Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 20

Nuclear Power Plants II

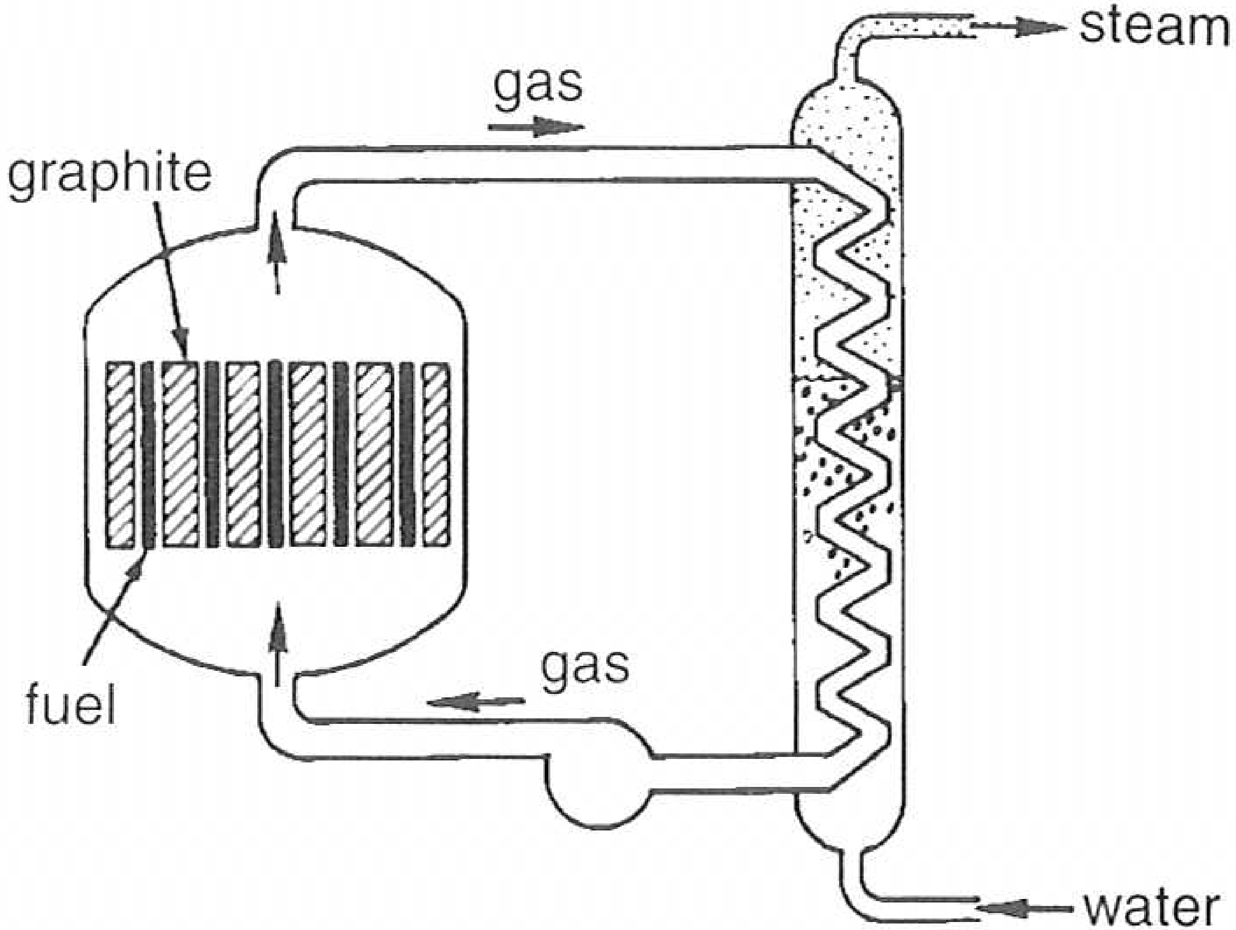
Nuclear Power Plants: Old and New

Spiritual Thought

"The Standard of Truth has been erected; no unhallowed hand can stop the work from progressing; persecutions may rage, mobs may combine, armies may assemble, calumny may defame, but the truth of God will go forth boldly, nobly, and independent, till it has penetrated every continent, visited every clime, swept every country, and sounded in every ear, till the purposes of God shall be accomplished, and the Great Jehovah shall say the work is done."

Joseph Smith Jr.

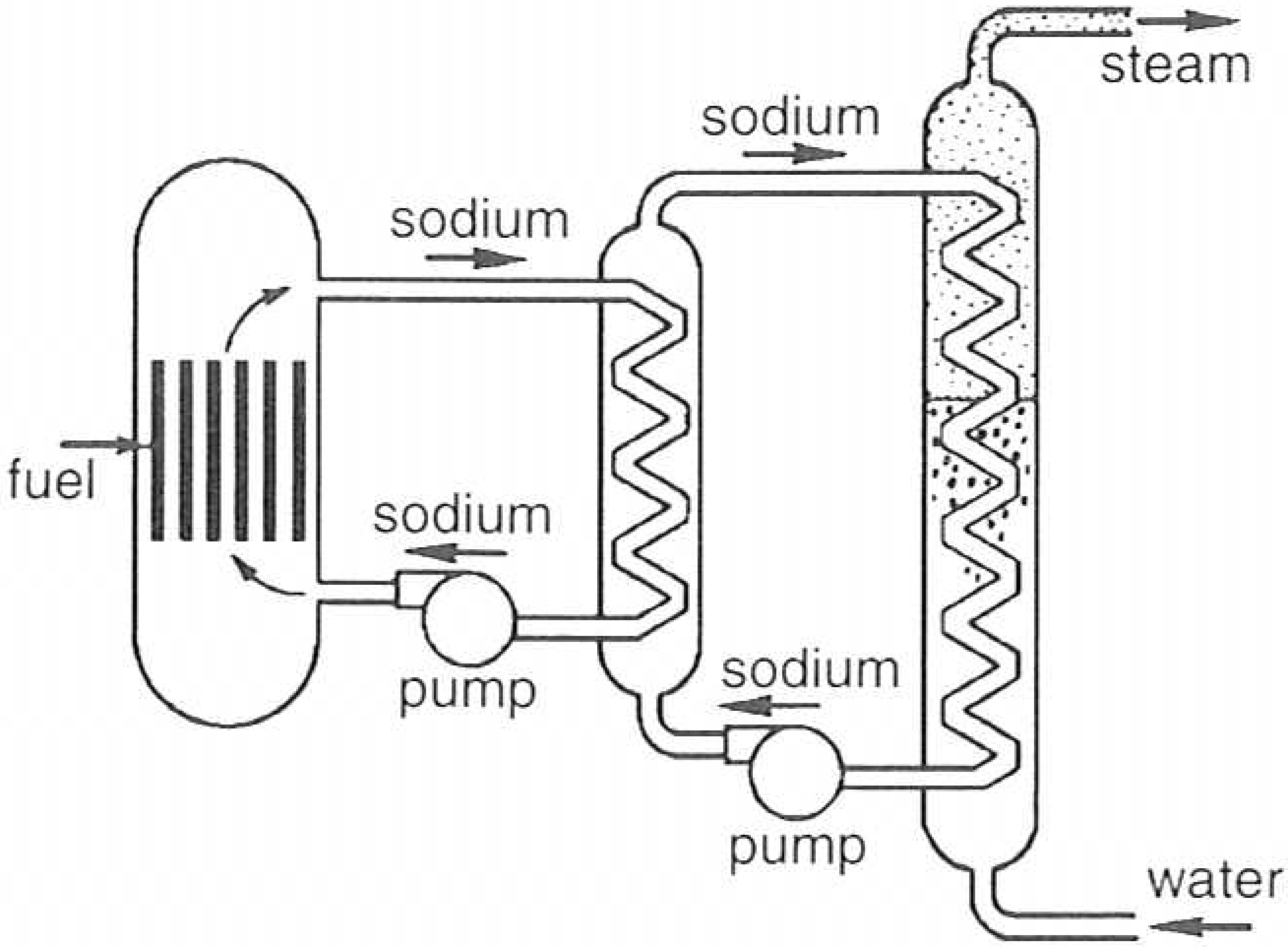
Gas-cooled Reactor (GCR)



Gas-cooled Reactor (GCR, HTGR)

- Gas (He or CO_2) used as coolant.
- Graphite typically used as moderator.
- Graphite (which remains solid) and gas need not be pressurized
  - No expensive pressure vessel
  - No Blowdown in accident
- Gas heats steam in secondary loop.
- In a gas-cooled reactor (GCR), gas passes through holes in graphite moderator.
- In a high-temperature gas-cooled reactor (HTGR), fuel channels and gas channels are drilled in graphite core.

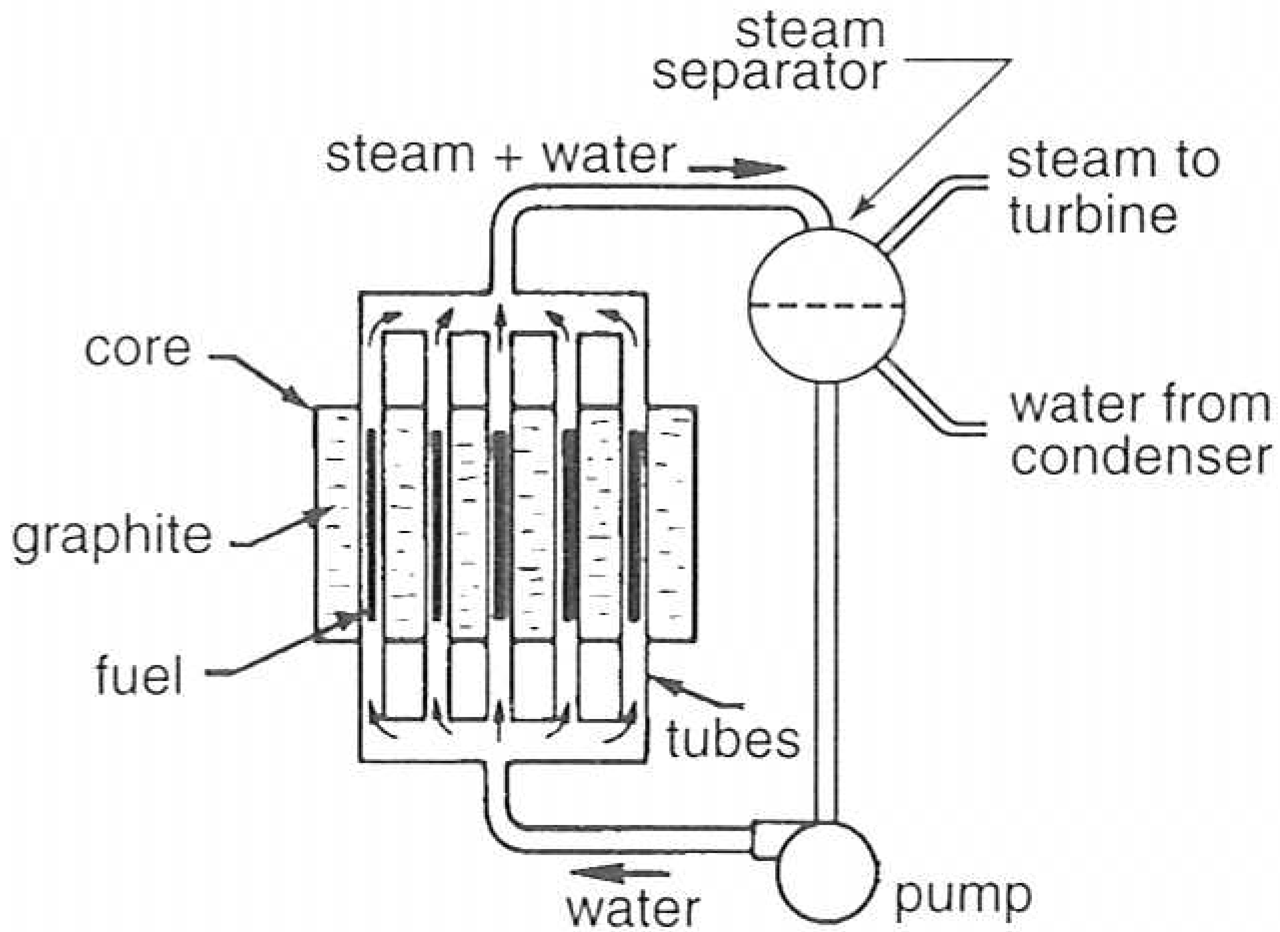
Liquid-metal fast breeder reactor



Liquid Metal Fast Breeder Reactor (LMFBR)

- Fast-neutron-based reactor scheme.
- No moderator (no light elements).
- Na or K-Na molten metal used as coolant.
- No pressurization, very high heat transfer coefficients.
- Na becomes radioactive and Na and K react violently with water (moderately with air).
- Second Na heat exchanger isolates Na/K coolant in core from turbine steam.
- New fuel to consumed fuel ratio raises from 0.6-0.8 in typical reactors to over 1 if designed as a breeder reactor.
- One in commercial operation (in Russia), though they are aggressively pursuing new designs.

Light-water-cooled graphite moderated reactor (LGR)



Light-water-cooled graphite moderated reactor (LGR)

- Soviet-designed reactor, called RBMK (reactory bolshoi moshchnosti kanalnye – high-powered pressure-tube reactor).
- Fuel in fuel pressurized fuel channels in graphite block.
- Steam passes directly to turbine.
- Fuel can be exchanged without reactor shutdown.
- Capable of operation on natural uranium.
- All systems since Chernobyl use higher (2.4%) uranium enrichment.

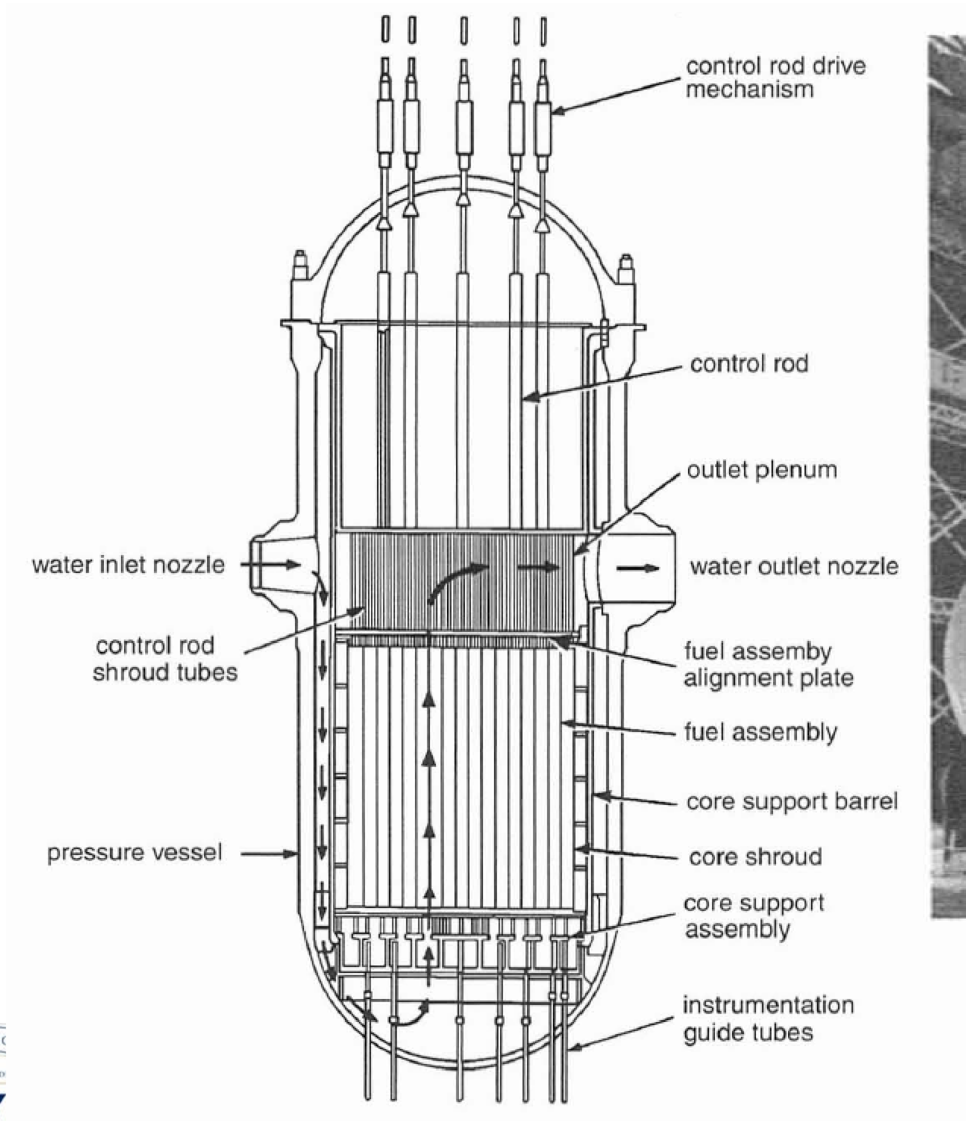
Reactor Startup

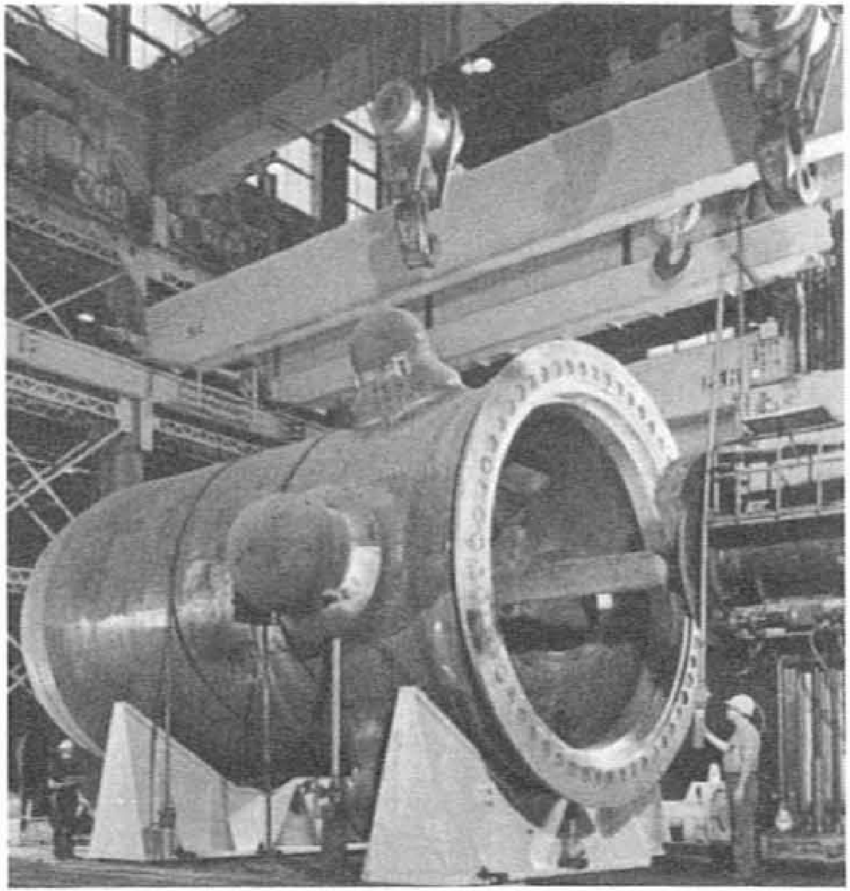
Typical PWR Specs

POWER	
thermal output	3800 MW
electrical output	1300 MW(e)
efficiency	0.34
CORE	
length	4.17 m
diameter	3.37 m
specific power	33 kW/kg(U)
power density	102 kW/L
av. linear heat rate	17.5 kW/m
rod surface heat flux	
average	0.584 MW/m^2
maximum	1.46 MW/m^2
REACTOR COOLANT SYSTEM	
operating pressure	15.5 MPa (2250 psia)
inlet temperature	292 °C
outlet temperature	329 °C
water flow to vessel	65.9×10^6 kg/h
STEAM GENERATOR (SG)	
number	4
outlet steam pressure	1000 psia
outlet steam temp.	284 °C
steam flow at outlet	1.91×10^6 kg/h

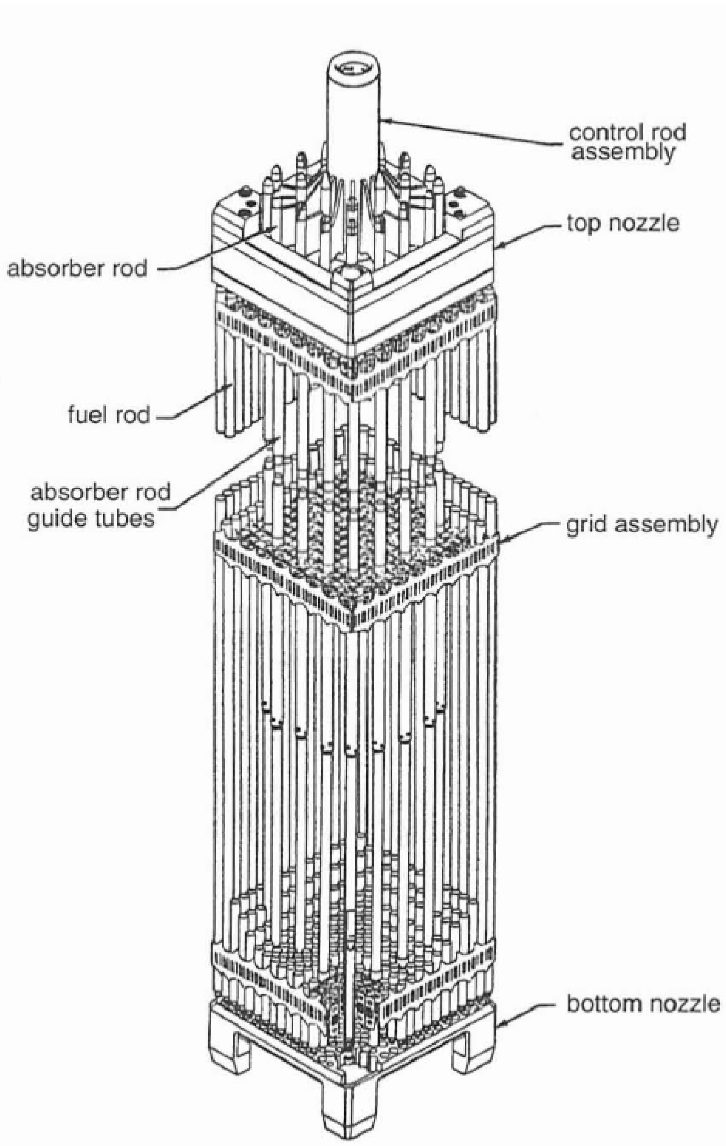
REACTOR PRESSURE VESSEL	
inside diameter	4.4 m
total height	13.6 m
wall thickness	22.0 cm
FUEL	
cylindrical fuel pellets	UO_2
pellet diameter	8.19 mm
rod outer diameter	9.5 mm
zircaloy clad thickness	0.57 mm
rod lattice pitch	12.6 mm
rods/assembly (17 × 17)	264
assembly width	21.4 cm
fuel assemblies in core	193
fuel loading	115×10^3 kg
initial enrichment % ^{235}U	1.5/2.4/2.95
equil. enrichment % ^{235}U	3.2
discharge fuel burnup	33 GWd/tU
REACTIVITY CONTROL	
no. control rod assemblies	68
shape	rod cluster
absorber rods per assembly	24
neutron absorber	Ag-In-Cd and/or B_4C
soluble poison shim	boric acid H_3BO_3

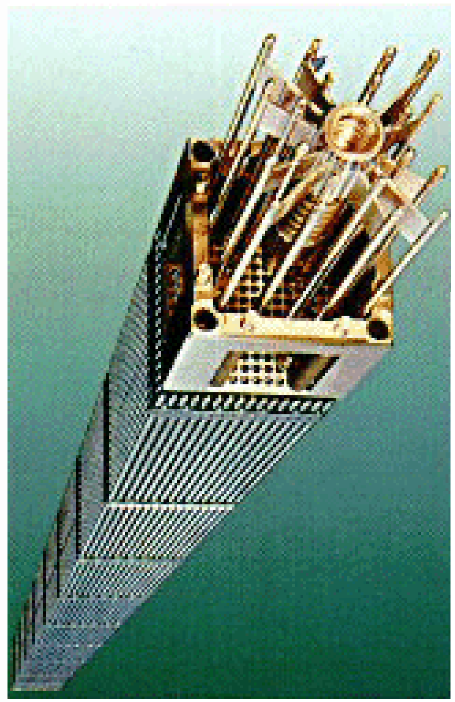
Reactor Core

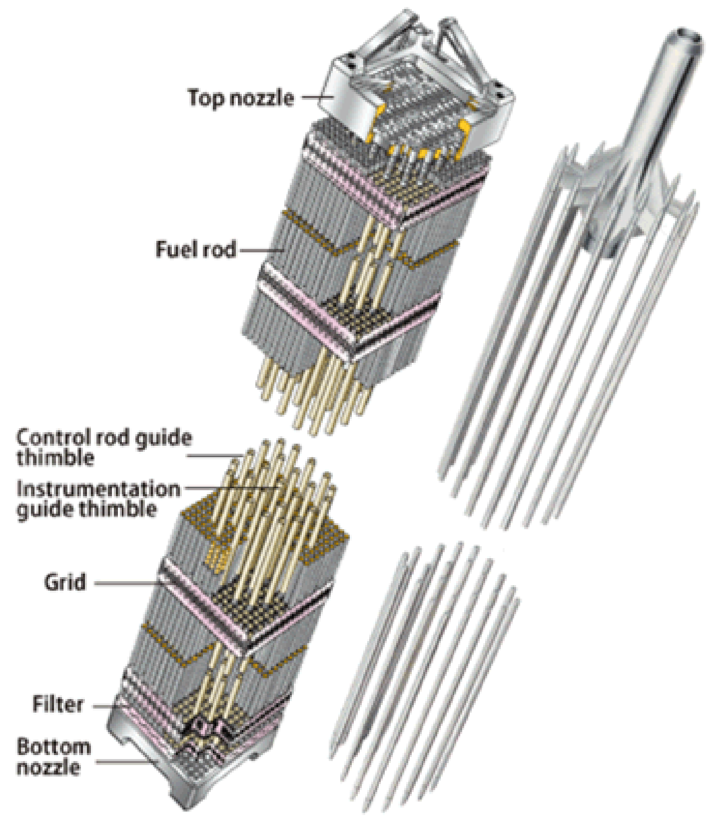




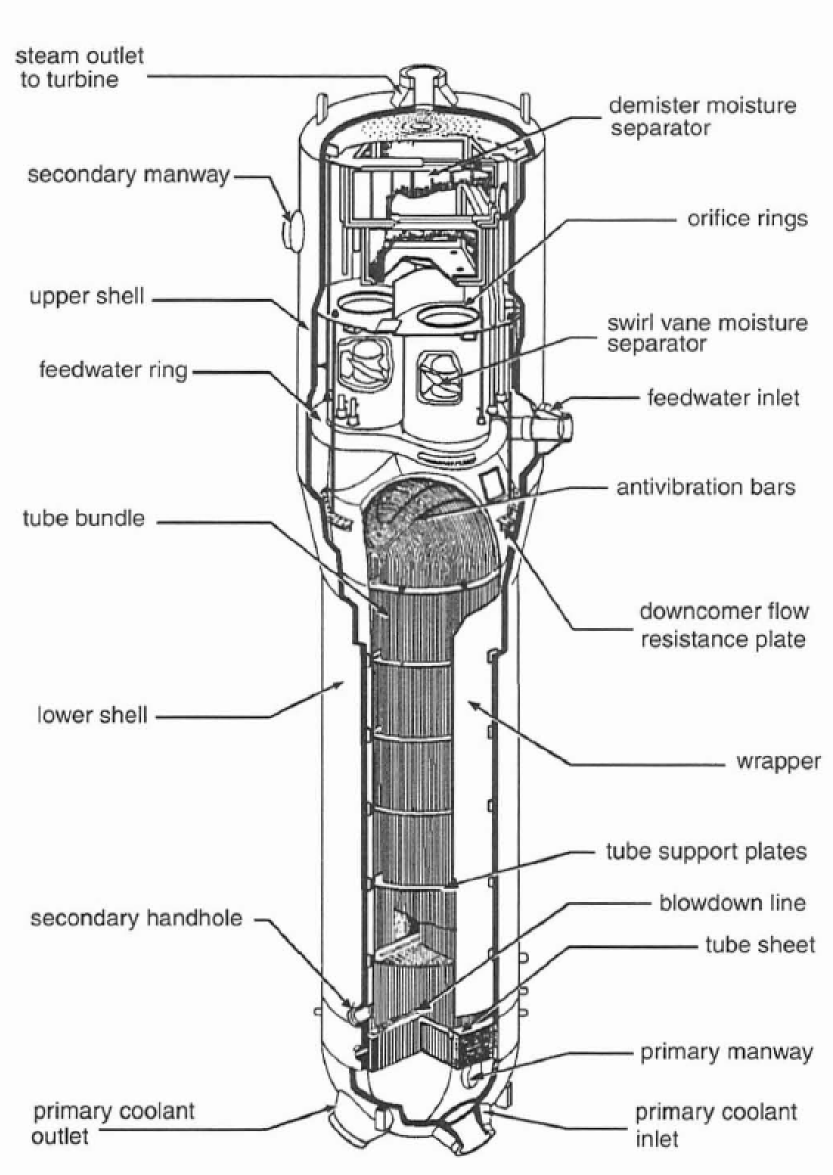
Fuel Assembly

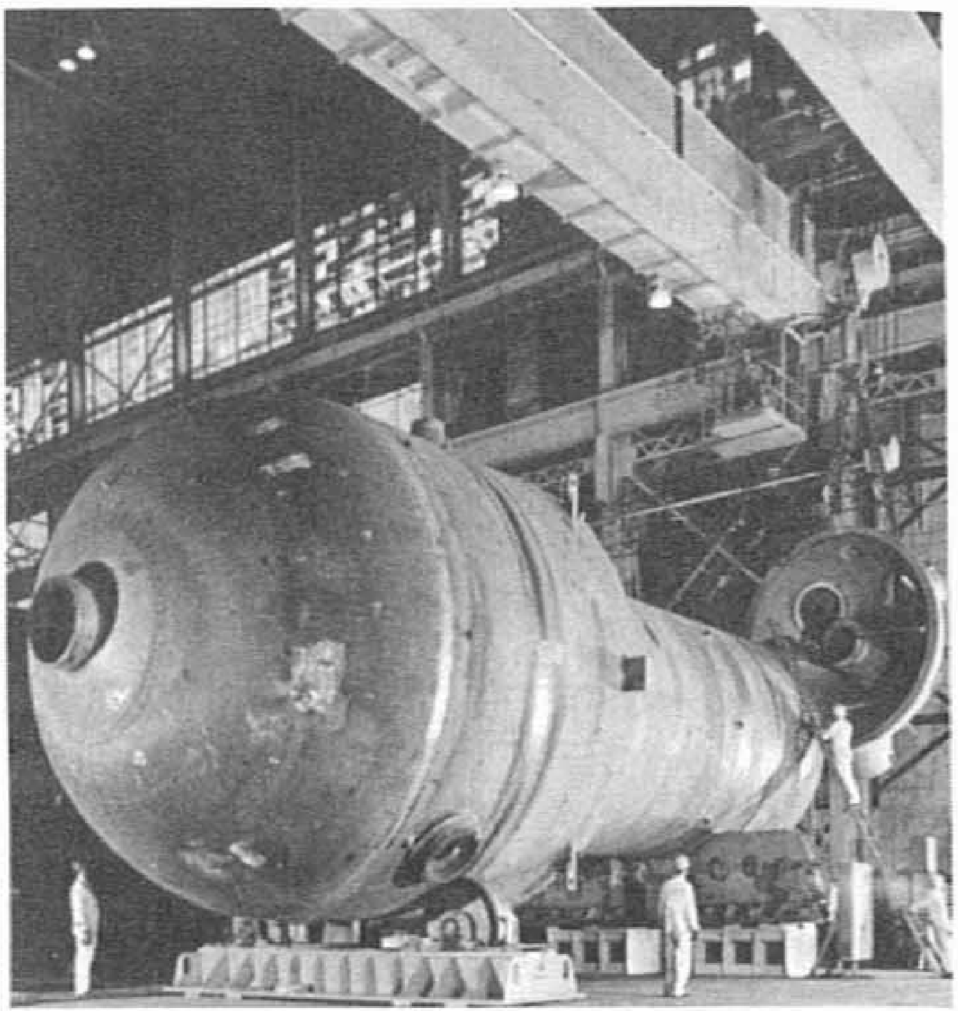




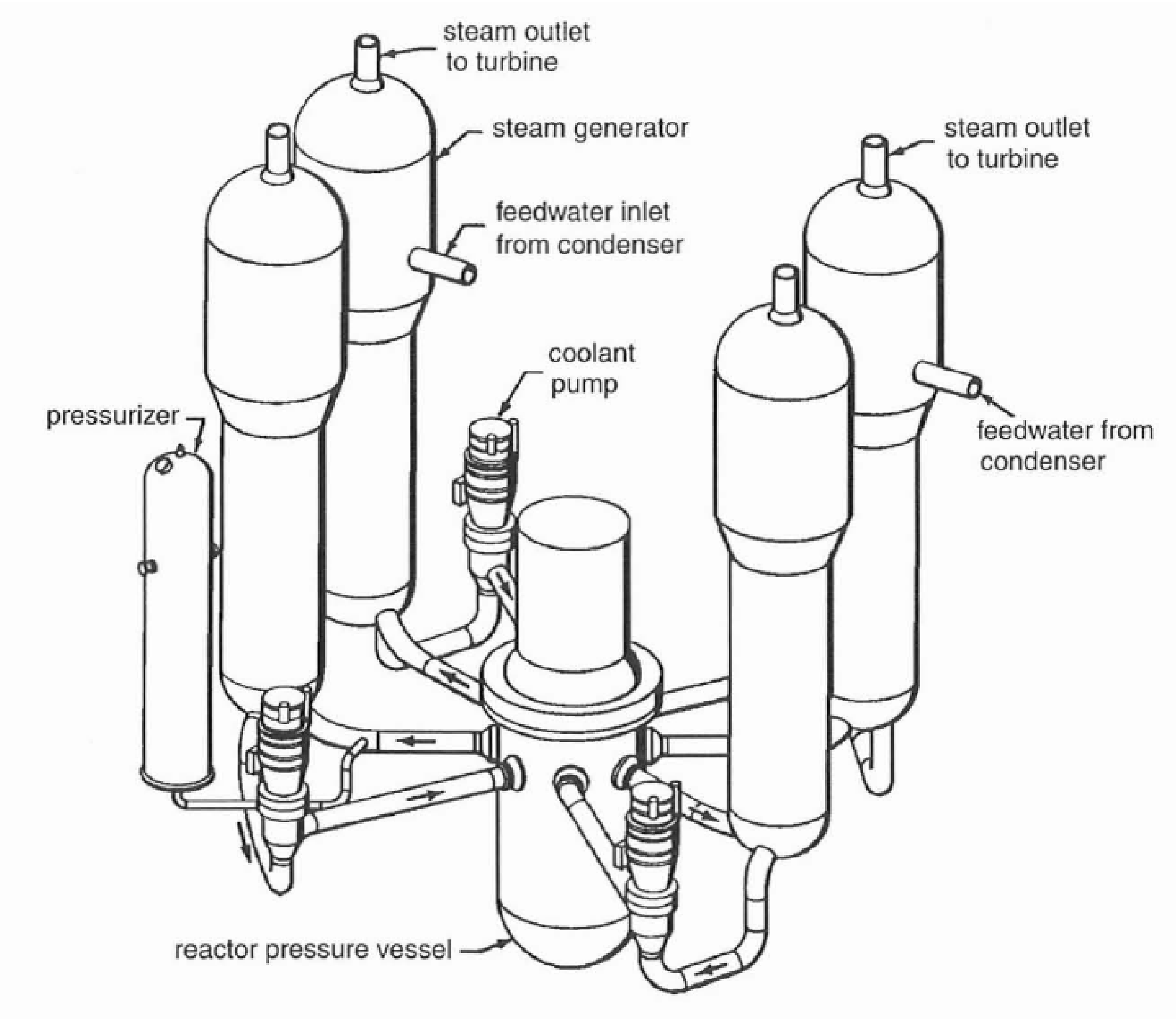


Steam Generator (Heat Exchanger)

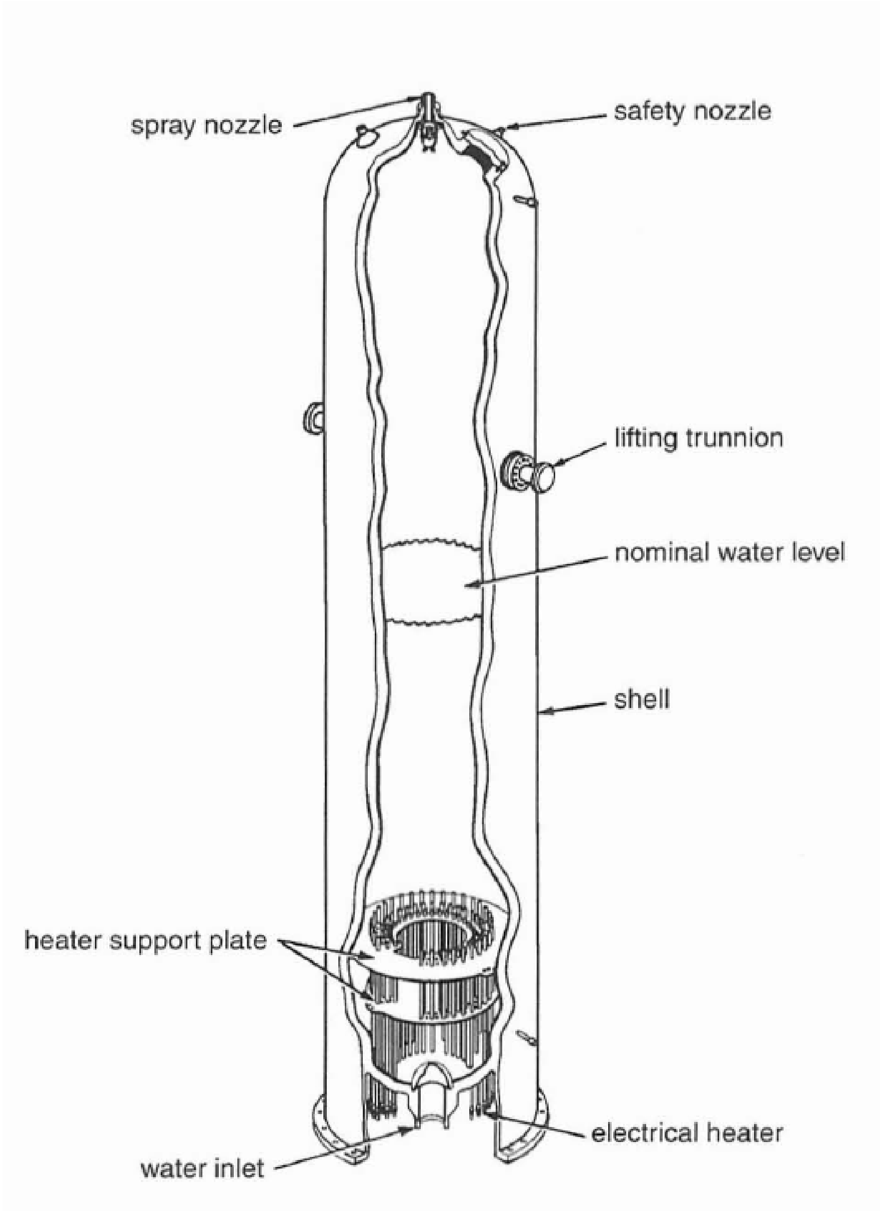




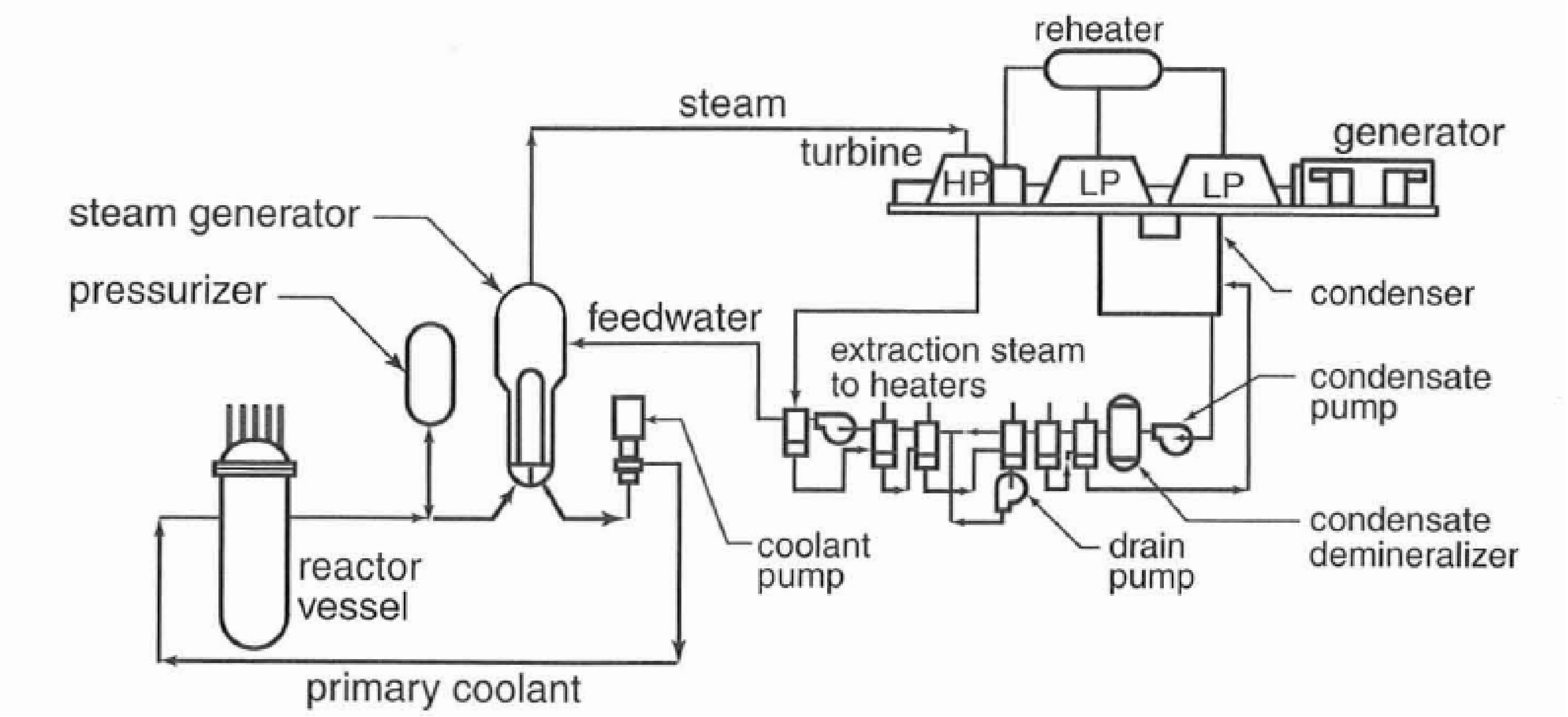
Overall Equipment Arrangement



Pressurizer



PWR Steam Cycle

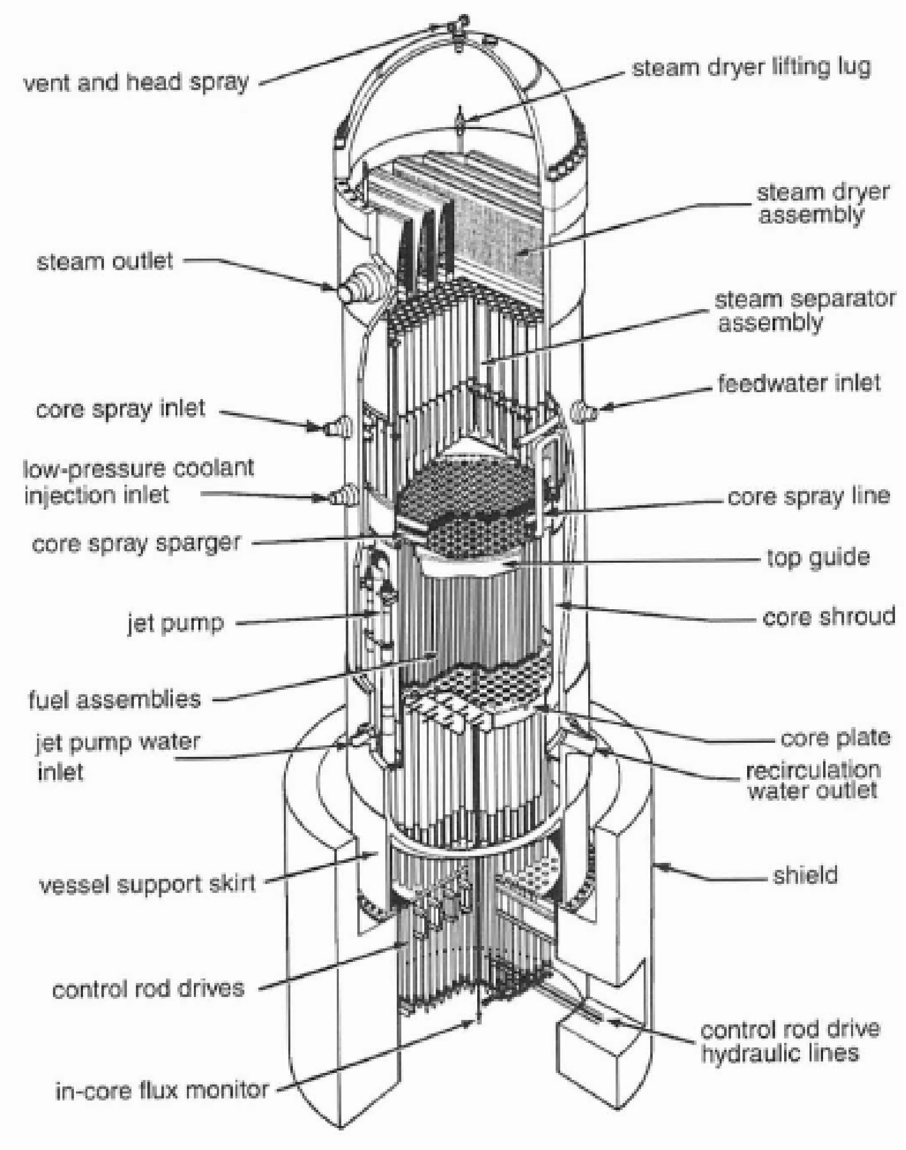


BWR Specifications

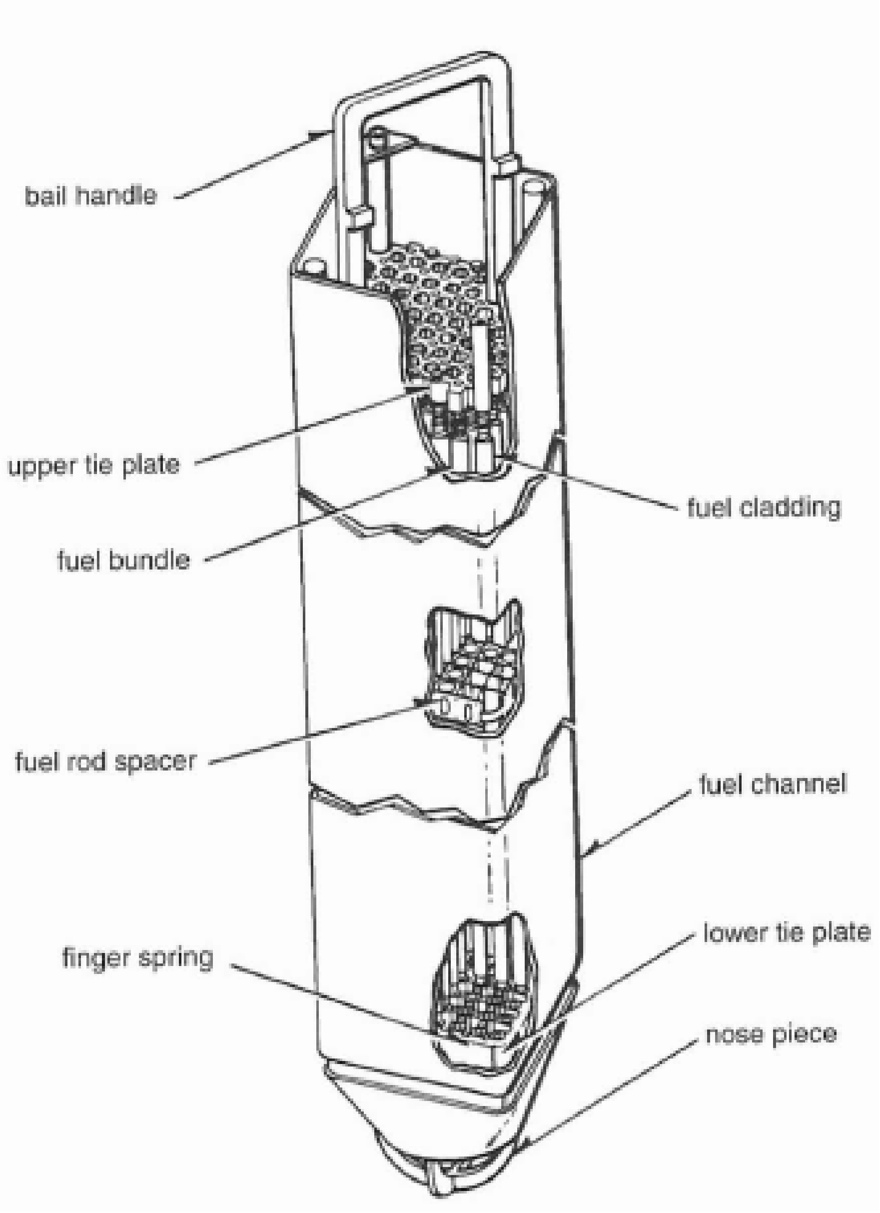
POWER	
thermal output	3830 MW
electrical output	1330 MW(e)
efficiency	0.34
CORE	
length	3.76 m
diameter	4.8 m
specific power	25.9 kW/kg(U)
power density	56 kW/L
av. linear heat rate	20.7 kW/m
rod surface heat flux	
average	0.51 MW/m^2
maximum	1.12 MW/m^2
REACTOR COOLANT SYSTEM	
operating pressure	7.17 MPa (1040 psia)
feedwater temperature	216 °C
outlet steam temperature	290 °C
outlet steam flow rate	7.5×10^6 kg/h
core flow rate	51×10^6 kg/h
core void fraction (av.)	0.37
core void fraction (max.)	0.75
no. in-core jet pumps	24
no. coolant pumps/loops	2

REACTOR PRESSURE VESSEL	
inside diameter	6.4 m
total height	22.1 m
wall thickness	15 cm
FUEL	
cylindrical fuel pellets	UO_2
pellet diameter	10.57 mm
rod outer diameter	12.52 mm
zircaloy clad thickness	0.864 mm
rod lattice pitch	16.3 mm
rods/assembly (8 × 8)	62
assembly width	13.4 cm
assembly height	4.48 m
fuel assemblies in core	760
fuel loading	168×10^3 kg
av. initial enrichment $\%^{235}U$	2.6%
equil. enrichment $\%\ ^{235}U$	1.9%
discharge fuel burnup	27.5 GWd/tU
REACTIVITY CONTROL	
no. control elements	193
shape	cruciform
overall length	4.42 m
length of poison section	3.66 m
neutron absorber	boron carbide
burnable poison in fuel	gadolinium

BWR Core


vent and head spray
steam dryer lifting lug
steam dryer assembly
steam outlet
steam separator assembly
feedwater inlet
core spray inlet
low-pressure coolant injection inlet
core spray line
core spray sparger
top guide
jet pump
core shroud
fuel assemblies
core plate
jet pump water inlet
recirculation water outlet
vessel support skirt
shield
control rod drives
control rod drive hydraulic lines
in-core flux monitor

BWR Fuel Assembly



Generations I-IV

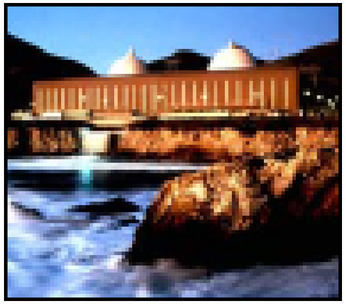
Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- AGR

Generation III

Advanced LWRs

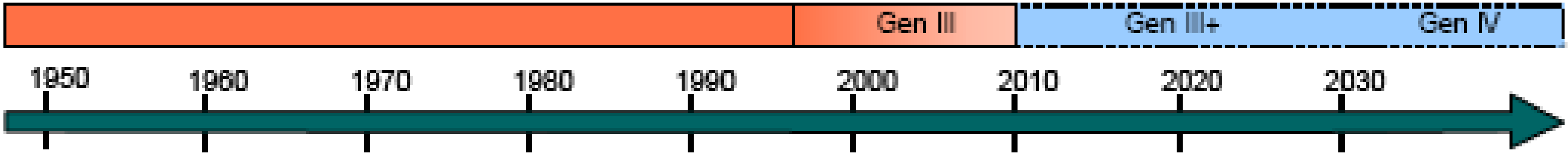
- ABWR
- System 80+

Generation III +

Evolutionary Designs Offering Improved Economics for Near-Term Deployment

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



Generation I

- Test reactors and small-scale systems

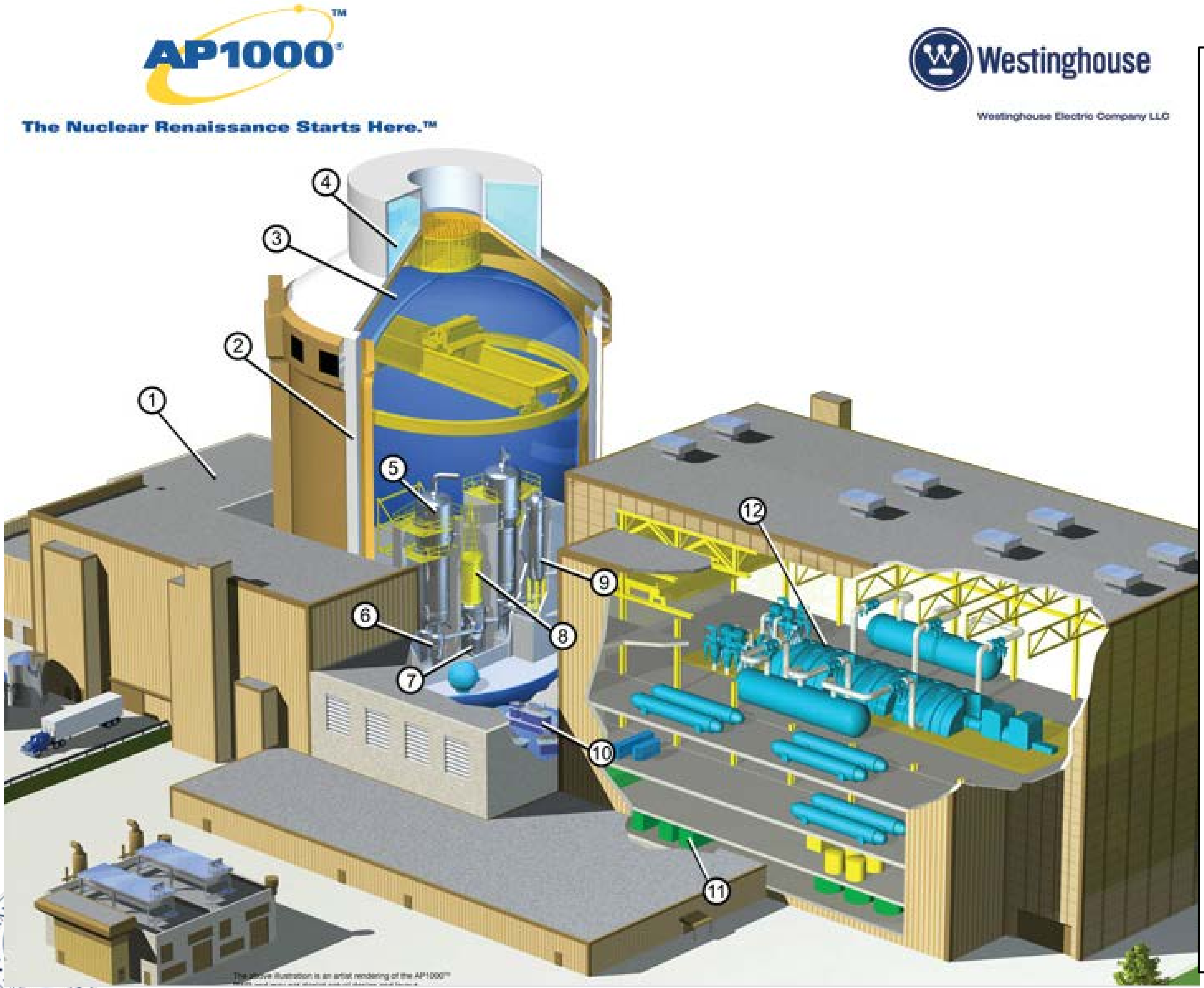
Generation II

- Most current commercial reactors
  - Largely adopted from ship propulsion systems
  - 60s-70s technologies
  - Perhaps more complex than needed

Generation III/III+

- Evolutions of Generation II reactors
  - Safer
  - Less complex
  - More economical

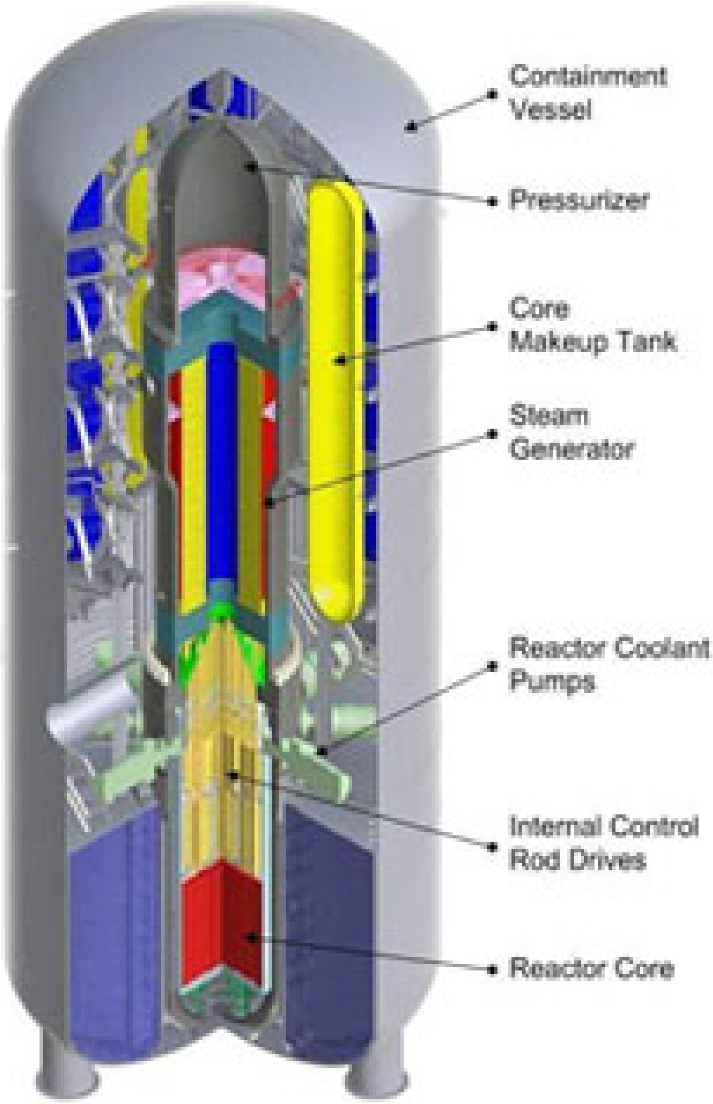
The AP1000 (Gen III+) Design

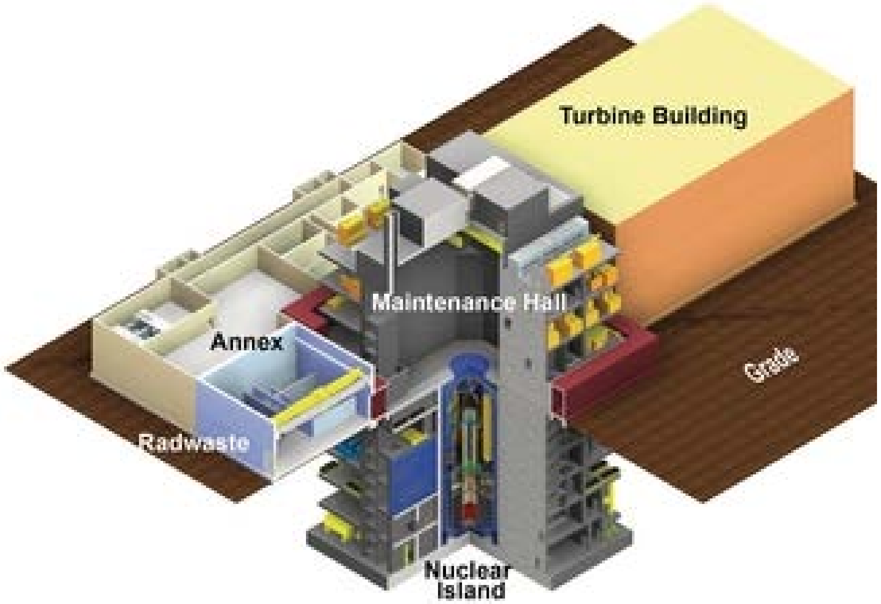


Small Modular Reactors

- Small is < 300 MW_e (IAEA definition) or < 500 MW_e (conventional definition).
- Modular means systems can be almost entirely fabricated in shops rather than on site, decreasing security and other risks.
- Primary advantage is decrease in capital cost, reducing financial risk, construction at a single location, ability to add incremental power.
- Primary disadvantage is loss of economies of scale. Four small reactors are more expensive to build and operate than one large reactor of equivalent size.
- Include III, III+, and IV or other designs

Westinghouse SMR





B&W/Bechtel mPower Reactor

- 530 MW_{th} developed by joint venture of Babcock & Wilcox and Bechtel, 155 to 180 MW_e output on air or water cooling, respectively
- 13 ft diameter, 83 ft tall
- $226 M in DOE cost-shared funding
- TVA Clinch River potential host site
- 5% enriched fuel for 4-yr core life
- Construction permit target date 2015
- 825 psi (56 bar) steam w/ 50 °F (28 °C) superheat

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Small Modular Reactors

Name	Power	Technology	Producer
VK-300	300 MWe	BWR	Atomstroyexport, Russia
S-PRISM	311 MWe	FBR	GE Hitachi Nuclear Energy
4S	10–50 MWe	FNR	Toshiba - Japan
GT-MHR	285 MWe	HTGR	General Atomics (USA), Minatom (Russia) et al.
PBMR	165 MWe	HTGR	Eskom, South Africa, et al.
BREST[2]	300 MWe	LFR	RDIPE (Russia)
Hyperion Power Module[1]	25 MWe	LFR	Hyperion Pwr Gen - Santa Fe, NM USA
SVBR[3]	10–100 MWe	LFR	OKB Gidropress (Russia)
MASLWR	45 MWe	LWR	NuScale Power LLC, USA
Fuji MSR	100–200 MWe	MSR	ITHMSO, Japan-Russia-USA
WAMSR	200 MW	MSR	Transatomic Power, USA
CAREM	27 MWe	PWR	CNEA & INVAP, Argentina
Flexblue	50–250 MWe	PWR	Areva TA / DCNS group, France
IRIS-100	100 MWe	PWR	Westinghouse-led, international
KLT-40	35 MWe	PWR	OKBM, Russia
mPower	180 MWE	PWR	Babcock & Wilcox, USA
MRX	30–100 MWe	PWR	JAERI, Japan
NP-300	100–300 MWe	PWR	Areva TA, France
SMART	100 MWe	PWR	KAERI, S. Korea
SMR-160	140 MWE	PWR	Holtec International, USA
Westinghouse SMR	225 MWe	PWR	Westinghouse Electric Company, USA
TerraPower (Test Reactor)	10 MWe	TWR	Intellectual Ventures - Bellevue, WA USA

BWR - boiling water reactor
FBR - fast breeder reactor
FNR - fast neutron reactor
HTGR - high-temperature gas reactor

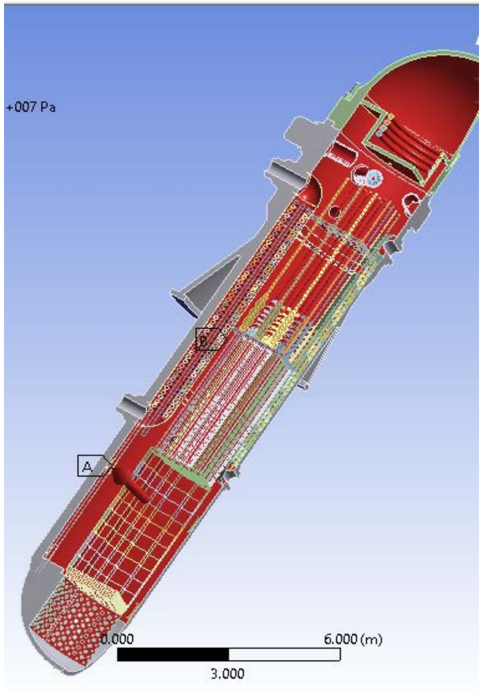
LFR - lead-cooled fast reactor
MSR - molten salt reactor
PWR - pressurized water reactor
TWR - traveling wave reactor

I2S-LWR

BYU – U. Cambridge – Florida Tech – Georgia Tech – INL – U. Idaho – U. Michigan – Morehouse – U. Zagreb – Westinghouse – VirginiaTech – U. Tennessee – SNOC - Politecnico di Milano –

I^2S–LWR

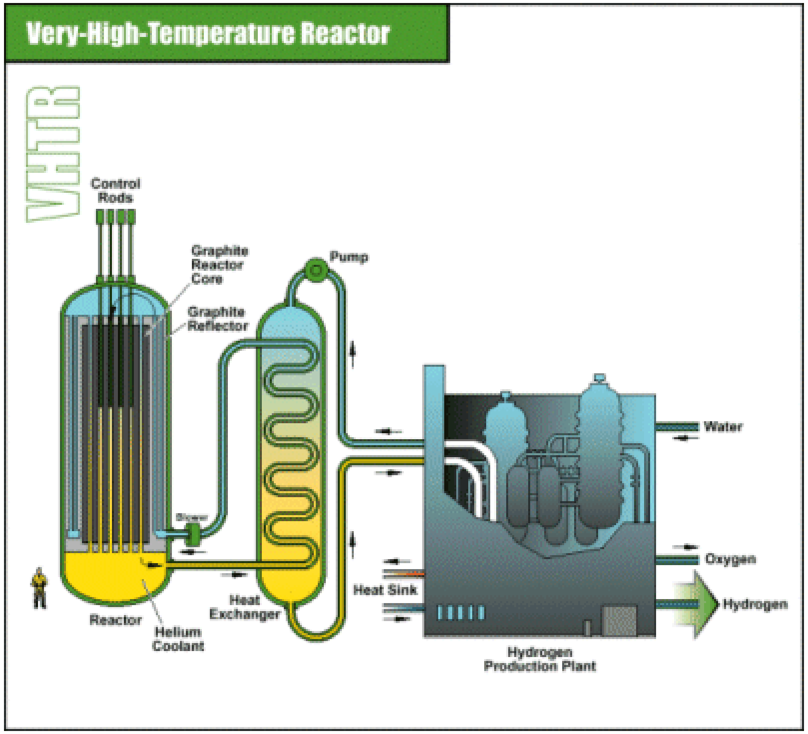
- Collaborative research led by GT with BYU, Westinghouse, Michigan, VT, and 6 others
- "Large" SMR
- 1000 Mwe PWR
- "Inherently" Safe
- Fuel testing in ATR



Generation IV

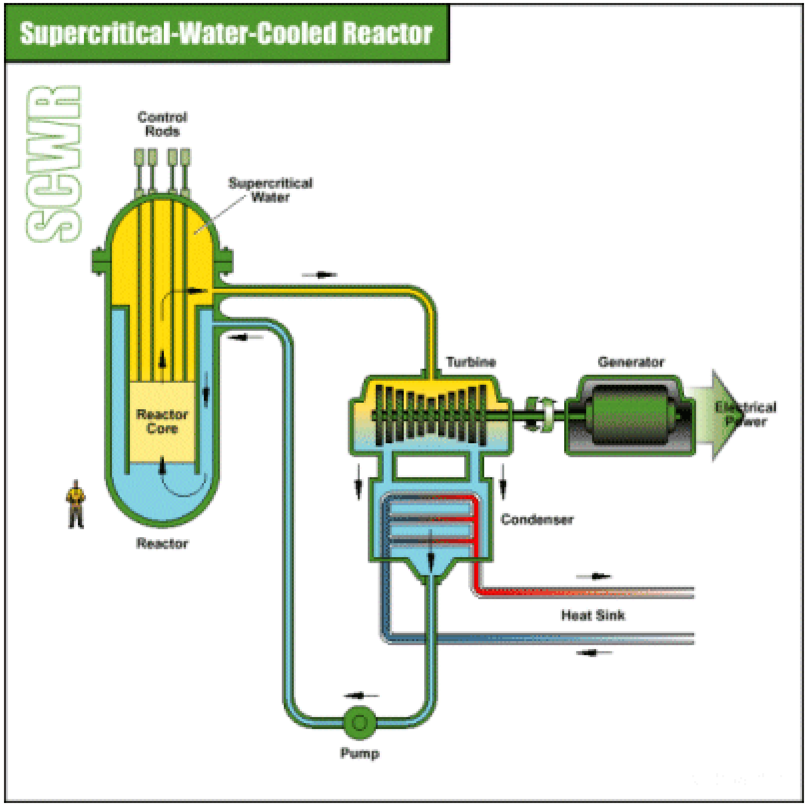
- Future designs inspired by international agreement
- Six designs – three each of thermal and fast reactors
- Most will not be deployed until 2030 under current plans (one exception – the Next Generation Nuclear Plant, or NGNP – targeted for 2021).

Very-High Temperature Reactor



- Graphite-moderated core
- Once-through U fuel cycle
- 1000 ° C steam outlet temperature
- Possible H_2 production
- Fuel Pebbles, ^{235}U

Supercritical-Water-Cooled Reactor



- SC Water (> 240 atm) for working fluid (similar to most modern coal boilers)
- 45% efficienct (compared to 33% in most current technologies)
- Combines LWR and fossil technology.
- Fuel Rods (UO_2 ceramic fuel), ^{235}U