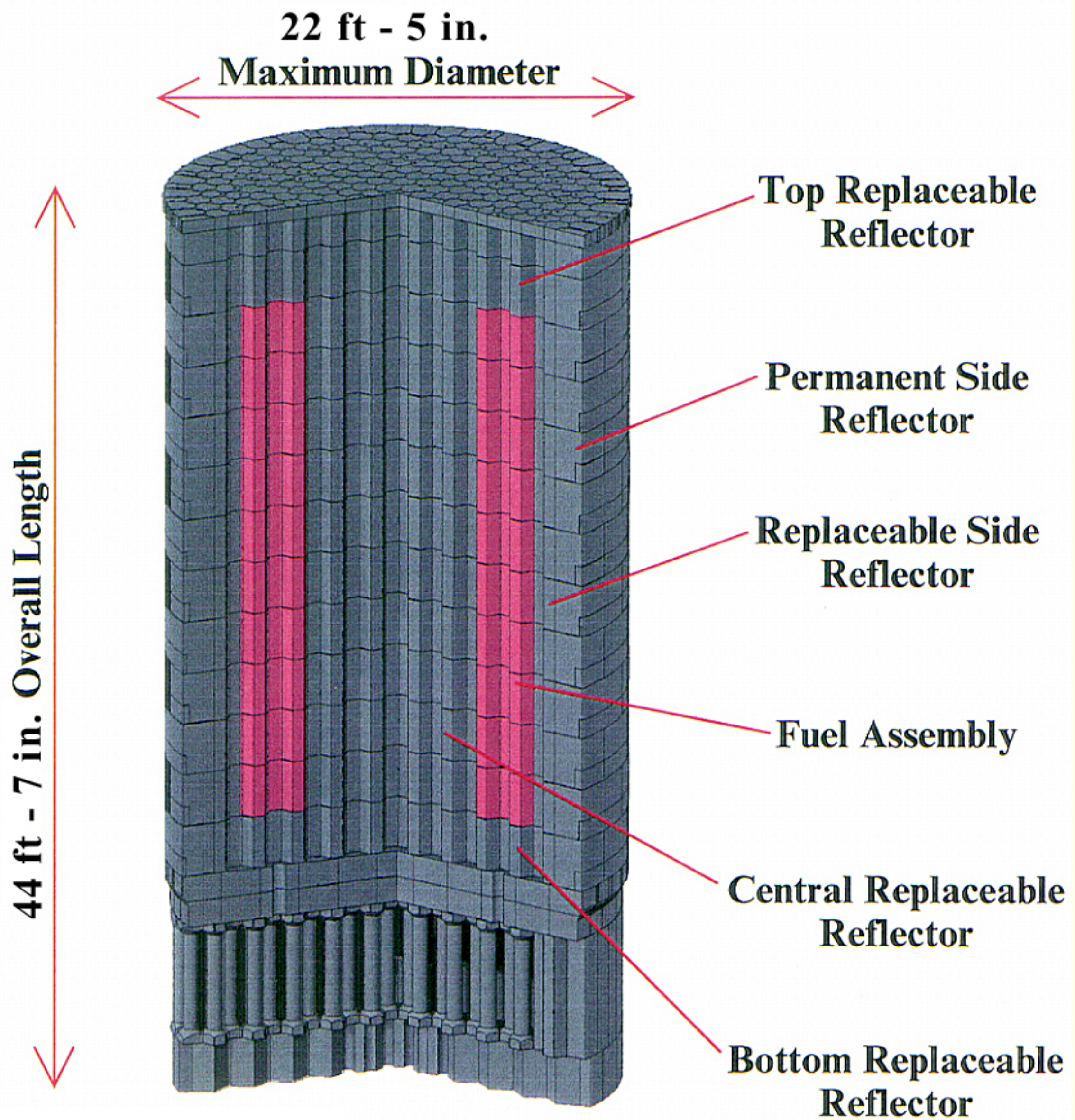
Very High Temperature Reactor (VHTR)



Block VHTR Core

- Material Graphite
- 102 Fuel Columns
- Hexagonal Fuel Block Dimensions:
  - Width Across Flats 0,36 m
  - Heigth 0,8 m
- Number of Fuel Blocks:
  - Standard 720
  - Control 120
  - Reserve Shutdown 180
- Number of Fuel Compacts 2919600
- Mass 870 tons

Outlet Temp 1000 C
Power Density: 6.5 kW/L
Thermal Efficiency: 47%



Block VHTR Features

- General Atomics reactor
- Passive cooling after accident
- Control rods contain boron carbide
- Still being developed
  - Materials
  - Optimization of temperatures
- Can be built in a variety of sizes
  - Current focus is 600 MWt
- Minor upgrade of GA's Gas Turbine – Modular Helium Reactor (GT-MHR)

What Needs Work

- These are high priority GEN IV designs
- High temperatures = materials problems
  - Graphite per se not an issue
  - Making fuel reliable
  - Metal components, esp. turbines, compressors, and heat exchangers
- Many countries pursuing VHTRs
  - US, South Africa, Japan, Russia, Netherlands, . .

Next-Generation Nuclear Plant

- NGNP is a DOE program to deploy a VHTR at Idaho National Laboratory
- Features
  - Dual purpose: electricity and process heat
  - Public-private partnership
  - NRC licensed
  - 2021 operation date planned
  - ≤600 MWt, 750 to 800

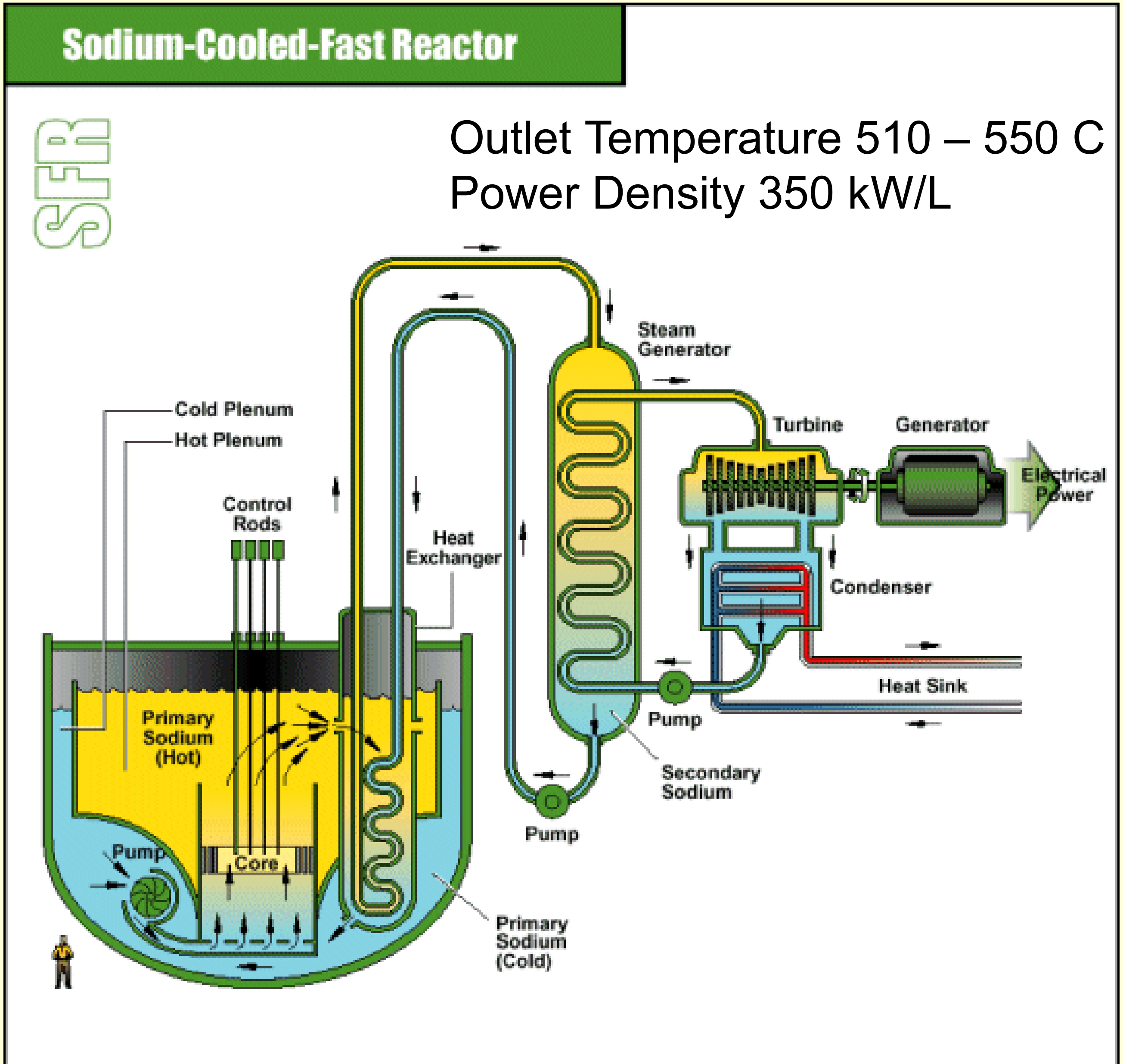
Fast (Unmoderated) Reactors

Sodium Cooled

Sodium (Na)

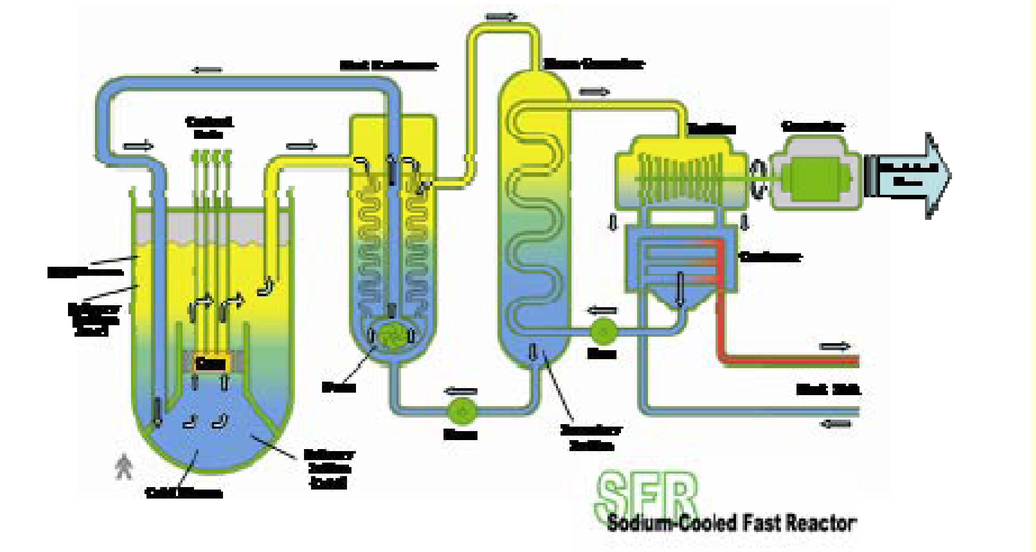
- Sodium
  - mp: 98 C/208 F
  - bp: 883 C/1621 F
- Advantages
  - Reactor operates at about atmospheric pressure
  - Excellent heat transfer properties
  - Not corrosive to stainless steel
- Disadvantages
  - Opaque
  - Reacts with air and can burn; reacts violently with water
  - Na^{24}, 15h half life, hard gamma

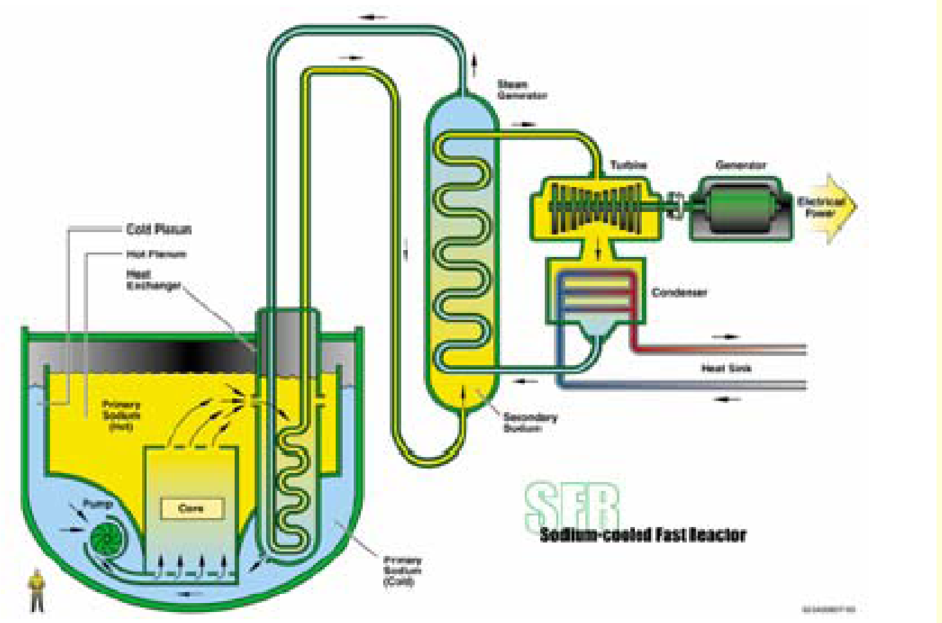
Sodium-Cooled Fast Reactor (SFR)



SFR Pool vs Loop

- Loop design has primary heat exchanger outside the pool of sodium
  - Favored by Japan
- Pool design contains primary loop in one vessel
  - Fewer pipes to break or leak
- GEN IV, high priority



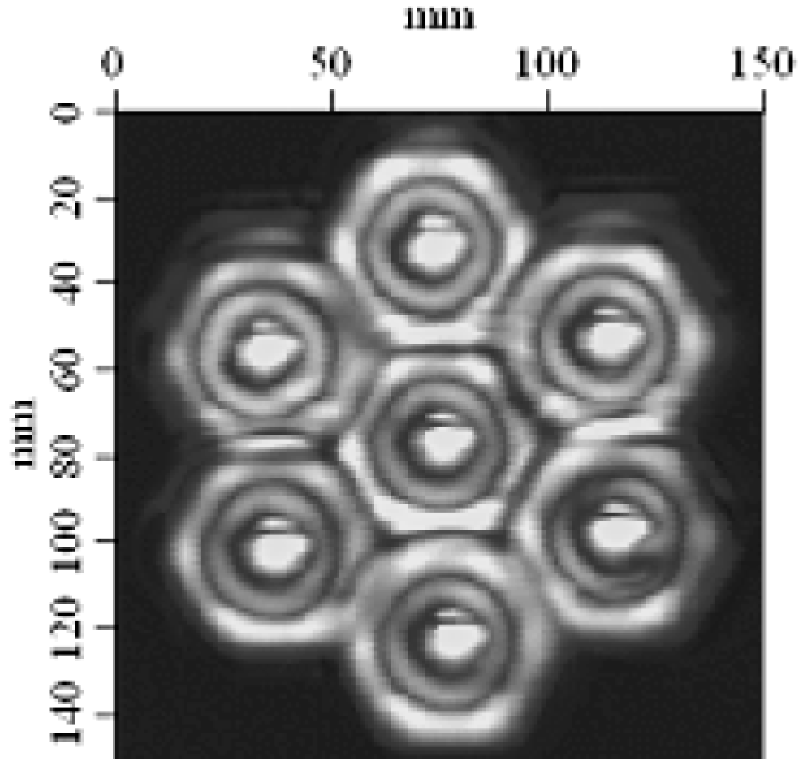


SFR Safety

- Criticality terminated by increased temperatures because of core expansion and increased neutron leakage
- Sodium boiling can insert positive reactivity (positive sodium void coefficient) but can be managed by design
  - Within limits: ^{238}U presence is a key factor
- Future reactors designed for natural sodium circulation and passive heat transfer to the atmosphere

SFR Refueling Imaging

- Ultrasonic images in liquid sodium



SFR Status

- 390 reactor-years worldwide
  - US: EBR-I, II; Fermi (commercial), Fast Flux Test Facility
  - France: Rhapsodie, Phenix, Superphenix
  - UK: Dounreay, Prototype Fast Reactor
  - Japan: Joyo, Monju
  - Russia: BN-350, 600
- Major issues
  - Reliability
  - Engineering to reduce cost

Small Modular Reactors

Small Modular Reactors (SMRs)

- No generally agreed definition
  - IAEA: <300 MWe, maybe 500 MWe
  - Conventional: <600 MWt (<200-300MWe)
    - Above 600 MWt natural circulation cooling becomes a challenge
- Objectives: One or more of the following
  - Factory construction and ship to site
    - Less costly than field construction
    - Power supply to remote sites or for small demand
  - Passively safe
  - Proliferation resistance
  - Build a module at a time: easier financing

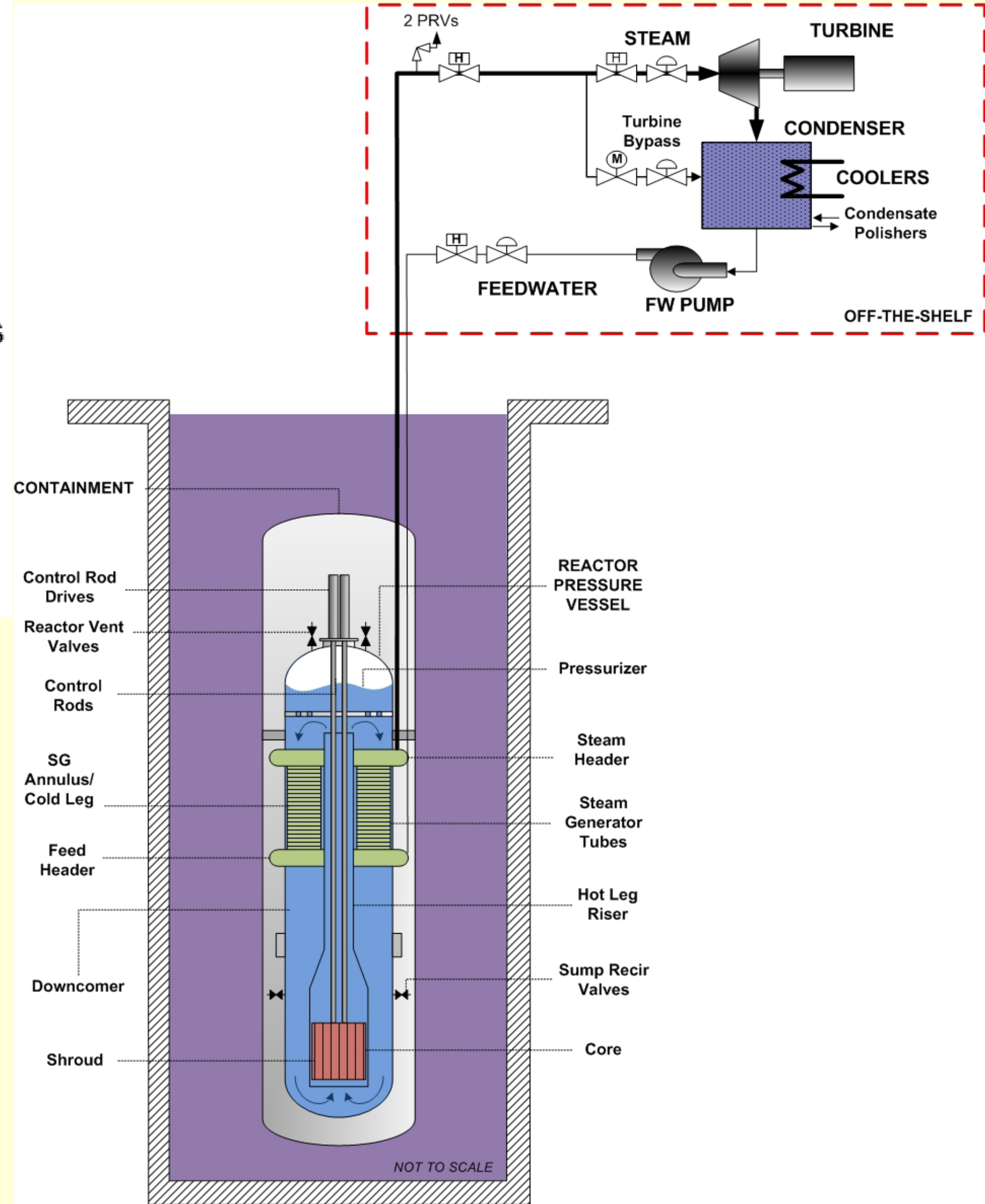
NuScale PWR

- **Vendor:** NuScale Power Inc.
- **Reactor Power:** 150 MWt
- **Electrical Output:** 45 MWe
- **Coolant:** Light Water
- **Outlet Temperature:** 296°C
- **Fuel Design:** 6' long,17 x 17 assemblies
  - 4.95% enrichment
- **Refueling:** 30 Months
- **Application:** Late 2010
- **Reference:** ML082130430

Cooling is natural circulation

Pool design

Integral steam generator

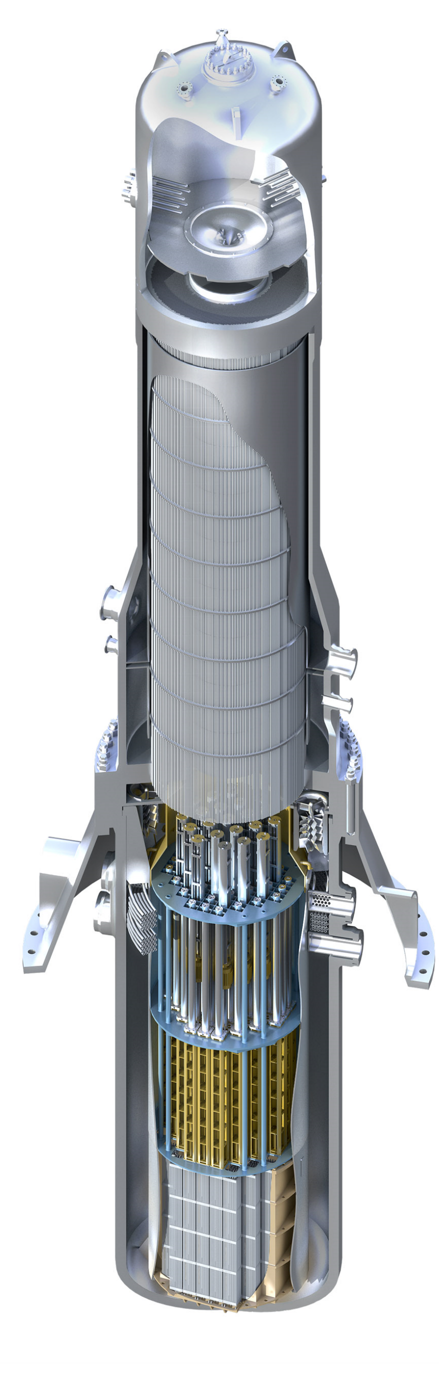


mPower PWR

Designer:	Babcock & Wilcox Company (B&W)
Reactor Power:	400 MWt
Electrical Output:	125 MWe
Outlet Conditions:	327°C
Coolant:	Light water
Fuel Design:	*Proprietary*
Refueling:	*Proprietary*
Letter of Intent:	April 28, 2009
Licensing Plan:	Design Certification
Expected Submittal:	Q4 CY 2012

Fuel is based on standard PWR design

Integral steam generators



Legacy Reactors

Reaktor Bolshoy Moschnosti Kanalniy (High Power Channel Reactor)

- RBMK: A Russian BWR

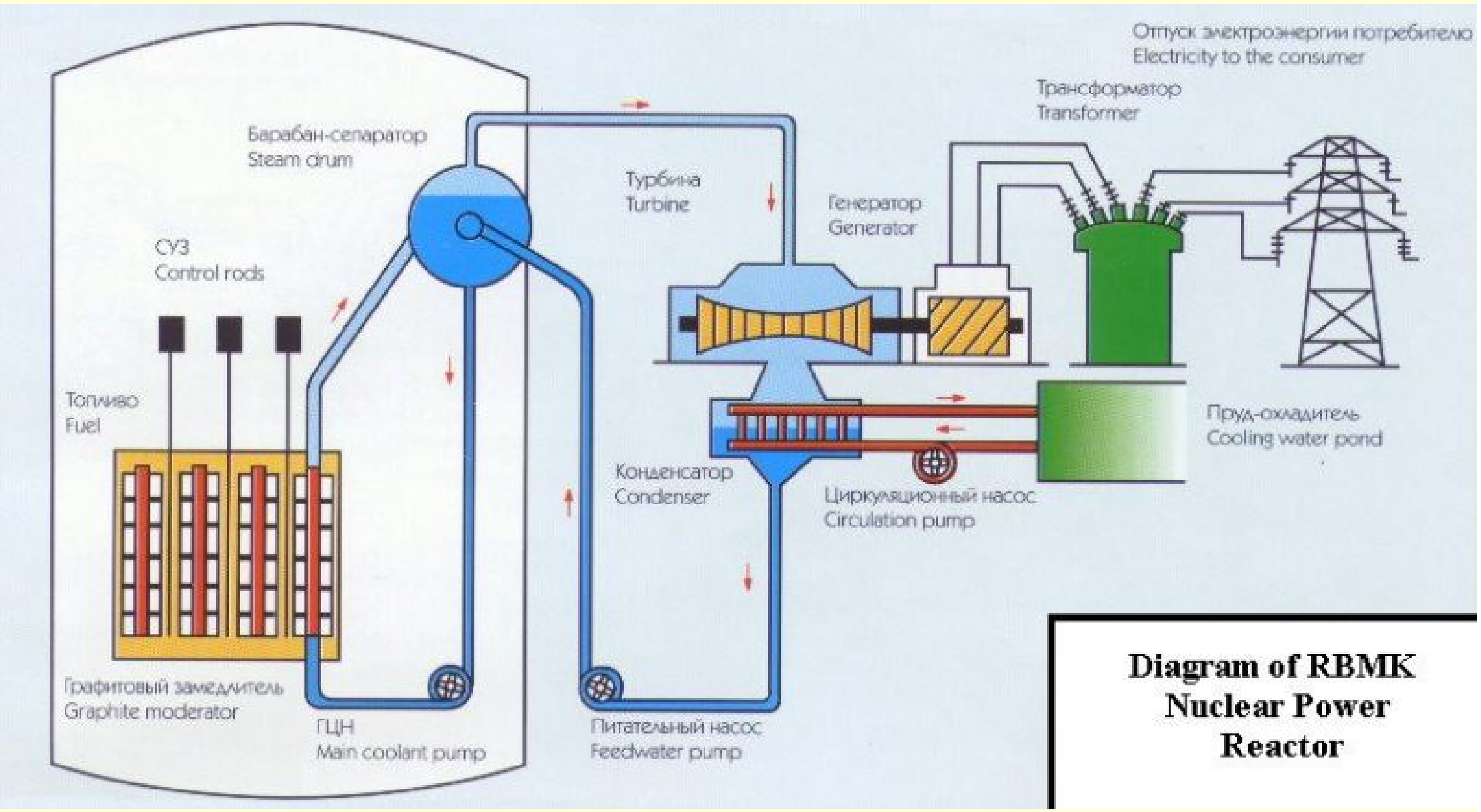
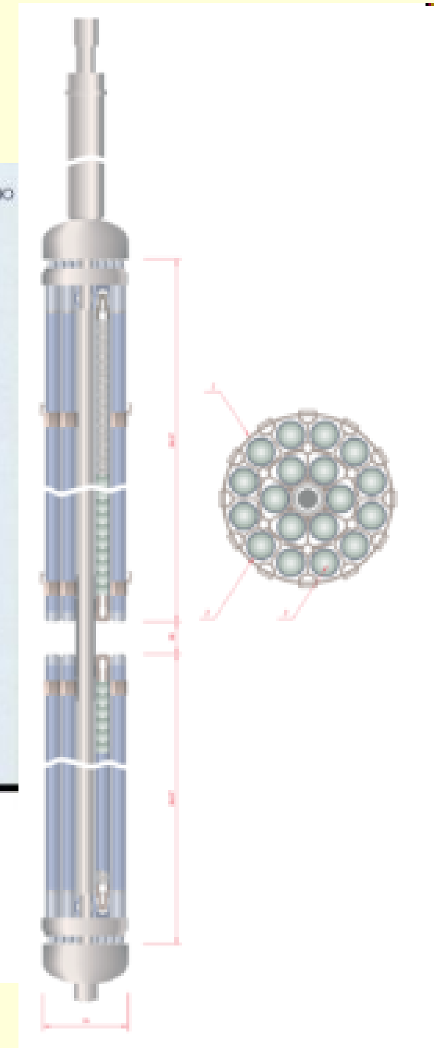


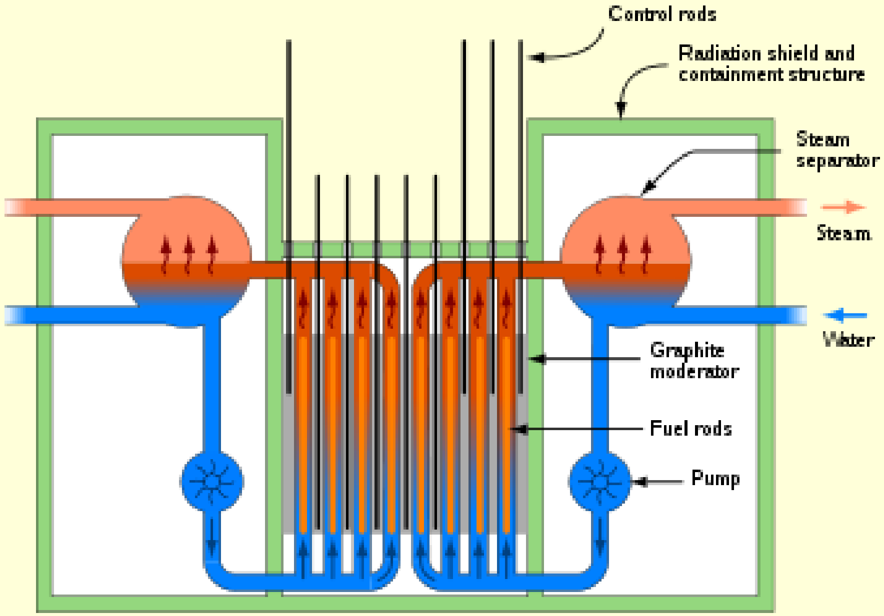
Diagram of RBMK Nuclear Power Reactor



Outlet Temperature 285 C
Power Density 5-8 kw/L

RBMK

- Graphite moderated, light water cooled
- Fuel in Zr pressure sleeves
- 2-3% enriched UO_2 fuel
- 18 built, 11 operating
  - No more will be build
- Positive void coefficient
- No or partial (after TMI) containment



RBMK: Chernobyl Accident

- Still uncertainties in cause and different versions of official reports exist
- Overview
  - Operating at low power to test system
  - Operators deviated from test procedures
  - RBMK reactors have inherent design flaws
    - Positive void coefficient
    - Control rods insert positive reactivity (graphite and water areas) before neutron poison is inserted
  - Nuclear reaction went out of control leading to steam explosions and fires
  - Hours required to extinguish fires

Reactor Deployment

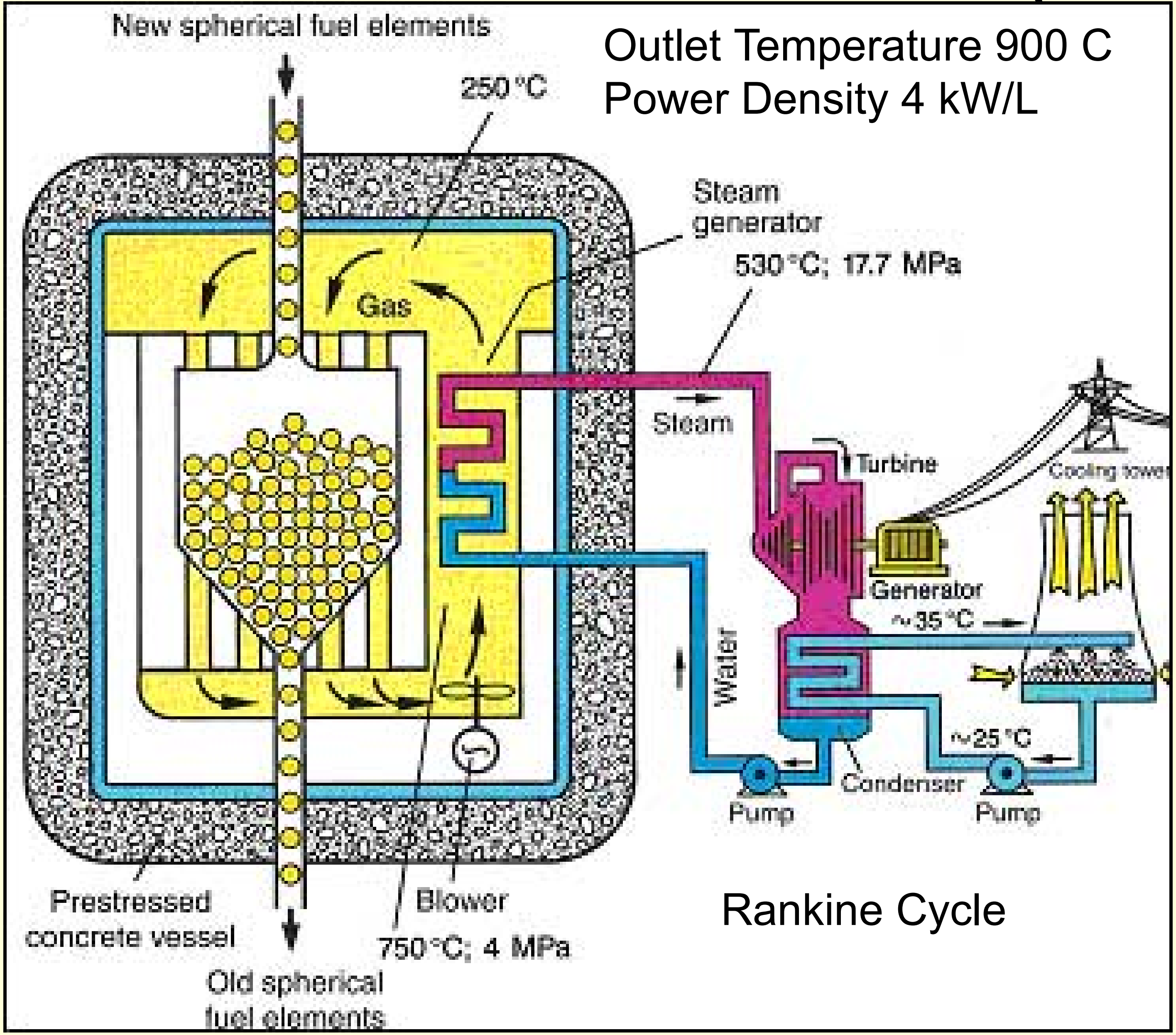
World Reactors

Region	Reactors in operation (2010)		Reactors under construction (2010)		Nuclear Power (2008)	
	Number	Net Capacity (MWe)	Number	Net Capacity (MWe)	Use (EJ)	% of country's electricity generation
North America	122	113,316	1	1,165	9.76	19.04
Latin America	6	4,119	2	1,937	0.32	2.38
Western Europe	129	122,956	2	3,200	8.97	26.68
Central and Eastern Europe	67	47,376	17	13,741	3.64	18.30
Africa	2	1,800	0	0	0.14	2.11
Middle East and South Asia	21	4,614	6	3,721	0.16	0.99
Far East	90	80,516	32	34,820	5.35	10.15
World	***441***	***374,697***	***60***	***58,584***	***28.34***	***14.03***

Backup Slides

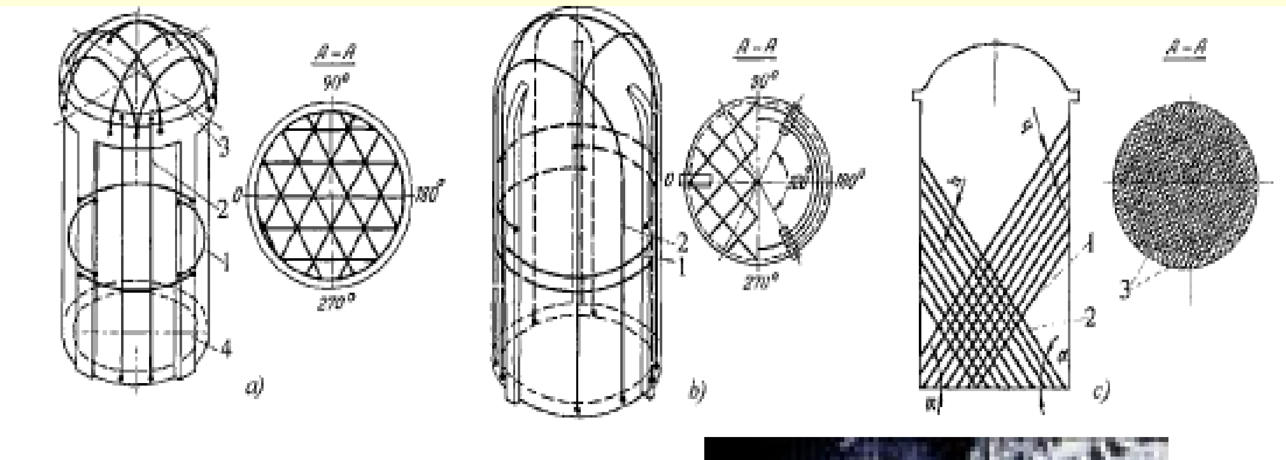
Pebble Bed Modular Reactor

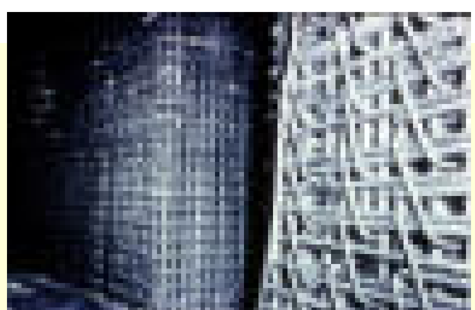
Pebble Bed Modular Reactor (PBMR)

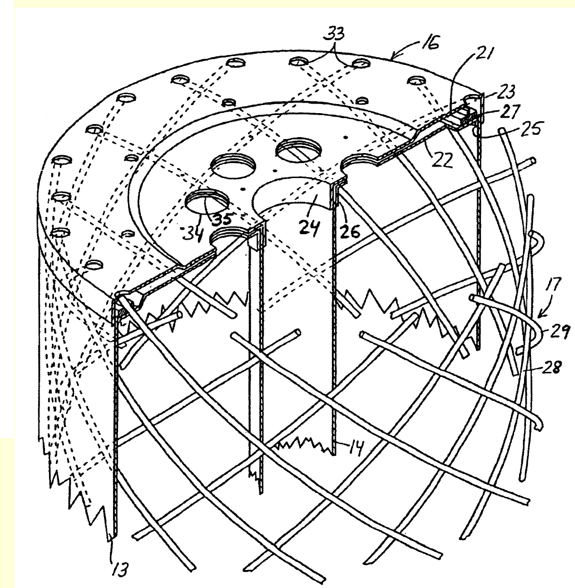


Pre-stressed Concrete Pressure Vessel (PCRV)

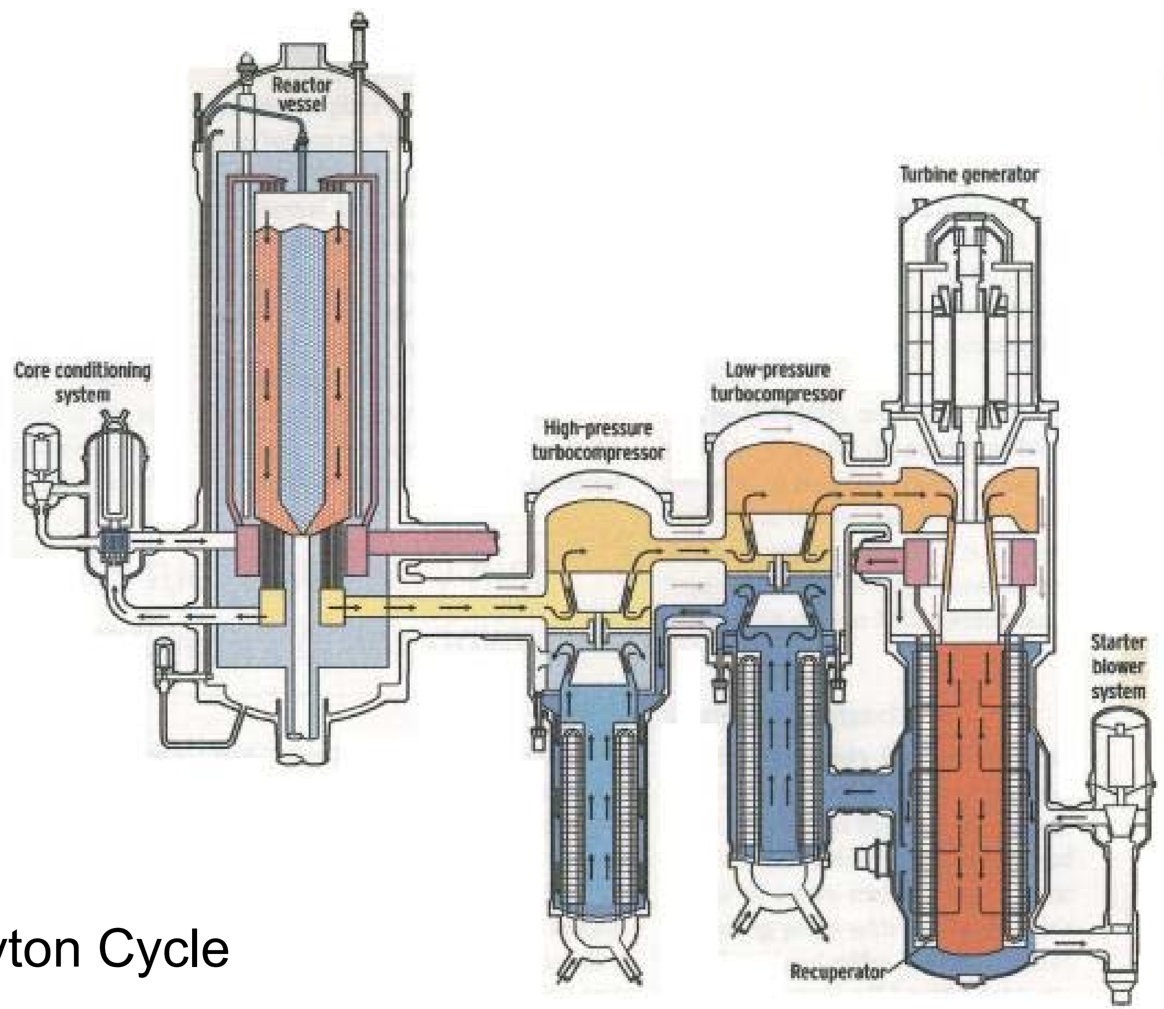
- Tension (stretch) steel cables in a form
- Pour concrete, cure; concrete bonds to cables
- De-tension cables → concrete compressed





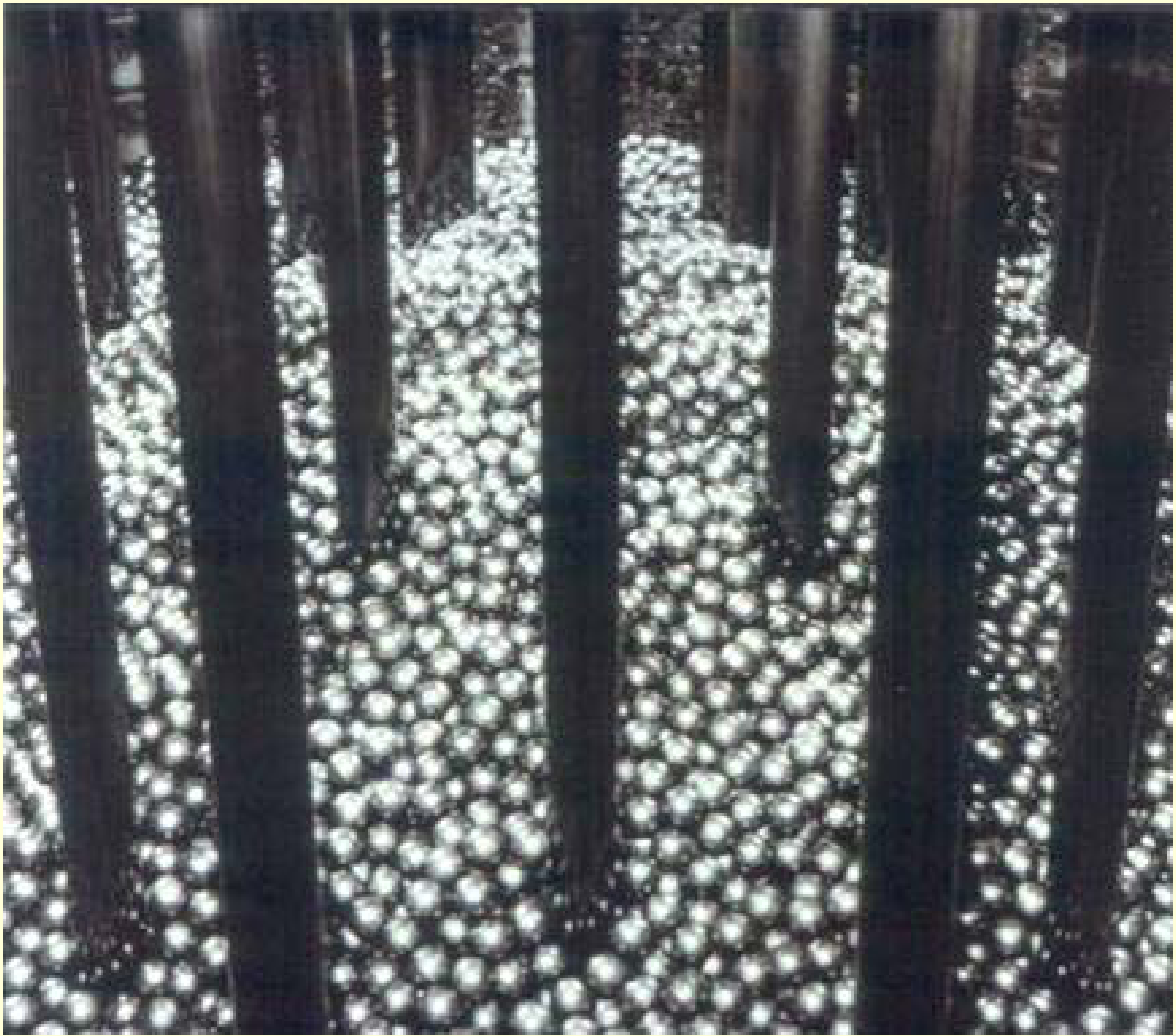


Pebble Bed Modular Reactor (PBMR)

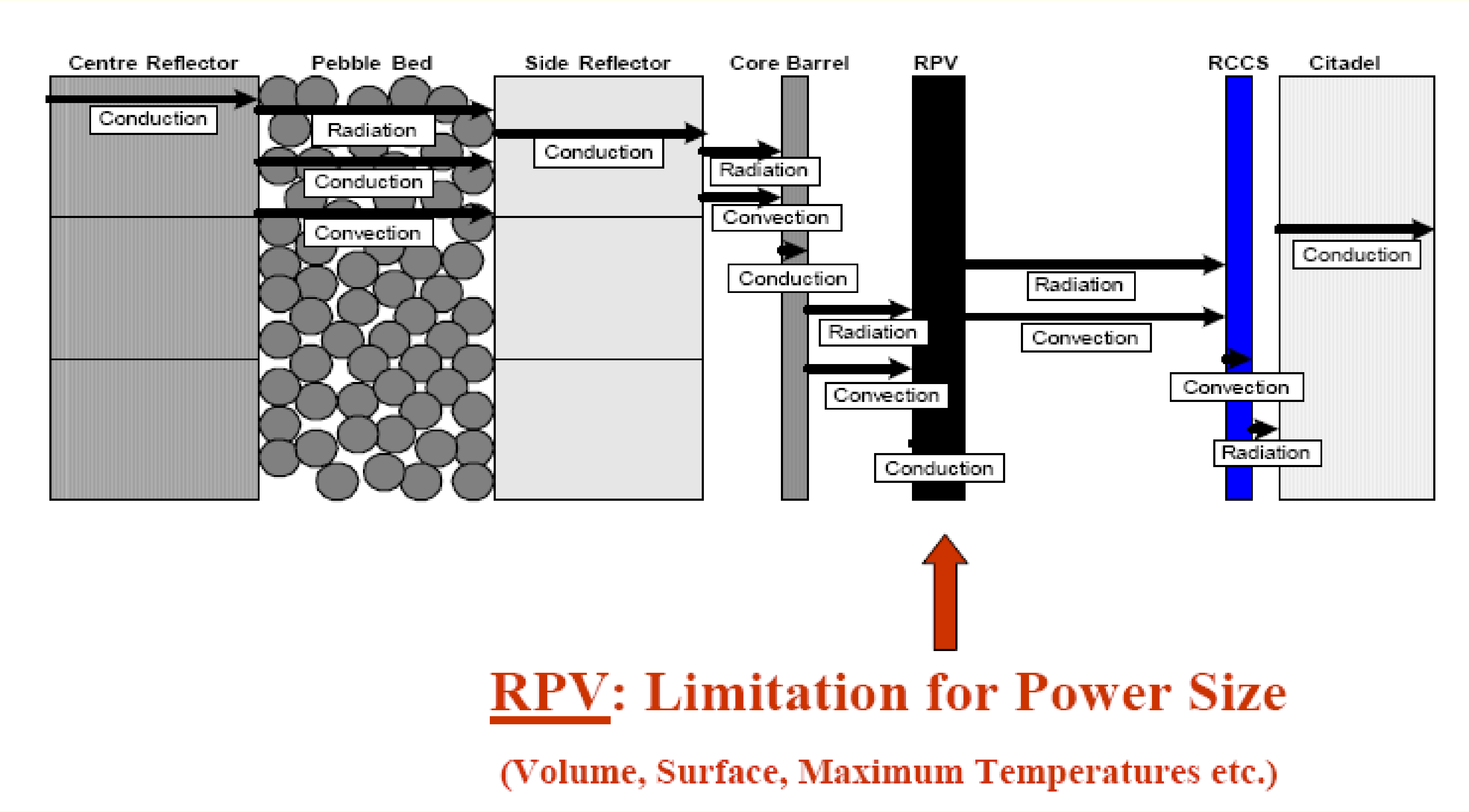


Brayton Cycle

Pebble VHTR Inside Reactor



Pebble VHTR Passive Heat Removal



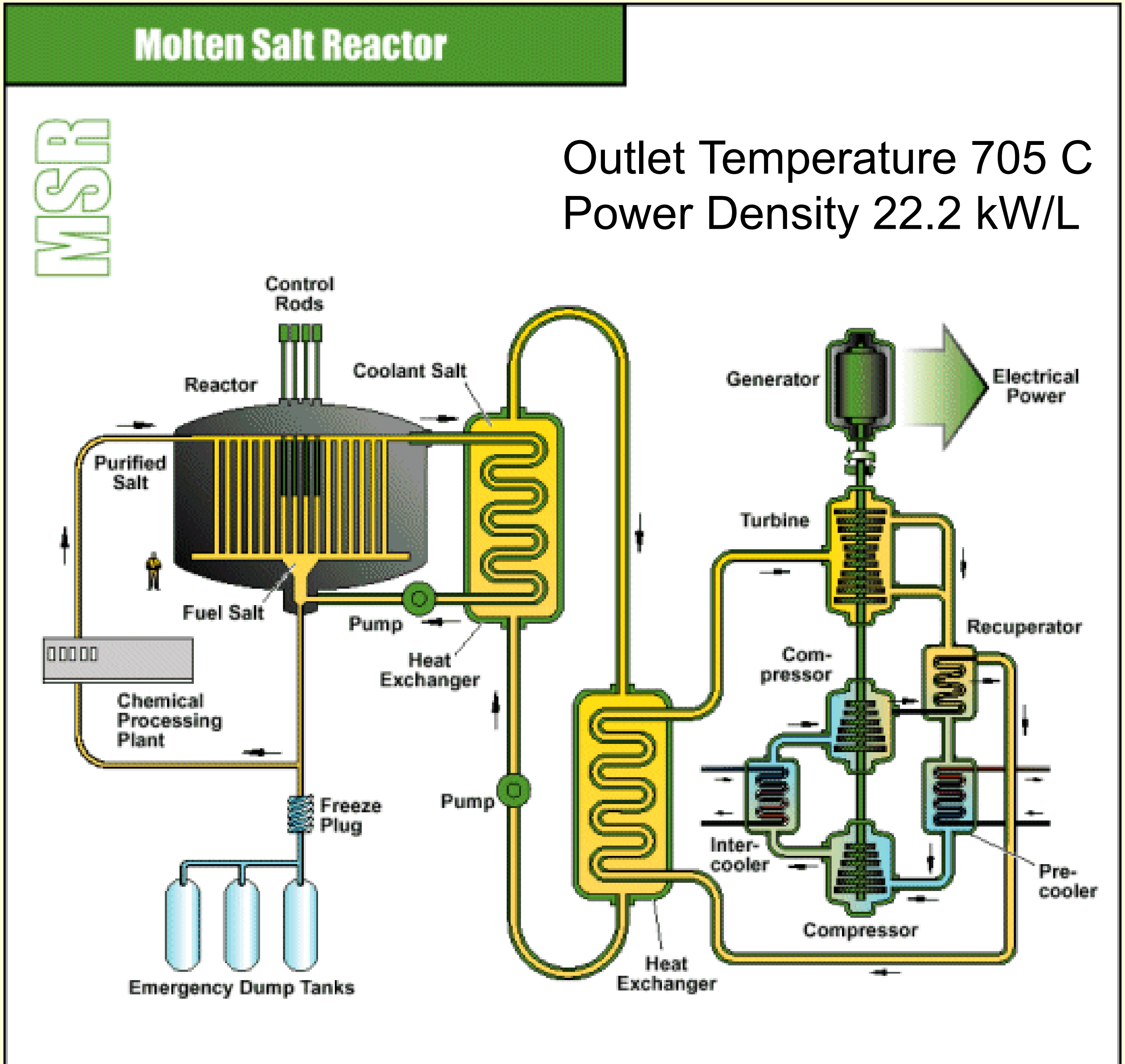
Pebble VHTR Features

- Being built by South Africa
- Passively safe
- As of early fall 2010 the South African government withdrew support for the PBMR
  - Prospects not good

Graphite Moderated

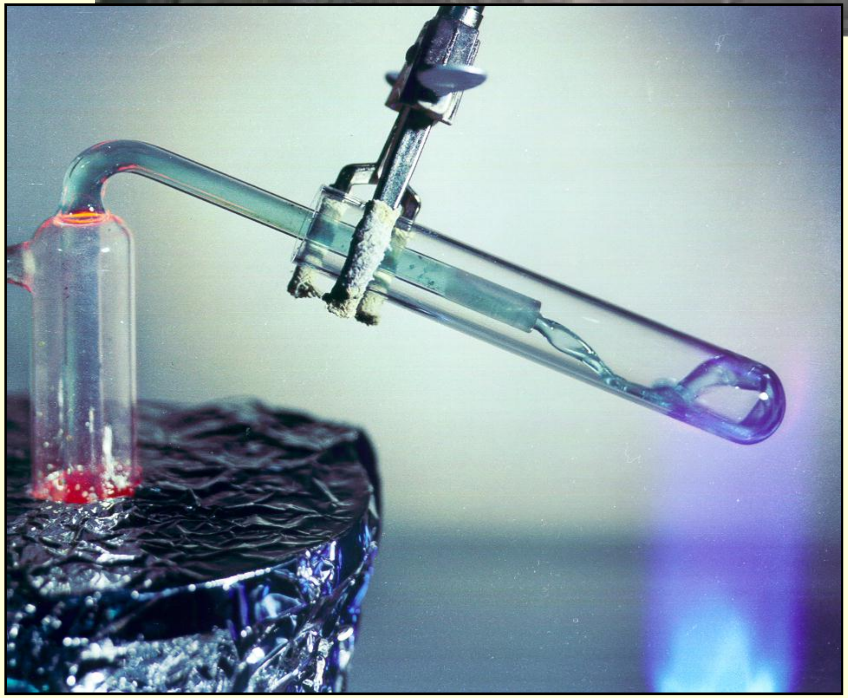
Molten Salt Cooled

Molten Salt Reactor (MSR)



MSR Salt

- Salt is typically mixture of Li-Be-Th-U fluorides
  - mp ~325 C, bp ~1400 C
  - Stable to radiation and air
  - Good heat transfer
  - Not inherently corrosive
  - Low pressure
- Fuel dissolved in salt as are fission and activation products
  - Mix is somewhat corrosive
- Can use online fuel/salt reprocessing



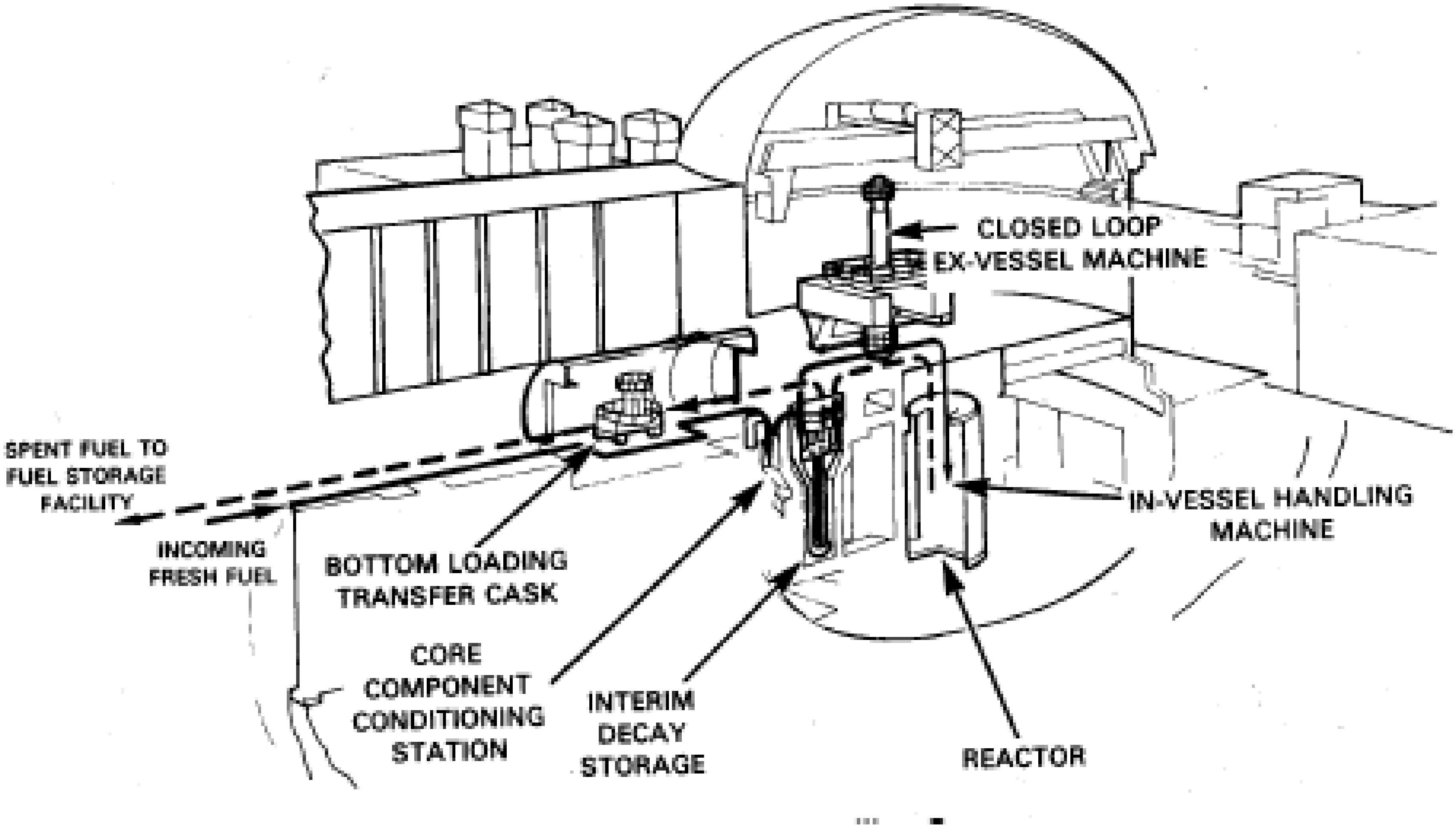
MSR Features

- Passively safe, atmospheric pressure
  - Old approach: freeze plugs draining to critically safe and passively cooled dump tanks
  - New approach: Heat transfer through walls and passive heat removal
    - Similar to VHTR
- Can be a breeder on the thorium fuel cycle
- Molten Salt Reactor Experiment was operated at ORNL
- GEN IV reactor but low priority: mostly academic studies
  - Materials are key issue

Fast (Unmoderated) Reactors

Sodium Cooled

SFR Refueling Sequence



SFR External Refueling Machine

Fast Reactors

Metal Cooled Except Na

Alkali Metals

- Lithium
  - Advantage: Low vapor pressure
  - Disadvantage: Expensive, high cross section, produces tritium
- NaK
  - Advantage: melting point below room temperature
  - Disadvantage: Poorer heat transfer, more expensive
  - Used in EBR-I and space power sources

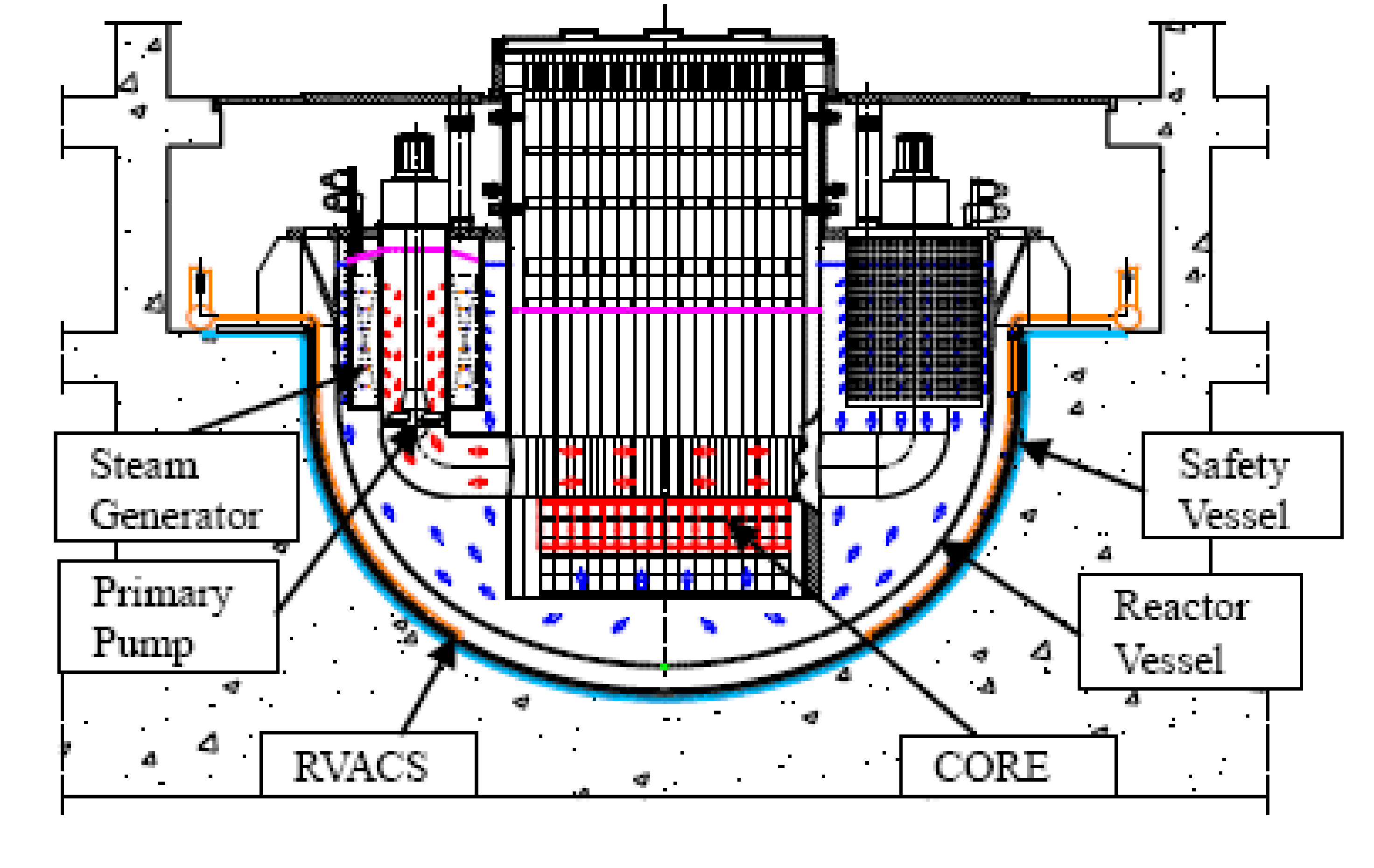
Heavy Metal: Hg and Pb/Bi

- Mercury
  - Advantage: None for power reactors
  - Disadvantages: Toxic, high cross section, high vapor pressure
- Lead-bismuth eutectic
  - Advantages: 200 C lower melting point than lead, more compatible with water than alkali metals
  - Disadvantages: Produces highly toxic and mobile Po^{210}, more corrosive than lead
  - Has been used in Russian submarine reactors

Lead-Cooled Fast Reactor (LCFR)

- European Lead System (ELSY)
- GEN IV, low priority

Outlet Temperature: 480 C



ELSY

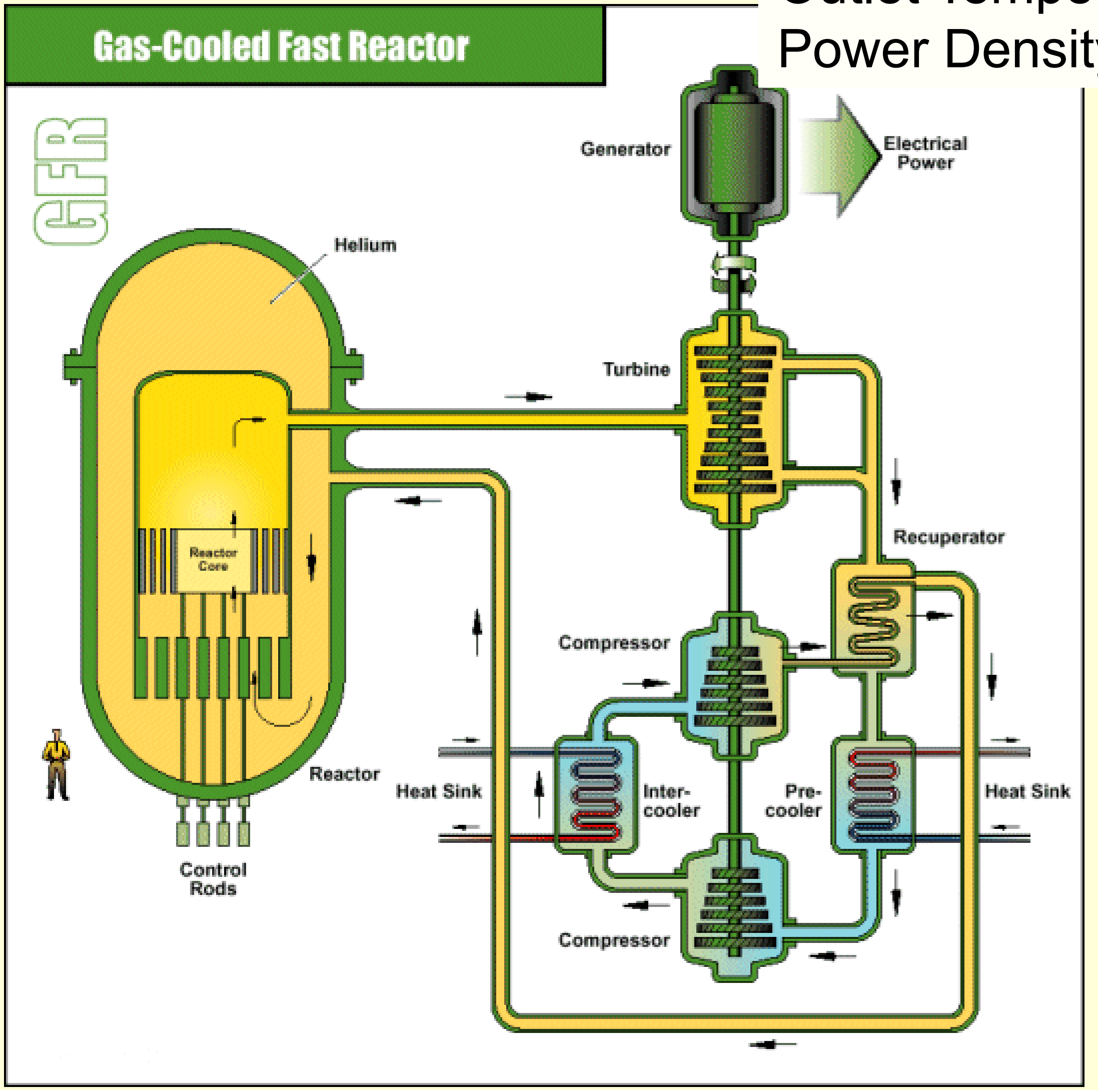
- Being developed by a consortium of European countries led by Euratom
  - Lead country unclear; Russia?
- Passively safe
- Little interest in the U.S.
- Major issue is finding compatible materials with lead at ~480 C

Fast Reactors

Gas Cooled

Gas-Cooled Fast Reactor (GCFR)

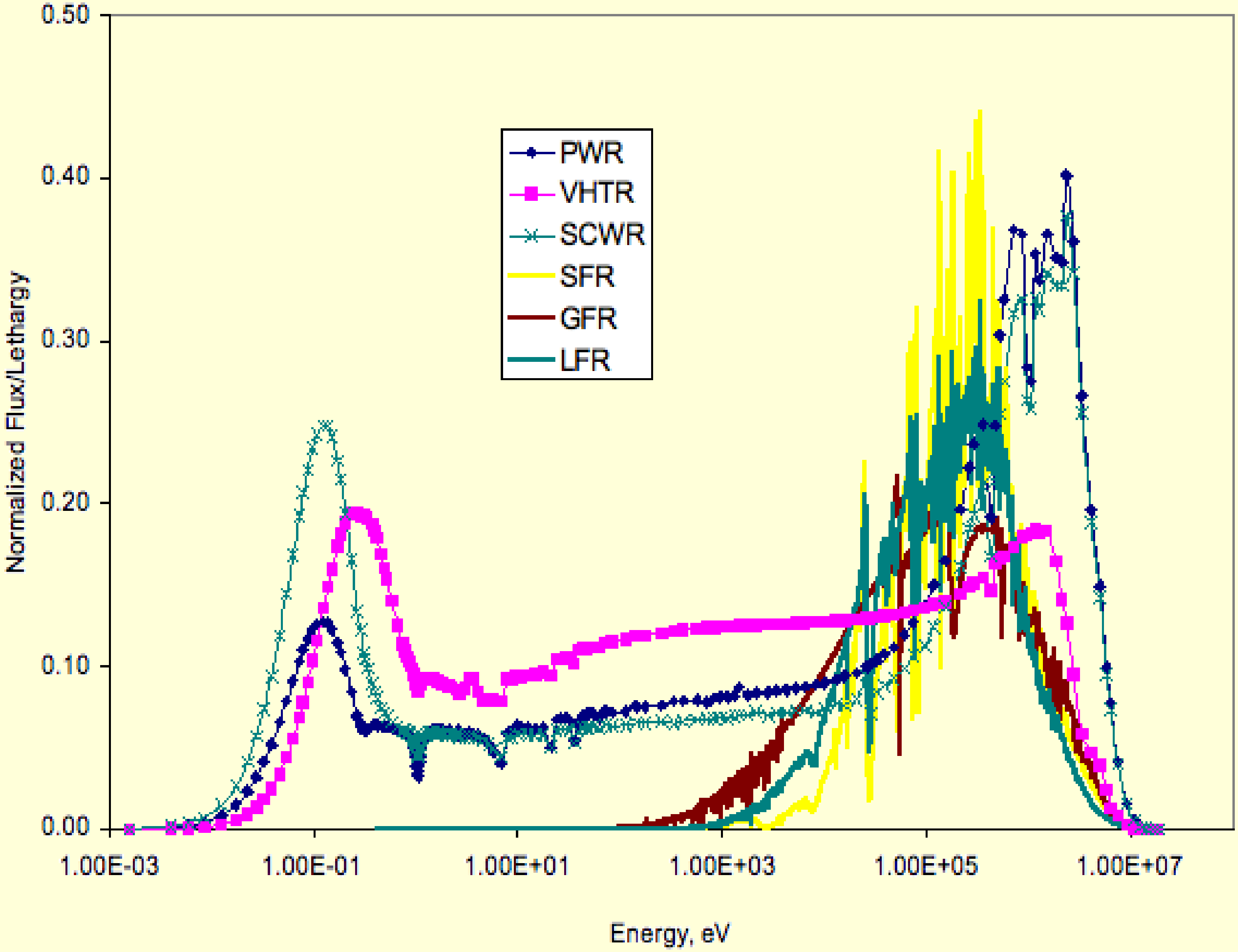
Outlet Temperature 850 C
Power Density ~100 kW/L



GCFR

- Essentially a VHTR using fuel pellets and assemblies instead of blocks or pebbles
- Low-priority GEN IV system
- Issues
  - 850 C (1560 F) outlet temperature and pressure (~10,000 psi) are very high
  - Materials for pressure vessel, equipment, and clad: ceramics?
  - Decay heat removal at shutdown and in accidents: low thermal inertia, He heat transfer properties not good relative to others
- Viability uncertain

GEN IV Reactor Neutron Spectra



Small Modular Reactors

SMRs

Name	Capacity	Type	Developer
KLT-40S	35 MWe	PWR	OKBM, Russia
VK-300	300 MWe	PWR	Atomenergoproekt, Russia
CAREM	27 MWe	PWR	CNEA & INVAP, Argentina
NHR-200	200 MWt	PWR	INET, China
IRIS	100-335 MWe	PWR	Westinghouse-led, international
mPower	125 MWe	PWR	Babcock & Wilcox, USA
SMART	330 MWt	PWR	KAERI, South Korea
NuScale	45 MWe	PWR	NuScale Power, USA
MRX	30-100 MWe	PWR	JAERI, Japan
HTR-PM	2x250 MWt	HTR	INET & Huaneng, China
PBMR	200 MWt	HTR	Eskom, South Africa
GT-MHR	285 MWe	HTR	General Atomics (USA), Minatom (Russia)
BREST	300 MWe	LMR	RDIPE, Russia
SVBR-100	100 MWe	LMR	Rosatom/En+, Russia
FUJI	100 MWe	MSR	ITHMSO, Japan-Russia-USA

VHTR (NGNP) can also be built as a small reactor
For more see http://www.world-nuclear.org/info/inf33.html

More SMRs

		CAREM	ENHS	IRIS-50	KLT-40	MRX	MSBWR	RS-MHR	TPS	4S
Designer		CNEA	UCB	W	OKBM	JAERI	GE/ Purdue U.	GA	GA	CRIEPI
Type		Integral PWR	LMR	Integral PWR	PWR	Integral PWR	BWR	HTGR	PWR	LMR
Rating		25 MWe	50 MWe	50 MWe	35 MWe	30 MWe	50 MWe	10 MWe	16.4 MWe	50 MWe
Primary System Pressure		12.3 MPa	N/A	-	13 MPa	12 MPa	-	-	3 MPa	N/A
Reactor Vessel	Height	11 m	19.6 m	14-16 m	3.9 m	9.4 m	8.5 m	8 m	11.6 m	23 m
	Diameter	3.1 m	3.2 m	3.5 m	2.2 m	3.7 m	3.5 m	3.4 m	2.8 m	2.5 m
Reactor Core	Height	1.4 m	1.25 m	1.8 m	0.95 m	1.4 m	1.9 m	3.6 m	1 m	4 m
	Diameter	1.3 m	2 m	1.5 m	1.2 m	1.5 m	3.1 m	3 m	1 m	0.8 m
Avg. Power Density*		55 kW/l	6 kW/m	13 kW/m	155 kW/l	42 kW/l	8.3 kW/m	4 kW/l	95 kW/l	61 kW/l
Fuel/Type		UO_2 pins	U-Zr metal	UO_2 pins	U-Al alloy	UO_2 pins	UO_2 pins	UO_2 particles	UZrH pins	U-Zr metal
Fuel Enrichment		3.4 %	13 %	4.95 %	-	4.3%	5 %	19.9%	19.9%	~15 %
Refueling Frequency (Percent Replaced)		~ 1 year (50%)	15 years (100 %)	5-9 years	2-3 years (100%)	~ 4 years (50%)	10 years	6-8 years	1.5 years (50%)	10 years (100%)
Coolant flow rate		410 kg/s	0.51 m/s	-	722 kg/s	1250 kg/s	620 kg/s	-	419 kg/s	633 kg/s
Core Inlet Temperature		284 °C	400 °C	-	278 °C	283 °C	279 °C	500 °C	182 °C	355 °C
Core Outlet Temperature		326 °C	550 °C	-	318 °C	298 °C	14.3% quality†	850 °C	216 °C	510 °C

* the amount of power generated in a given volume of the reactor core kW per liter, or power in a given length kW per meter.

† BWRs measure performance in terms of steam quality (percent by weight of vapor versus liquid) at the core outlet

"-"= Not Provided

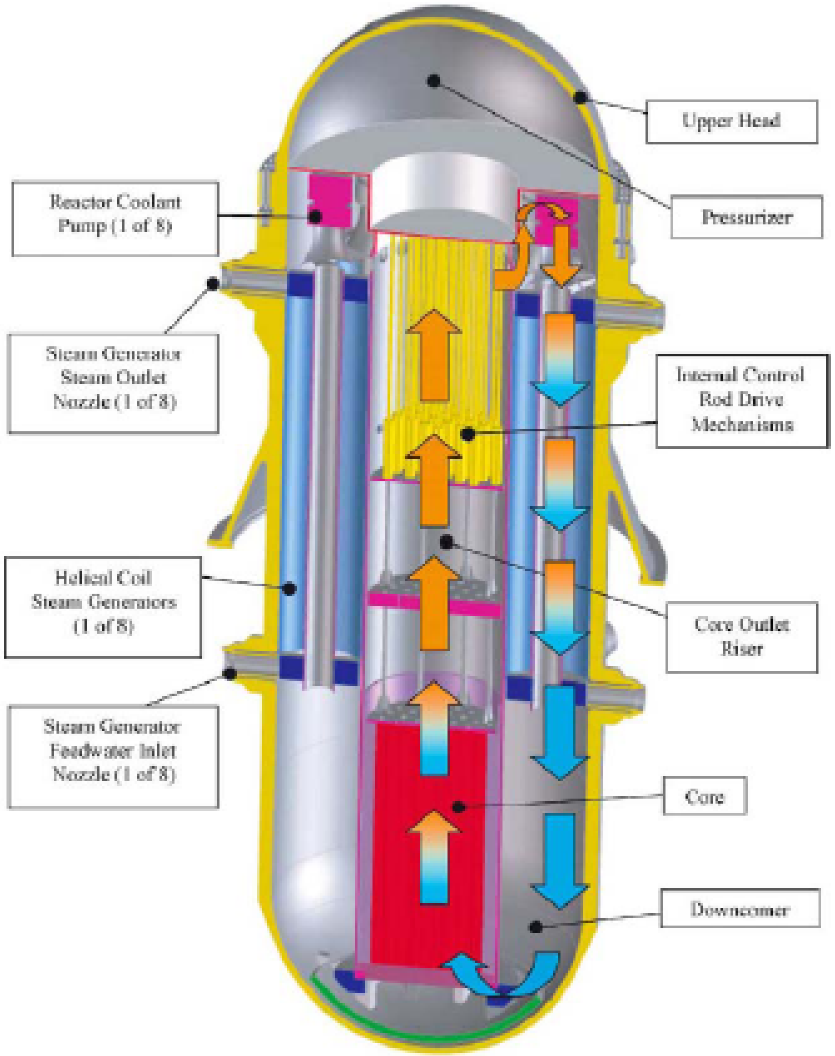
International Reactor Innovative Secure (IRIS) PWR

- **Vendor:** Westinghouse
- **Reactor Power:** 1000 MWt
- **Electrical Output:** 335 MWe
- **Coolant:** Light water
- **Outlet Temperature:** 327°C
- **Fuel Design:** 17 x 17 assemblies
  - 4.95% enrichment UO2
- **Refueling:** 3 – 3.5 years
- **Application:** Late 2012
- **Reference:** ML081270251

Can be scaled down to 100 MWe

Forced circulation in operation

Integral steam generator



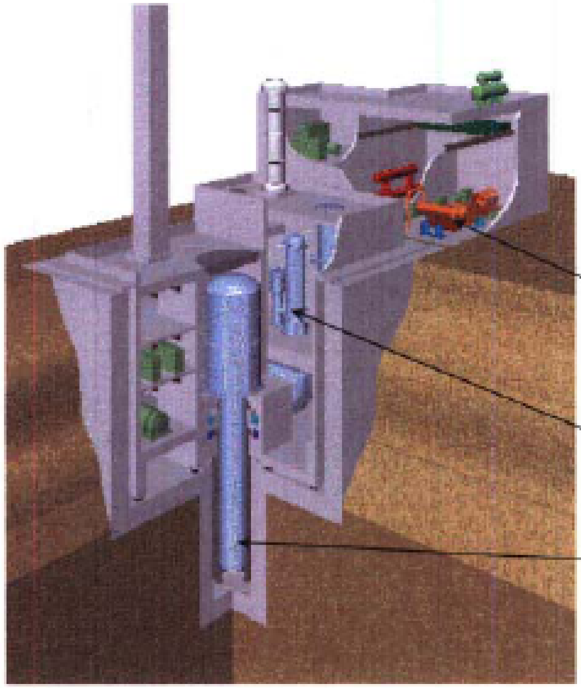
Hyperion LMR

Reactor Power	70MW thermal
Electrical Output	25MW electric
Lifetime	8 – 10 years
Size (meters)	1.5w x 2.5h
Weight (ton)	Less than 50
Structural Material	Stainless Steel
Coolant	PbBi
Fuel	Stainless clad, uranium nitride
Enrichment (% U-235)	<20%
Refuel on Site	No
Sealed Core	Yes
License	Design Certification
Passive Shutdown	Yes
Active Shutdown	Yes
Transportable	Yes – intact core
Factory Fueled	Yes

Quartz neutron reflector

Super-Safe, Small, and Simple (4S)

- **Vendor:** Toshiba
- **Reactor Power:** 30 MWt
- **Electrical Output:** 10 MWe
- **Coolant:** Liquid- Metal (Sodium)
- **Outlet Temperature:** 510^{o}C
- **Fuel Design:** Hexagonal fuel assemblies
  - U-10%Zr Alloy
- **Refueling:** 30 years
- **Application:** Late 2009
- **Reference:** ML072950025

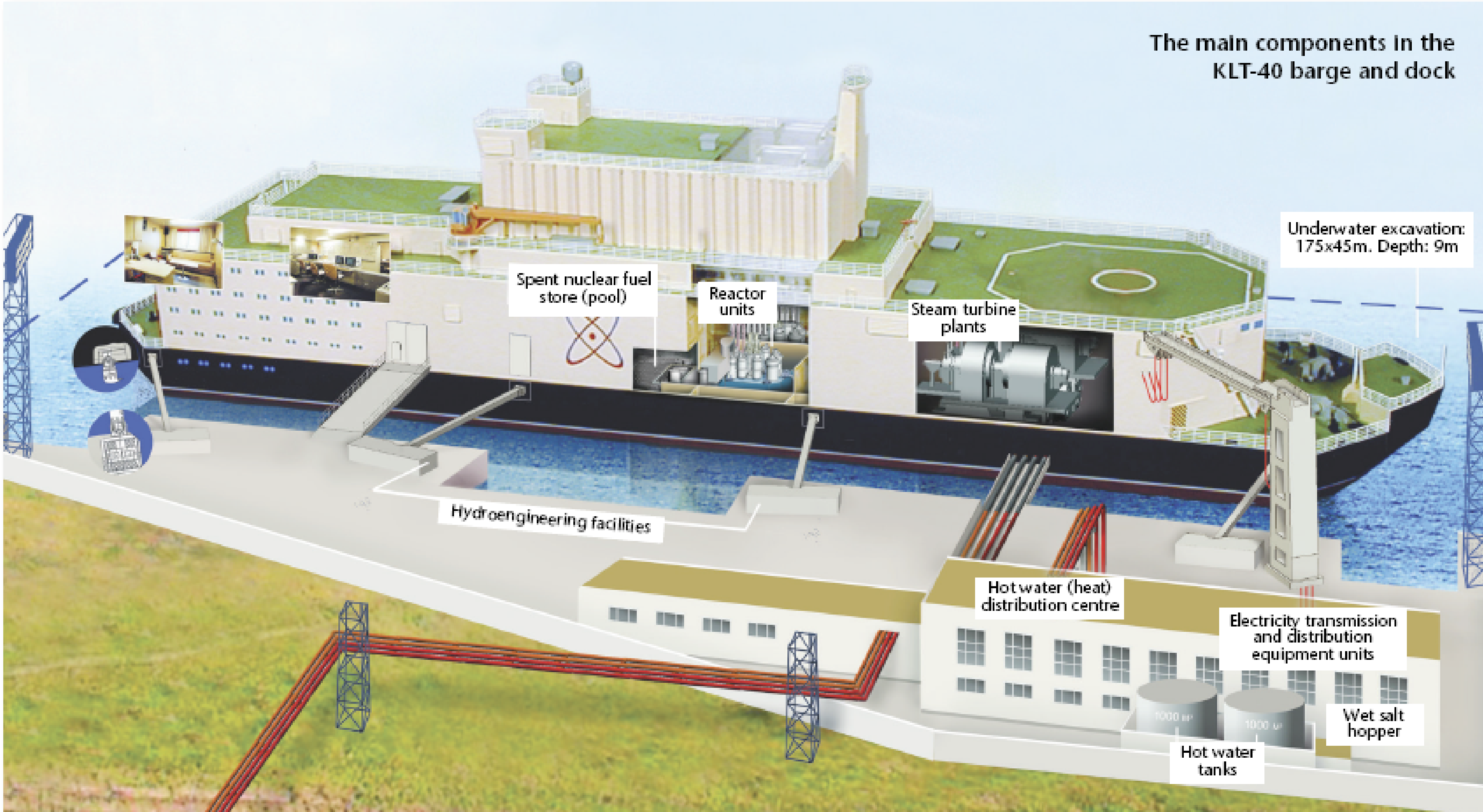


Reflector moves down core at 1 mm/week

After 14 y a neutron absorber in the center of the core is removed & the process is repeated

Example of a "traveling wave reactor"; also called a "nuclear battery"

Russia: KLT-40S PWR



Two reactors on one barge

Russia: KLT-40S PWR

- Based on icebreaker reactor design
  - _ Natural convection cooling
  - _ Prototype due to be completed next year

Main data for the KLT-40S reactor

Reactor type	Pressurised-water, with vessel
Thermal power (MWt)	150
Electric power (MWe)	35 (with 25 Gcal/h of low-grade heat output); 19.4 (with max thermal power output, 73 Gcal/h)
Number of fuel assemblies	121
Refuelling interval (years)	2.3 (prototype) 3.5 (serial production)
Primary circuit pressure (MPa)	12.7
Primary circuit temperature at core outlet/inlet (°C)	316/280
Steam output (t/h)	240
Superheated steam pressure at steam generator outlet (MPa)	3.72
Superheated steam temp. at SG outlet (°C)	290

KLT-40S core characteristics

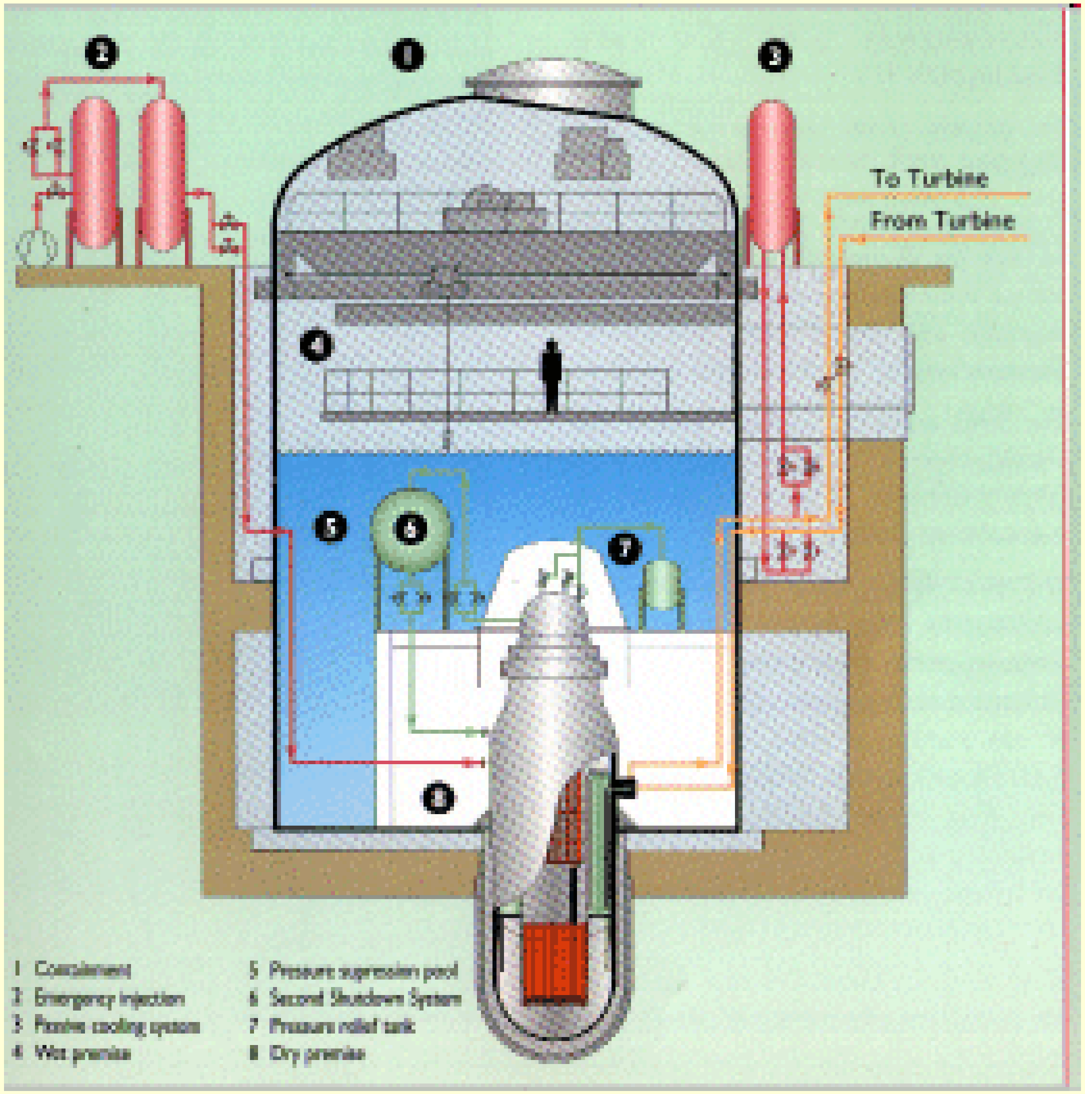
Energy supply per core load (TWh)	2.1
Service life (h)	21,000
Campaign duration (years)	2.3
Core height (mm)	1200
Core diameter (mm)	1219
Specific fuel rating (kW/l)	119
Maximum fuel enrichment (%)	15.7
U235 charge (kg)	179.2
Uranium charge (kg)	1273
Number of fuel elements in the core	8673 (in 121 assemblies)
Maximum fission fragment density in the fuel (g/cm^3)	0.72
Maximum fast neutron fluence with E>0.1MeV (m^{-2})	1.4×10^{26}
Average unloaded fuel burn-up for ceramic fuel (MWday/kgU)	46

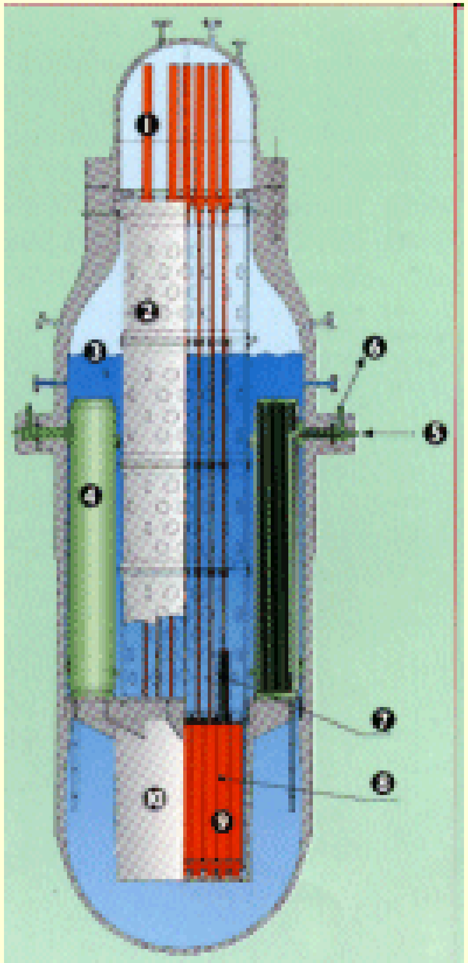
Fuel form unknown, perhaps U-Zr alloy

Other Russian SMRs

- All do or can involve co-generation
- RITM-200: Replacement for KLT-40S
  - 210 MWt, 55 MWe, one reactor per barge
  - Internal steam generators
  - Passive safety features
- VBER-150, 300: Larger barge mounted units
  - Based on VVER (fairly standard PWR) technology
- VK-300
  - 110 MWe plus steam

CAREM PWR


To Turbine
From Turbine
1 Containment
2 Emergency injection
3 Passive cooling system
4 Wet premise
5 Pressure supression pool
6 Second Shutdown System
7 Pressure relief tank
8 Dry premise



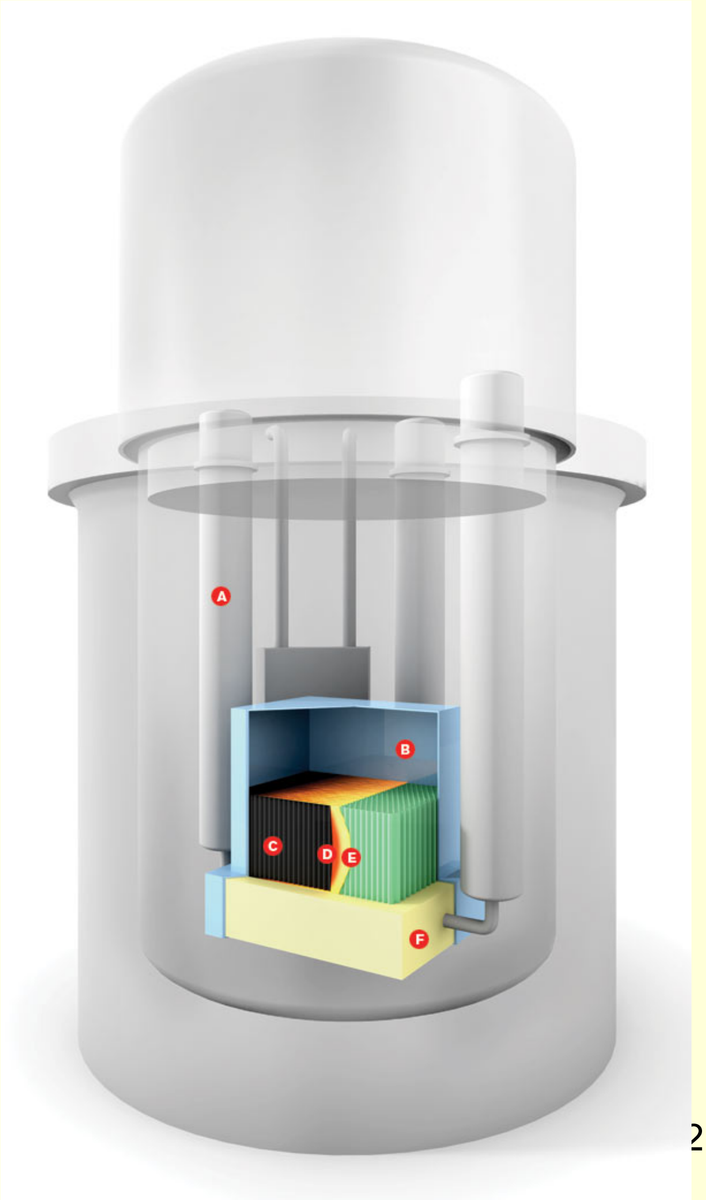
CAREM PWR

- Designed by INVAP (Argentina)
- 100 MWt, 25 MWe
- Cooling: Natural
- Integral steam generators
- Low enriched uranium dioxide fuel
  - Gadolinia burnable poison

Traveling Wave Reactor

- A: Coolant (Na) pumps
- B: Gas expansion area
- C: Depleted uranium metal fuel (black spent, green unburned)
- D: Fission wave (red)
- E: Breeding wave (yellow)
- F: Liquid sodium coolant (core temp high: 550 C)
- Claim up to 60y of operation

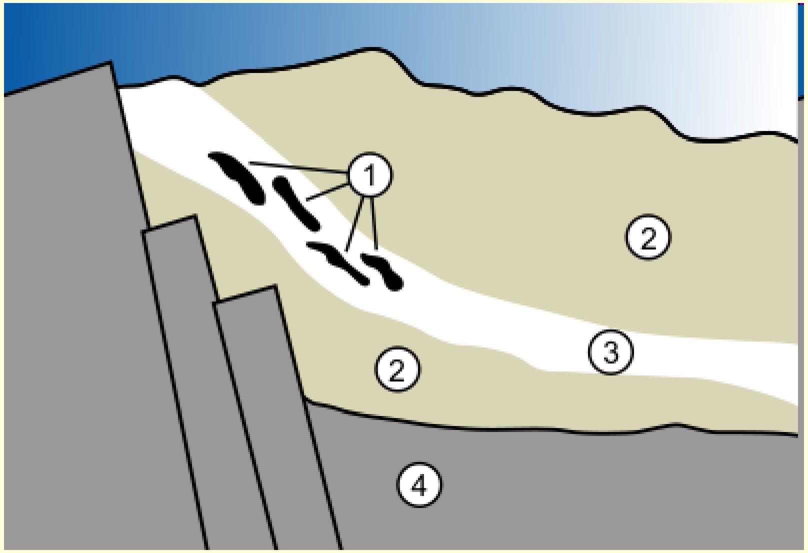
Being developed by TerraPower as a private venture



Legacy Reactors

Ultimate Legacy Reactor: Oklo

- French U mine in Gabon (1.8 GY old) found abnormally low ^{235}U content (0.44% vs 0.71%)
- Analysis found remnants of fission products
- Explanation
  - Uranium concentrations were high
  - ~100MY ago the ^{235}U concentration was ~3%
  - Water entered and the ore deposit was periodically critical



Oklo geological situation
1. Nuclear reactor zones
2. Sandstone
3. Uranium ore layer
4. Granite

Chicago Pile 1

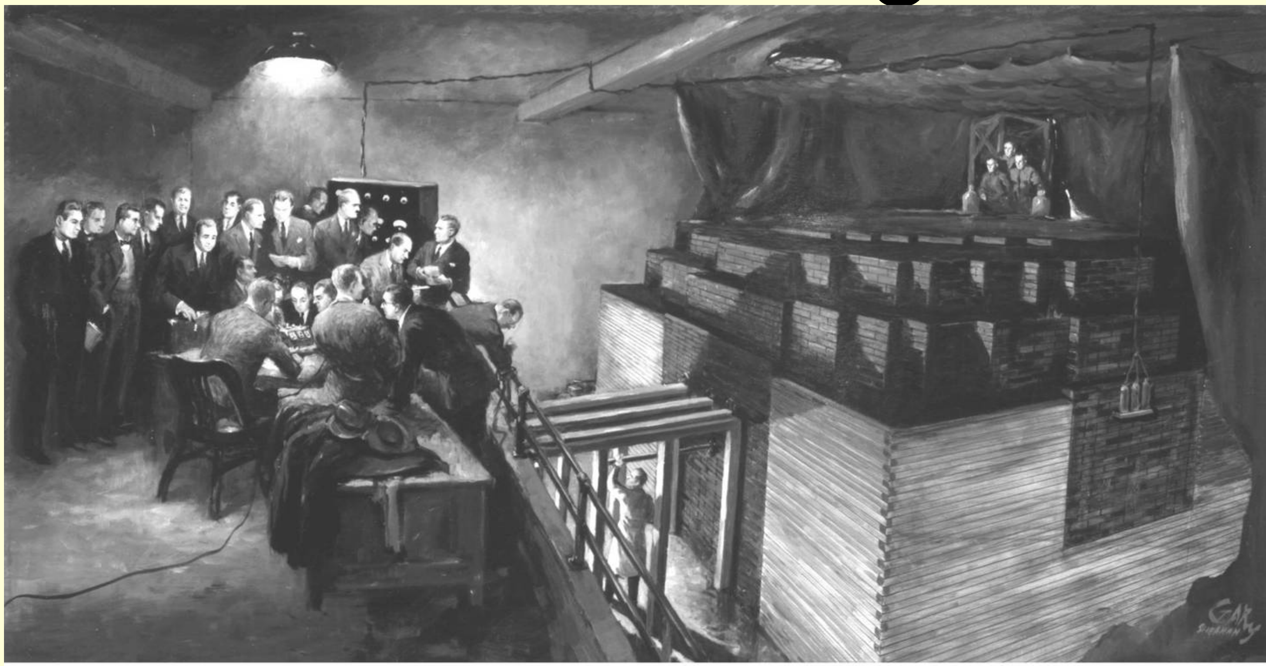
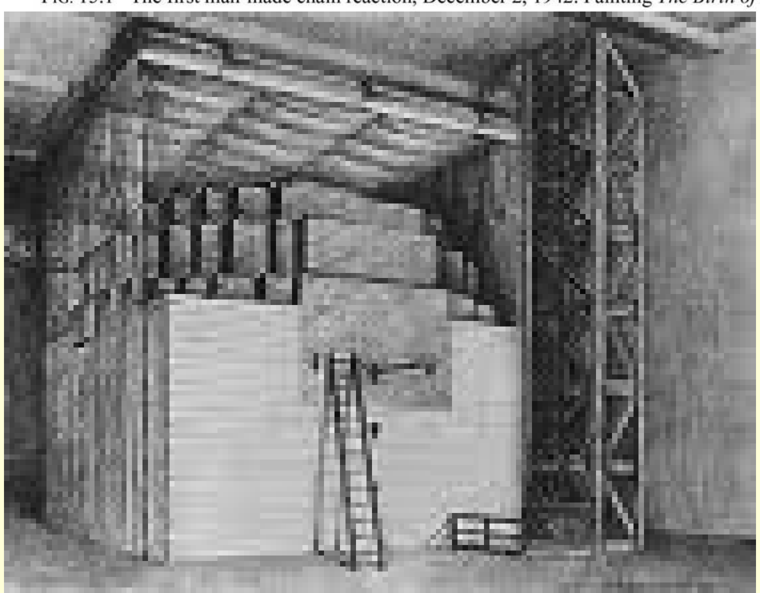


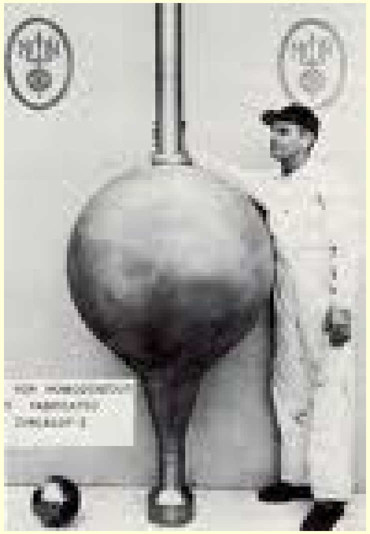
FIG. 15.1 The first man-made chain reaction, December 2, 1942. Painting *The Birth of the Atomic Age* by Gary Sheahan,



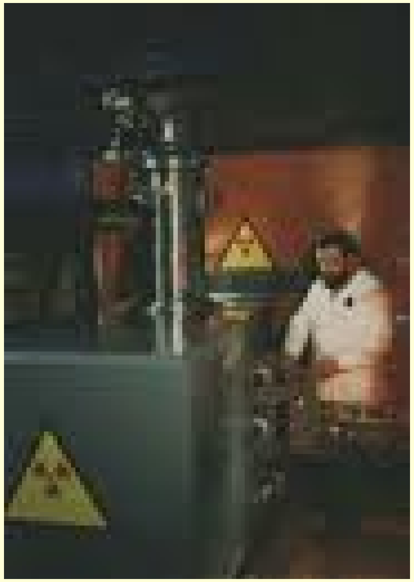
SCRAM = Safety Control Rod Axe Man?

Aqueous Homogeneous Reactor

- Dissolve fuel in aqueous acid: sulfuric, nitric
- HRE: 1 MWt, made power
  - Sulfuric acid
  - Critical in the bulge
  - Vessel corroded through
- ARGUS: 20 kWt
  - Sulfuric acid
  - Used for isotope production
- B&W: Proposed
  - Acid system unknown
  - Produce Mo-99 for medicine



Homogeneous Reactor Experiment



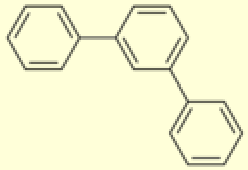
ARGUS

B&W Isotope Production Reactor

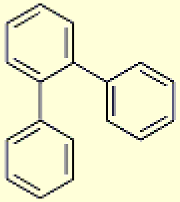
Organic-Cooled Reactors

- Organic coolant moderator
  - Advantages
    - Good moderating properties
    - Low vapor pressure
  - Disadvantages
    - Radiolytic/thermal instability
    - Poor heat transfer
- Reactors
  - Piqua, OH: 45 MWe
    - Organic degradation forced closure
  - Canada: 60 MWe, heavy water moderated, organic cooled
- No current interest

Terphenyls



Meta

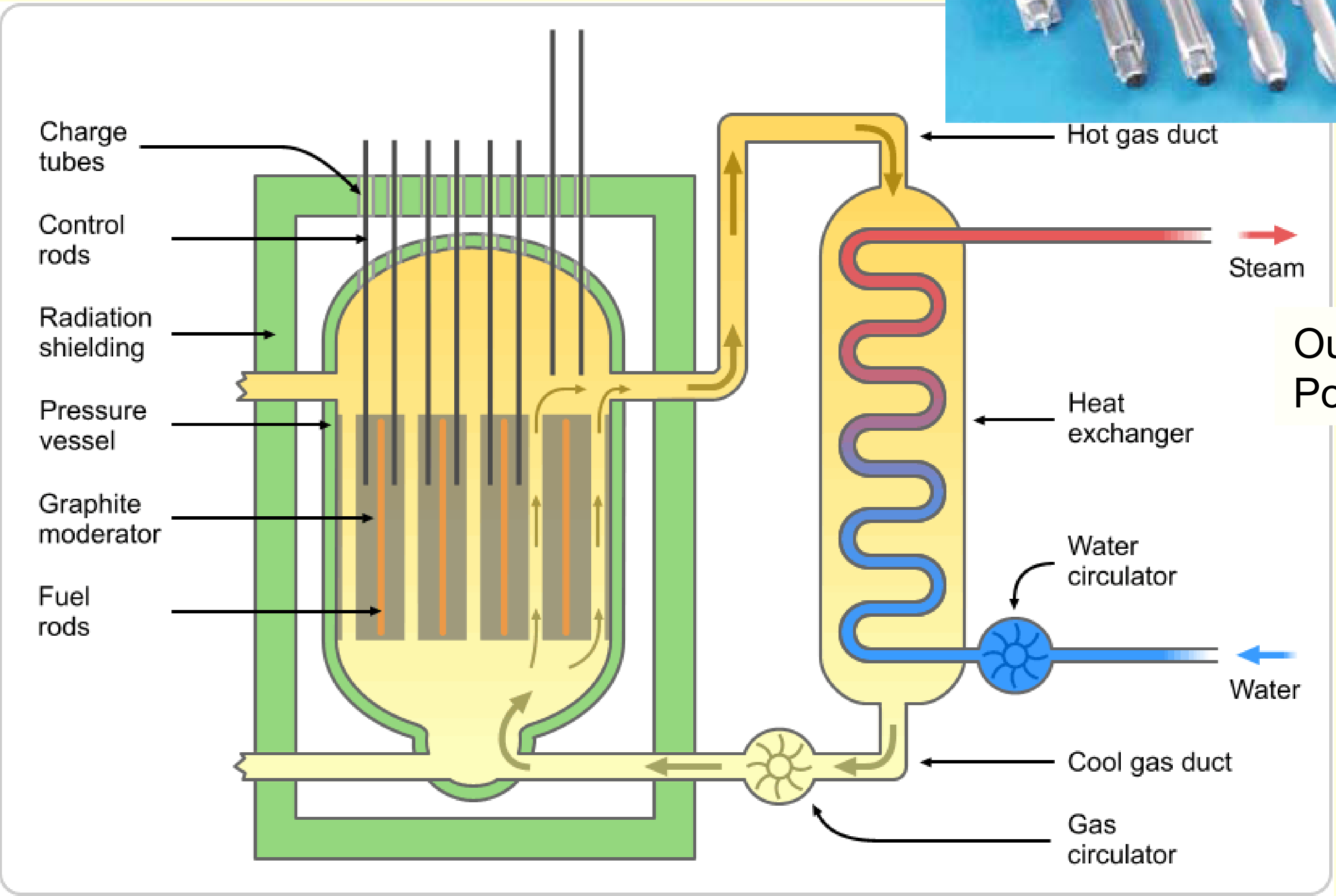


Ortho

Para

Magnesium Non-Oxidizing Reactor

- MAGNOX reactor



Outlet Temperature 350-400C
Power Density <1 kW/L

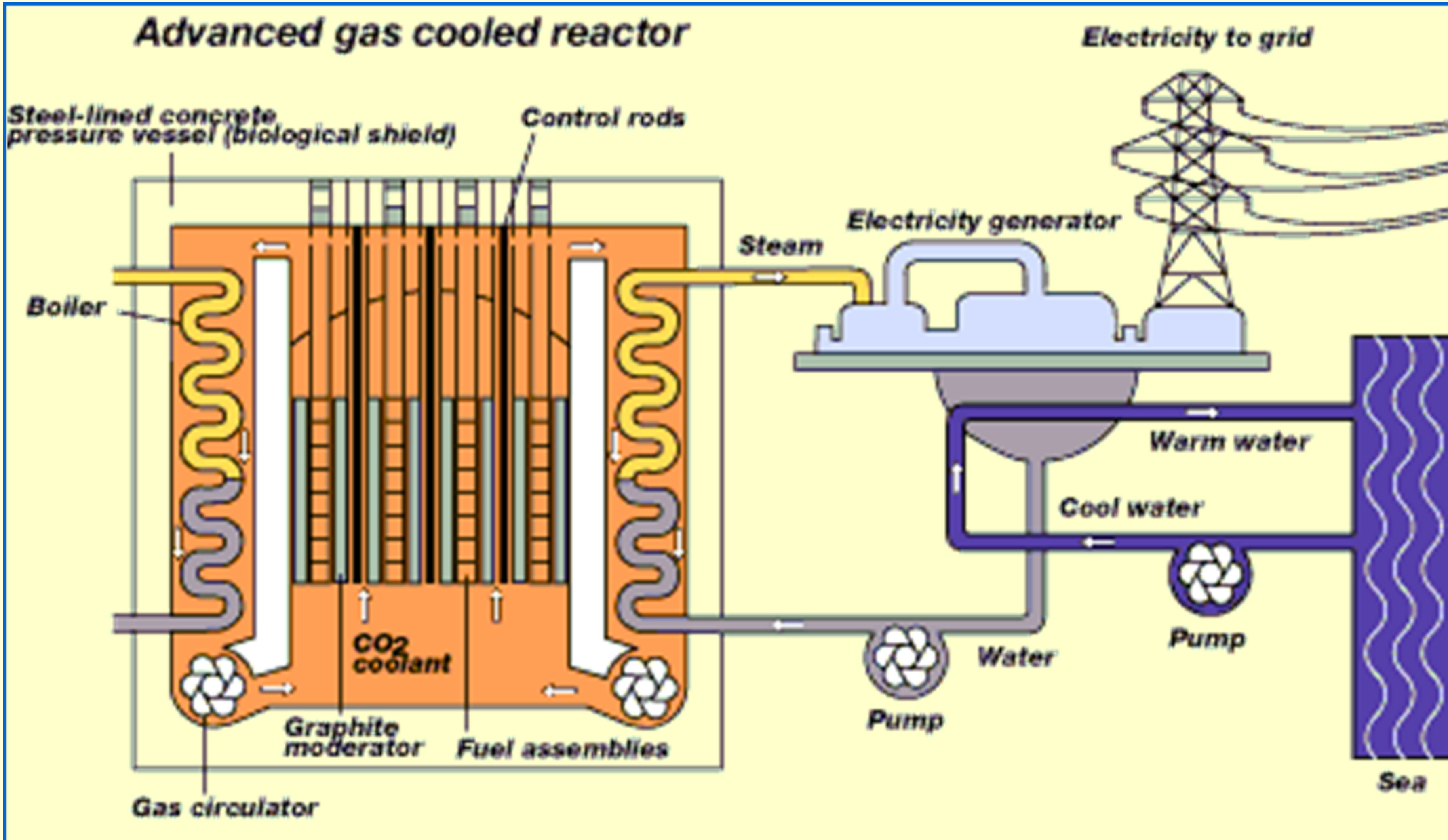
MAGNOX

- Named for alloy used in fuel
- Key features
  - Graphite moderator
  - CO_2 Coolant
  - Online refueling, PCRV
  - Natural uranium
- Used for Pu and power production in UK, France
- Most shut down or close to it
- UK MAGNOX design is the basis for the North Korean Pu production reactors

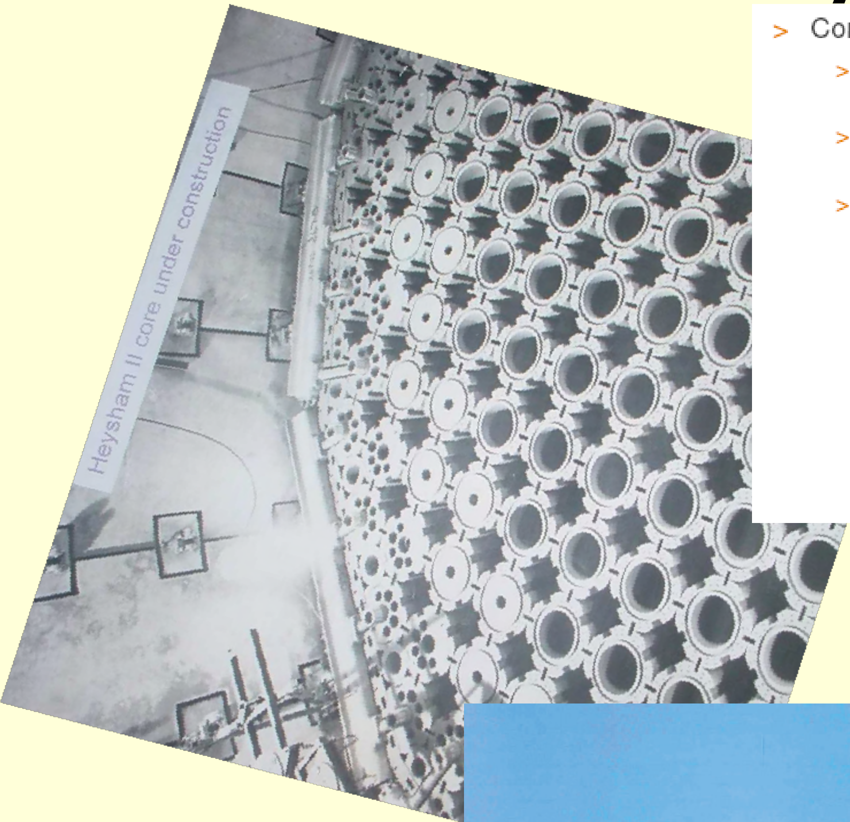
Advanced Gas-Cooled Reactor

- AGR

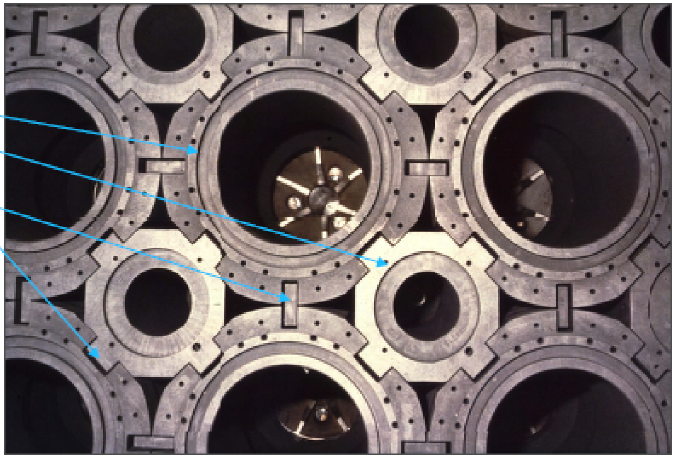
Outlet Temperature 635 C
Power Density ~2 kW/L

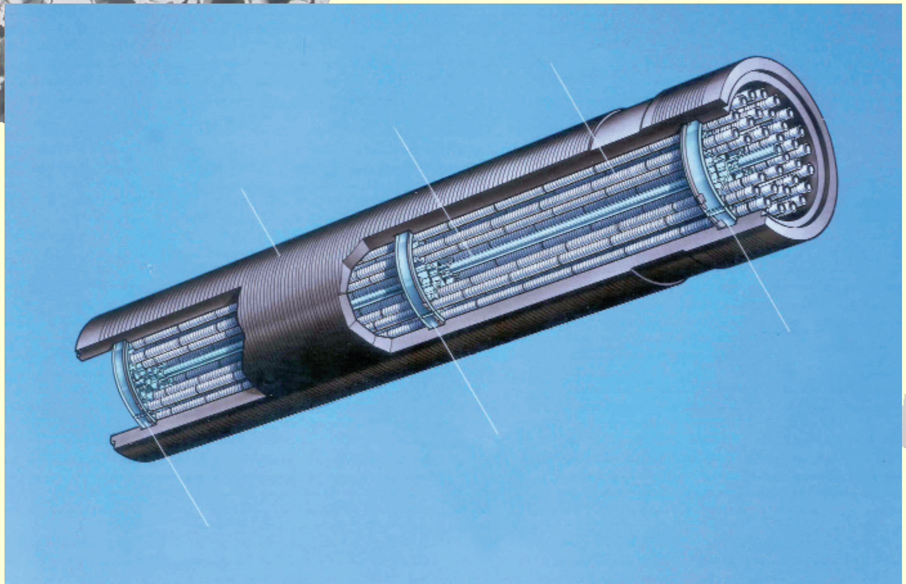


AGR



- Core is an arrangement of
  - Fuel bricks (forming channels for fuel)
  - Interstitial bricks (forming channels for control rods
  - Keying system which holds structure together





AGR

- An improved MAGNOX
- Uranium dioxide fuel in tubes, 2-3% enriched
- 15 built, 14 still operating
  - Some operating with restrictions
- 15th: Windscale/Sellafield
  - Accident