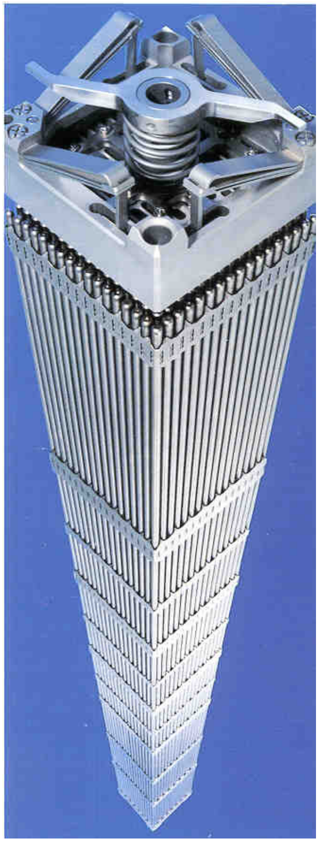
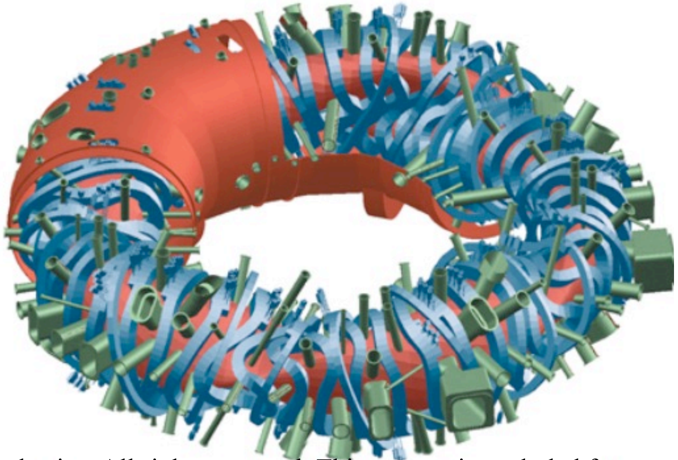


[JB]

Introduction to Nuclear Energy

22.01 – Introduction to Radiation

2024

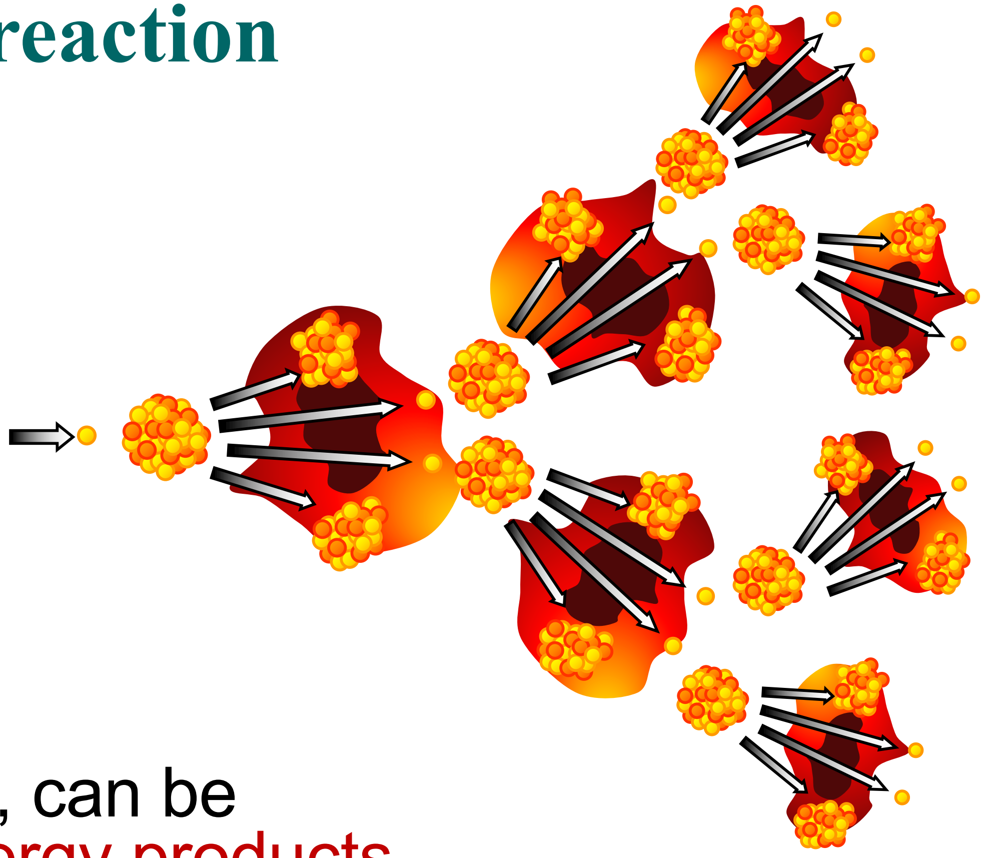


*Some slides marked [JB] are courtesy of Prof. Jacopo Buongiorno, used with permission.

The Nuclear Fission Process

Neutron-driven chain reaction producing heat

- Uranium-235 is the fuel: 2.5 million times more energy per kg than coal
- Only 37 tons of fuel (3%-enriched uranium) per year needed for 1000 MWe reactor
- Emission-free heat source, can be converted into multiple energy products



[JB]

Nuclear Compared to Fossil Fuel

Fuel energy content

Coal (C): $C + O_2 \rightarrow CO_2 + \mathbf{4\ eV}$

Natural Gas (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O + \mathbf{8\ eV}$

Nuclear (U): ${}^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n + \mathbf{200\ MeV}$

Fuel Consumption, 1000 MWe Power Plant (~740,000 homes)

Coal (40% efficiency): **6750 ton/day**

Natural Gas (50% efficiency): **64 m^3/sec**

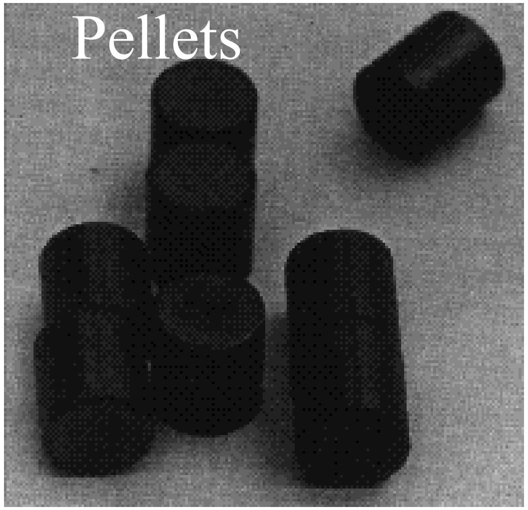
Nuclear (33% efficiency): **3 kg/day**

[JB]

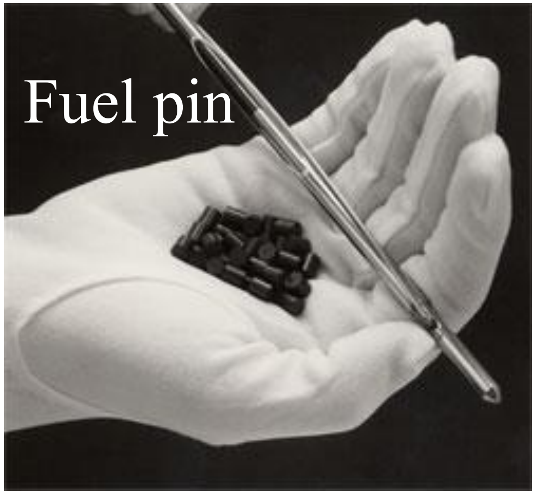
From Rocks to Reactors

U ore

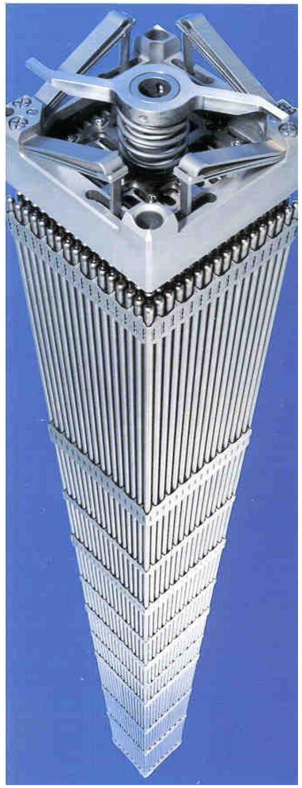
Yellow cake



Pellets



Fuel pin



Fuel assembly

[JB]

Reactor Intro: Acronyms!!!

LBEFR

RBMK

CANDU

LFR

LBE

NNFR

IFR

PHWR

AGR

MSR

GFR

VHTR

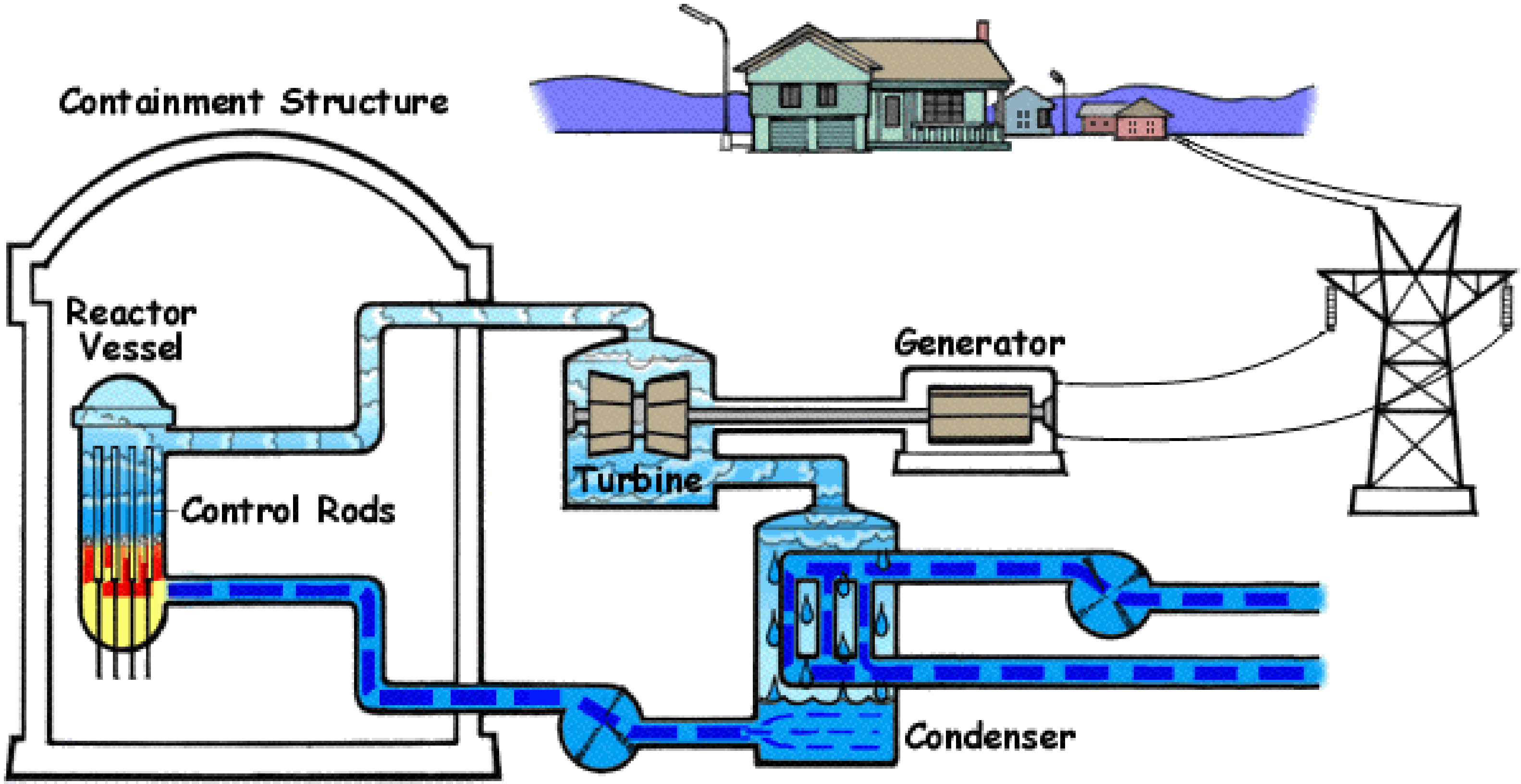
SCWR

SFR

PBMR

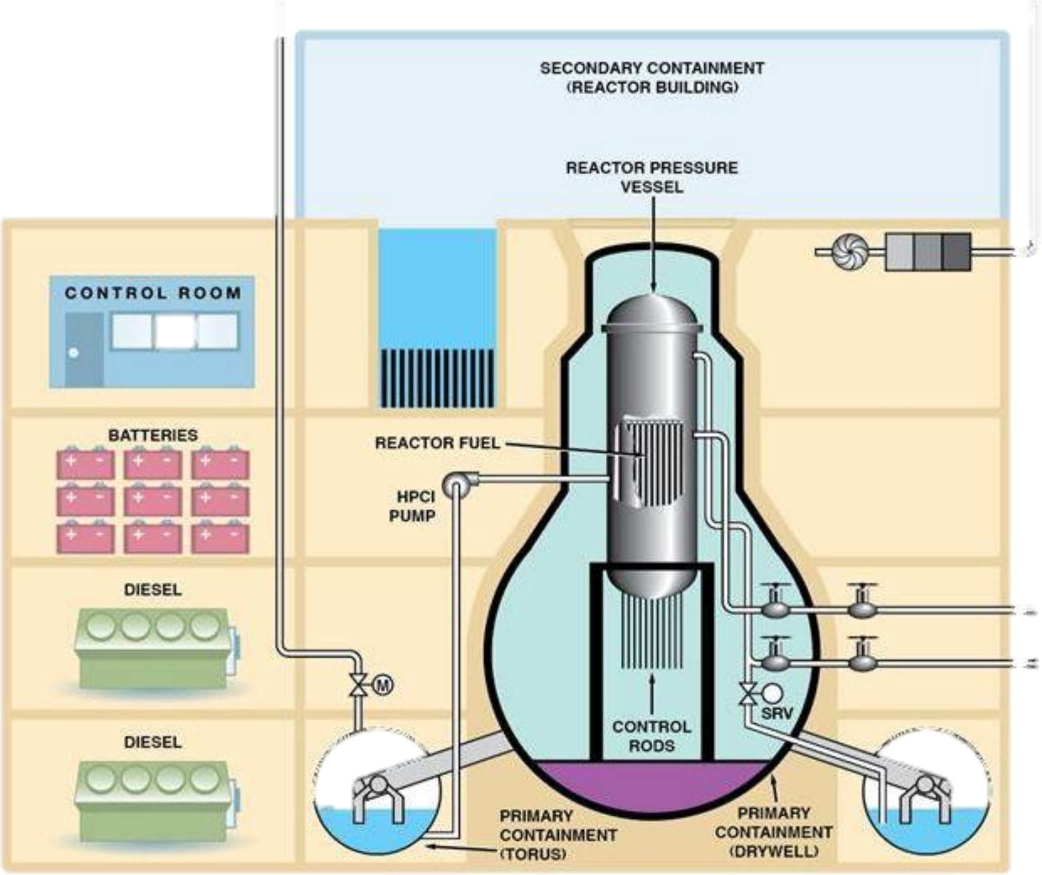
NaK

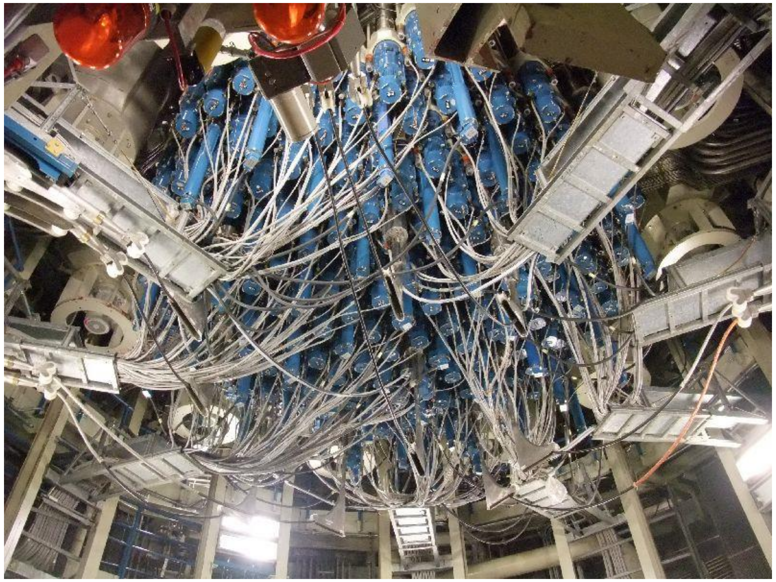
Boiling Water Reactor (BWR)



Public domain image, from U.S. NRC.

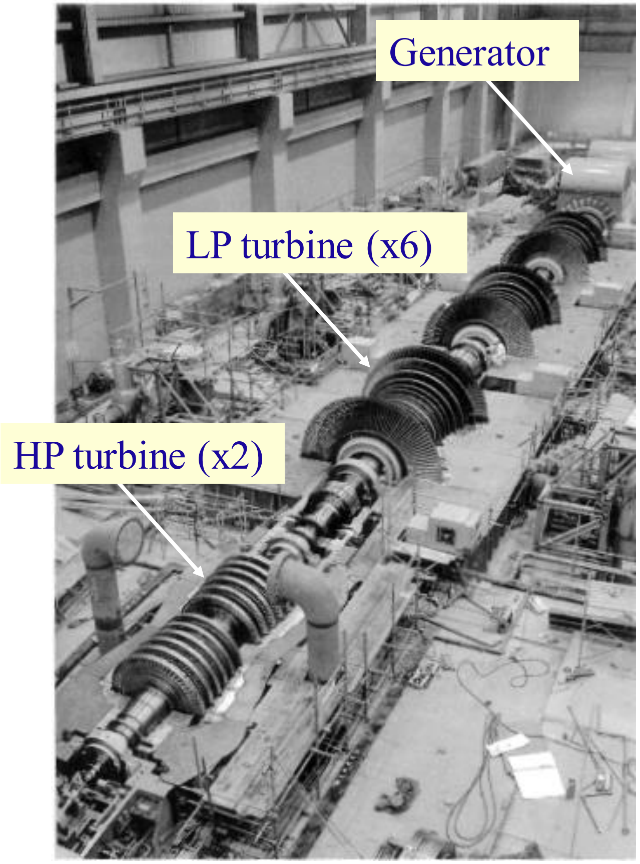
BWR Primary System





BWR Underside

Turbine and Generator

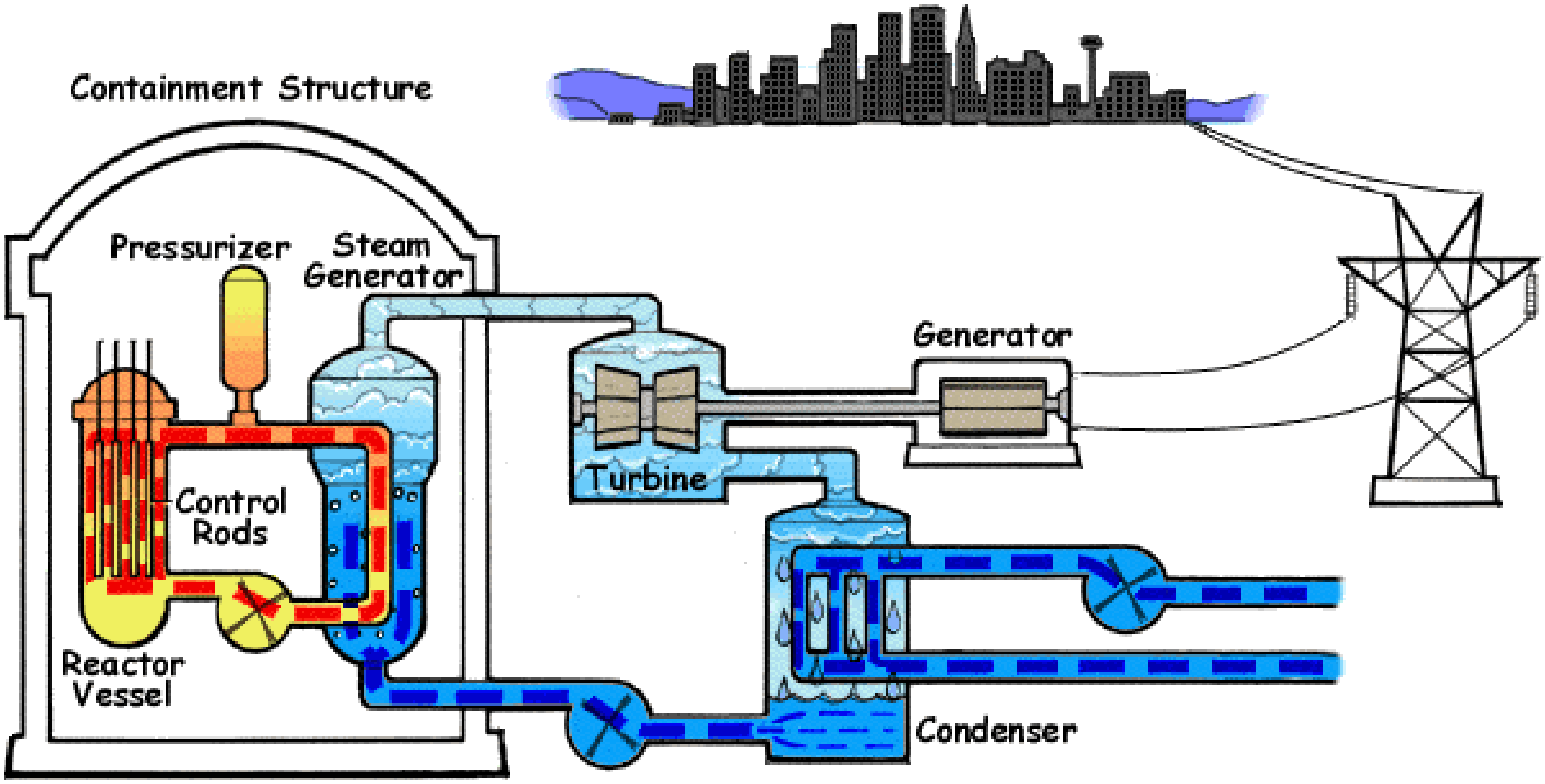


Turbine-generator

turns heat into work, then electricity

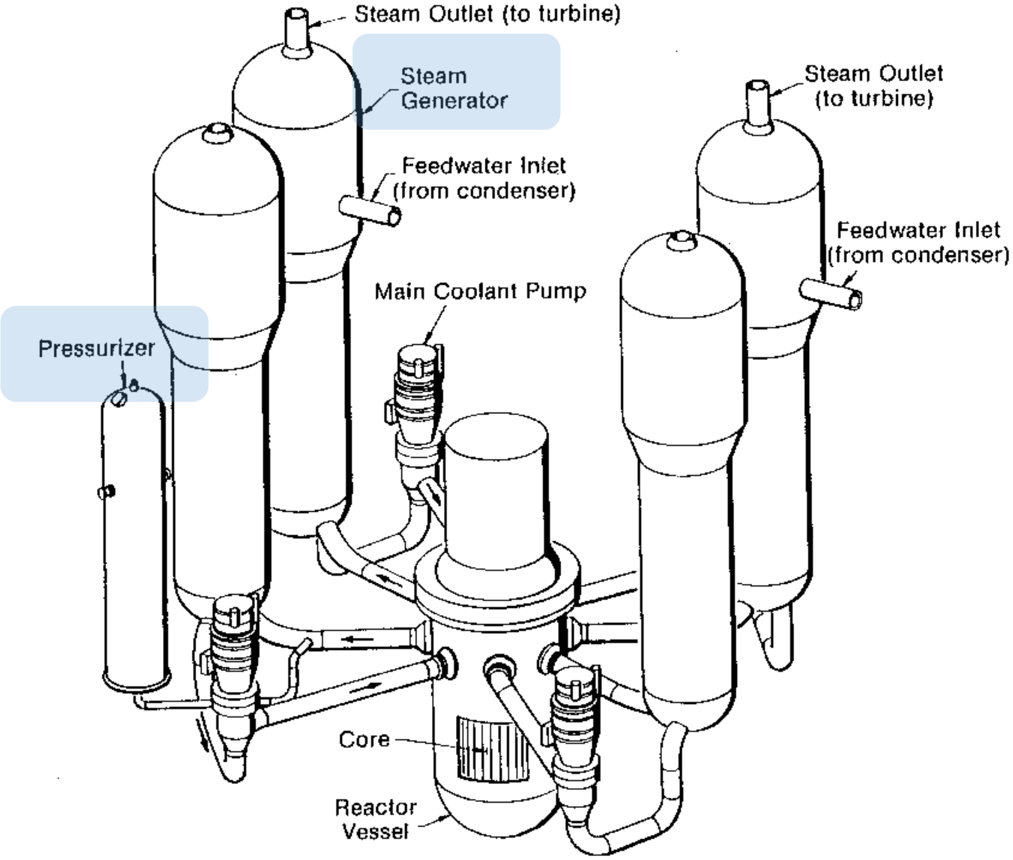
[JB]

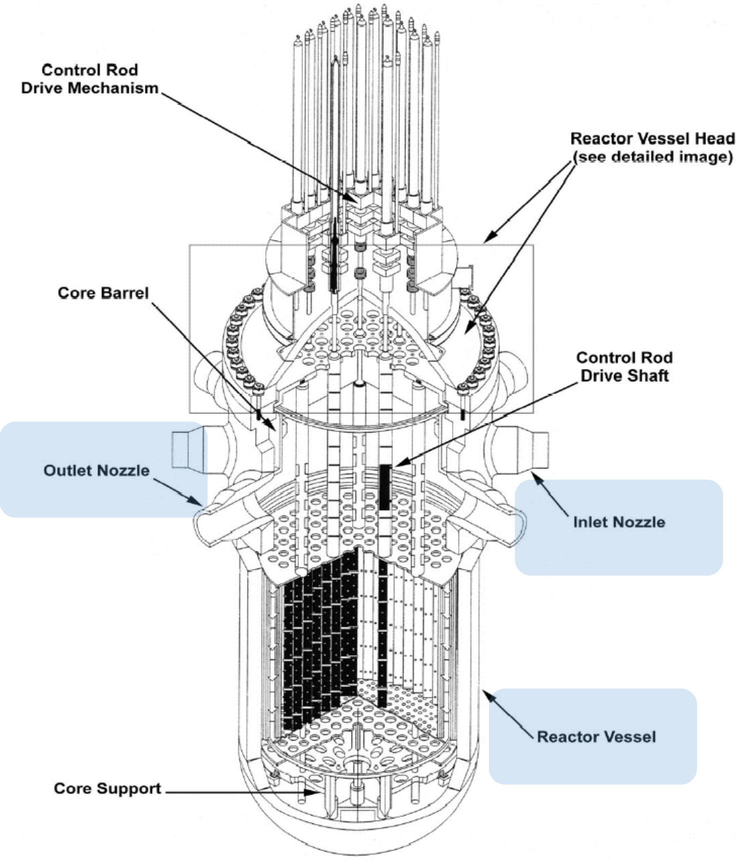
Pressurized Water Reactor (PWR)



Public domain image, from U.S. NRC.

PWR Primary System





[JB]

The MIT Research Reactor

- 6 MW power
- Located near NW12, Albany St.
- Operated by MIT students
- In service since 1954!

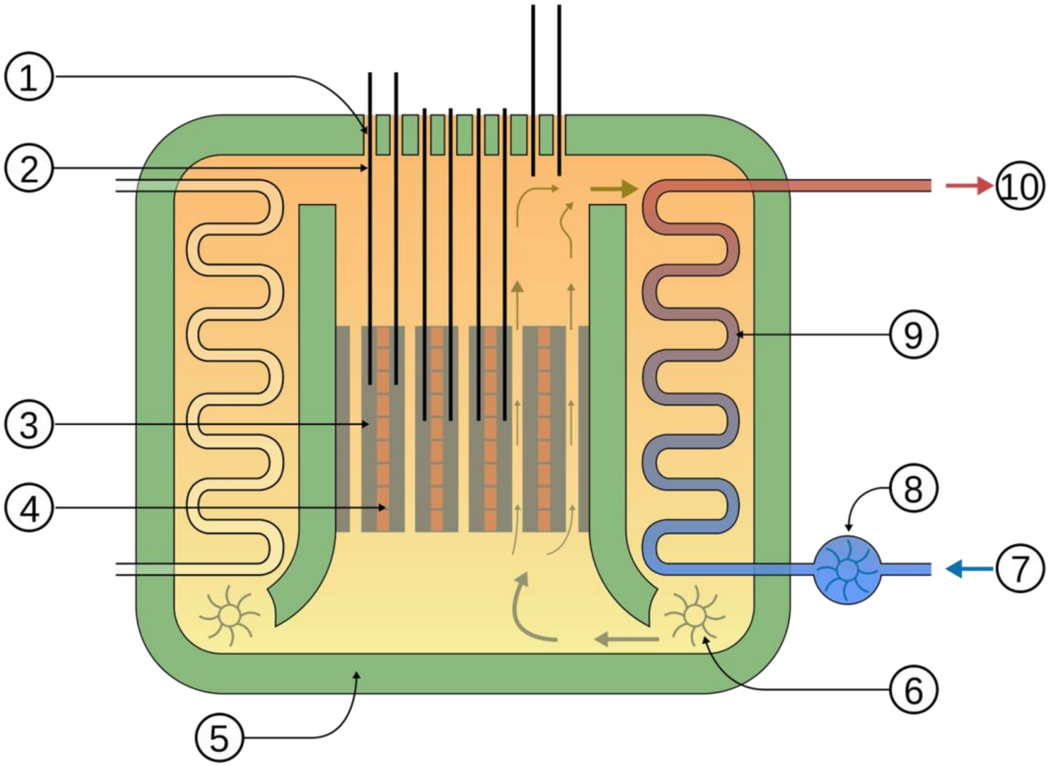
Gas Cooled Reactors

More acronyms:

-NU (natural uranium)

-(L,M,H)EU – (low, medium, high) enriched uranium

AGR
(Advanced Gas-cooled Reactor)



Coolant: CO_2

T_{out}: Med-high

Fuel: LEU

Moderator: Graphite

Power level: Med.

Power density: Low
(Why?)

Feasibility: High

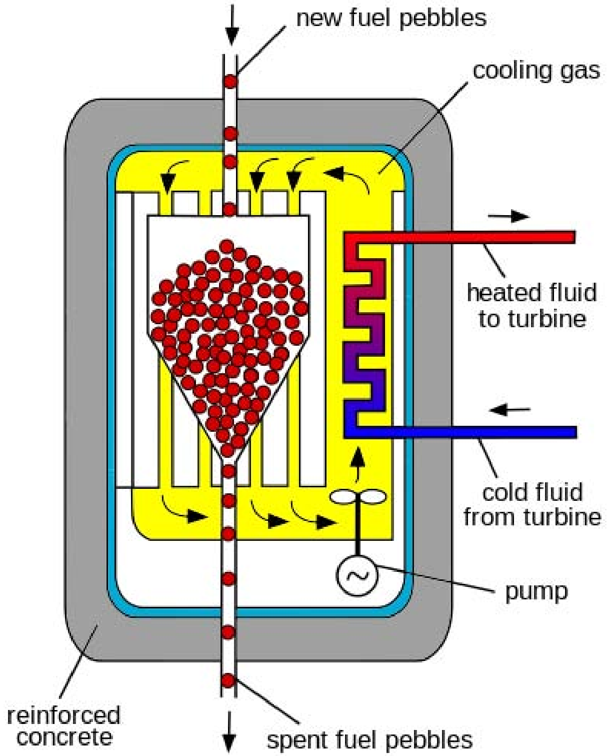
AGR
Special Features, Peculiarities

Courtesy of Sellafield Ltd. Used with permission.

Windscale Prototype AGR
Image source: http://www.sellafieldsites.com/

- Capable of on-load fueling (or part-load)
- Graphite moderator must be cooled due to oxidation in CO_2

PBMR
(Pebble Bed Modular Reactor)



Public domain image.

https://en.wikipedia.org/wiki/Pebble-bed reactor

Coolant: Helium

T_{out}: High

Fuel: LEU - MEU

Moderator: Graphite

Power level: Low – Med.

Power density: Low

Feasibility: Low – Med.

PBMR
Special Features, Peculiarities

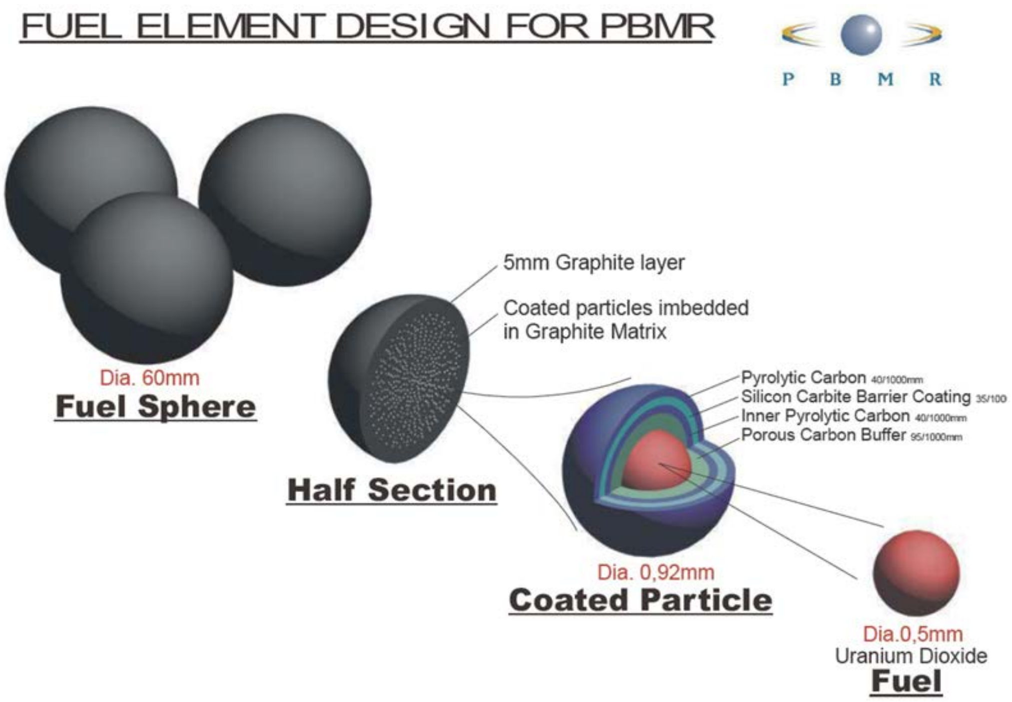
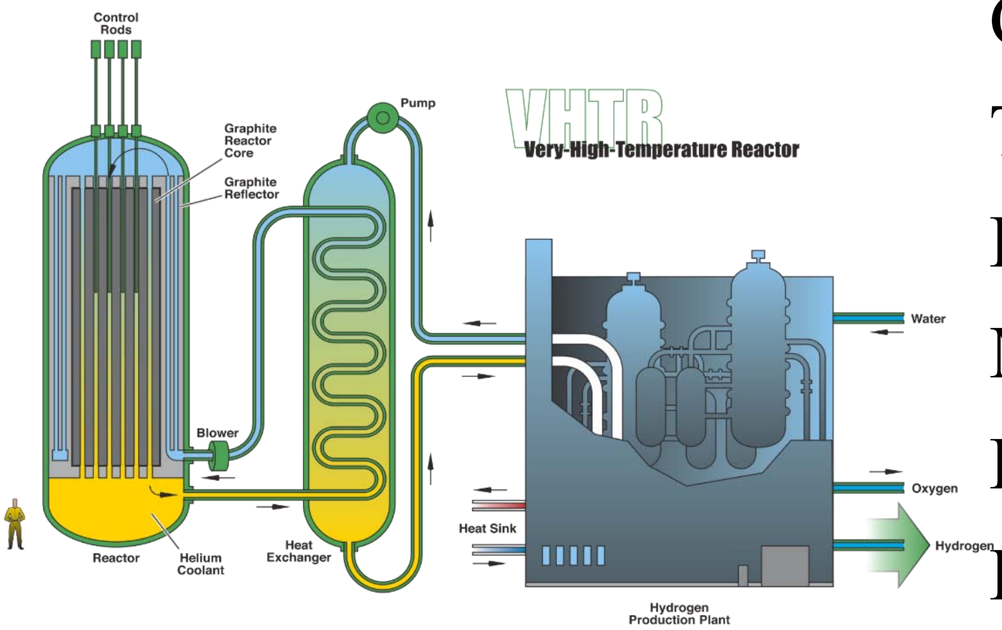


Image source: “High Temperature Gas Reactors: The Next Generation?” Andrew C. Kadak, MIT, July 14, 2004

Courtesy of Andrew C. Kadak. Used with permission.

- Continuous fuel cycle
- Pebble fuel (not rods)
- Pebbles act as built-in disposal methods
- Very passive safety systems (nat. circ.)
- Unknowns: material concerns (fission products), stresses

VHTR (Very High Temperature Reactor)



Courtesy of Idaho National Laboratory. Used with permission.

Coolant: Helium, molten salt

T_{out}: High (very!)

Fuel: LEU - MEU

Moderator: Graphite

Power level: Low

Power density: Low or high

Feasibility: Low – Med.

VHTR
Special Features, Peculiarities

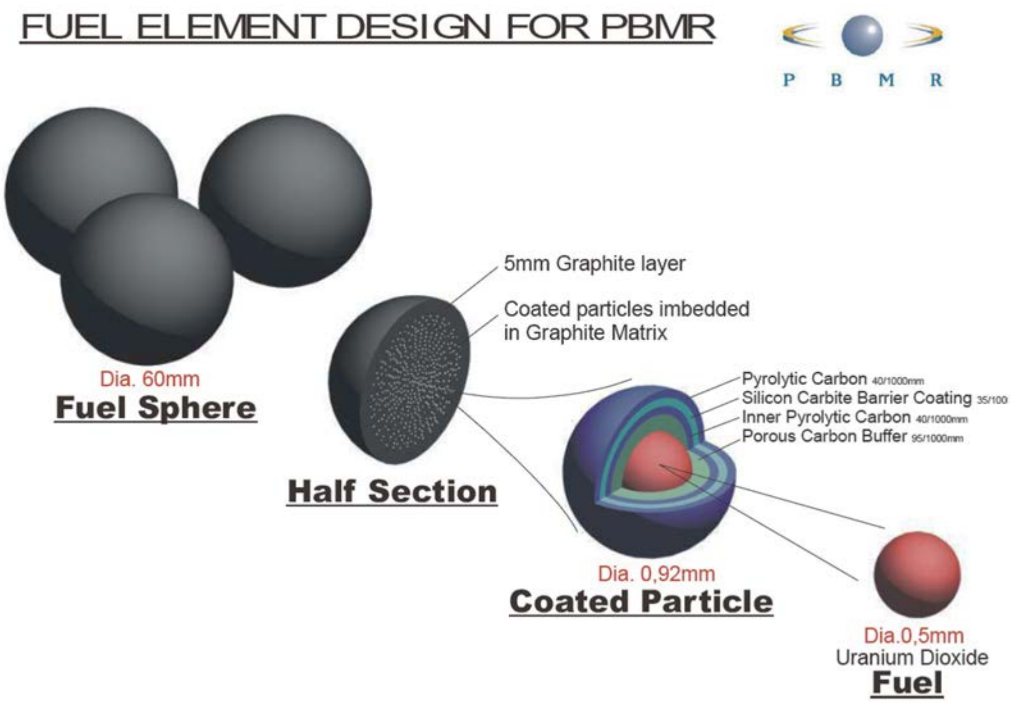


Image source: “High Temperature Gas Reactors: The Next Generation?” Andrew C. Kadak, MIT, July 14, 2004

Courtesy of Andrew C. Kadak. Used with permission.

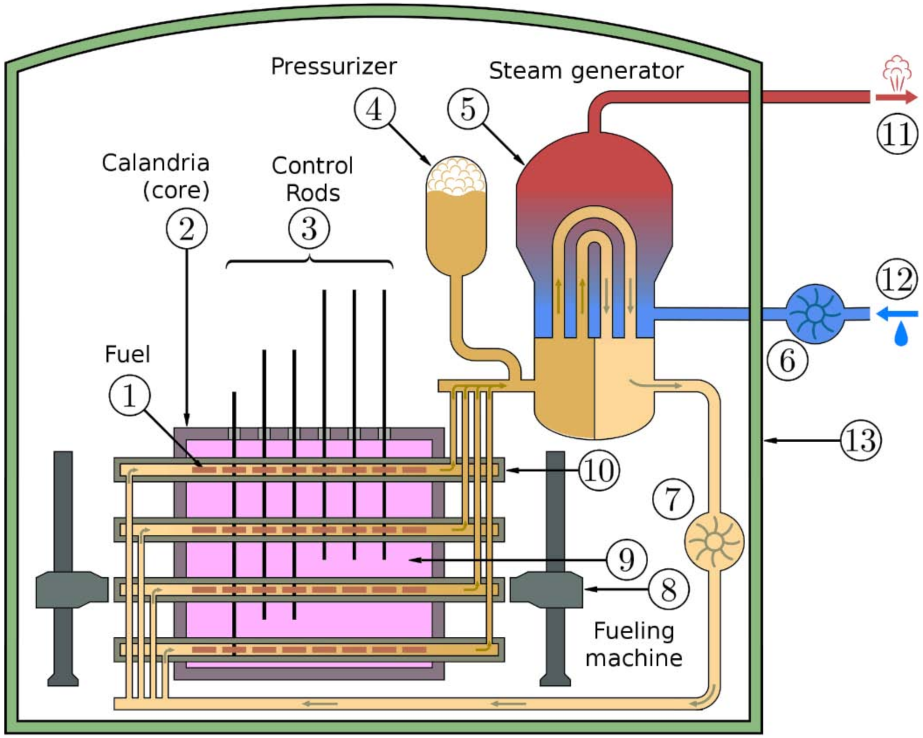
- High T_{out} opens up all doors to hydrogen
- Significant high-T materials concerns
- Molten salt variety can be more corrosive
- Single phase coolant
- TRISO particles, ups & downs

Water Cooled Reactors

More acronyms/symbols:

-D_2O – Deuterium oxide (heavy water)

CANDU – (CANada Deuterium-Uranium reactor)



Courtesy of Wikipedia User: Inductiveload. Used with permission.

Coolant: D_2O

T_{out}: Low

Fuel: NU - LEU (Why?)

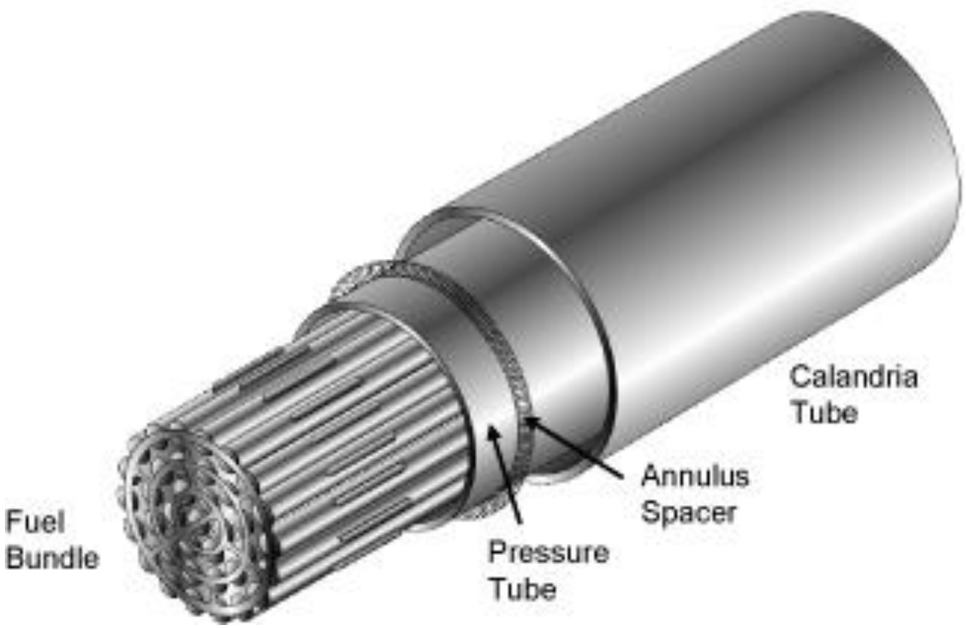
Moderator: D_2O

Power level: Med. - High

Power density: Med.

Feasibility: High

CANDU
Special Features, Peculiarities



Courtesy of NSERC-UNENE Industrial Research Chair Program at University of Waterloo. Used with permission.

CANDU fuel bundle. Image source: http://www.civil.uwaterloo.ca/watrisk/research.html

Continuous fuel cycle

Expensive moderator

-~25% of capital cost

Moderator is unpressurized, thermally insulated

RBMK – Reaktor Bolshoy Moshchnosti Kanalniy

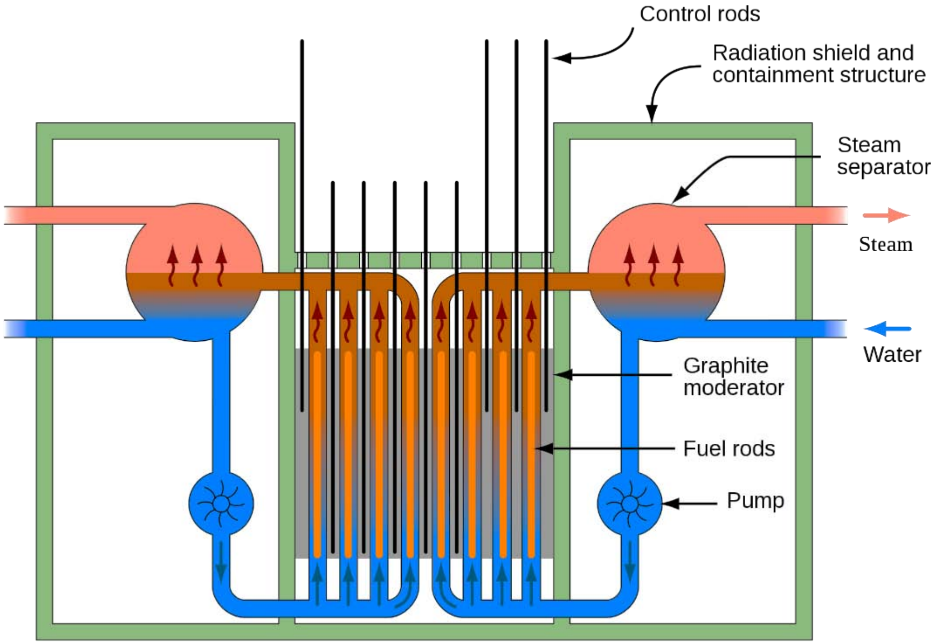


Image source: Wikimedia Commons

Coolant: H_2O

T_{out}: Low

Fuel: NU - LEU

Moderator: Graphite

Power level: High

Power density: Low

Feasibility: Med. (safety)

RBMK
Special Features, Peculiarities

Chernobyl-3 RBMK Reactor Hall. Image source: http://www.sciencephoto.com/media/342208/enlarge

Online refueling possible

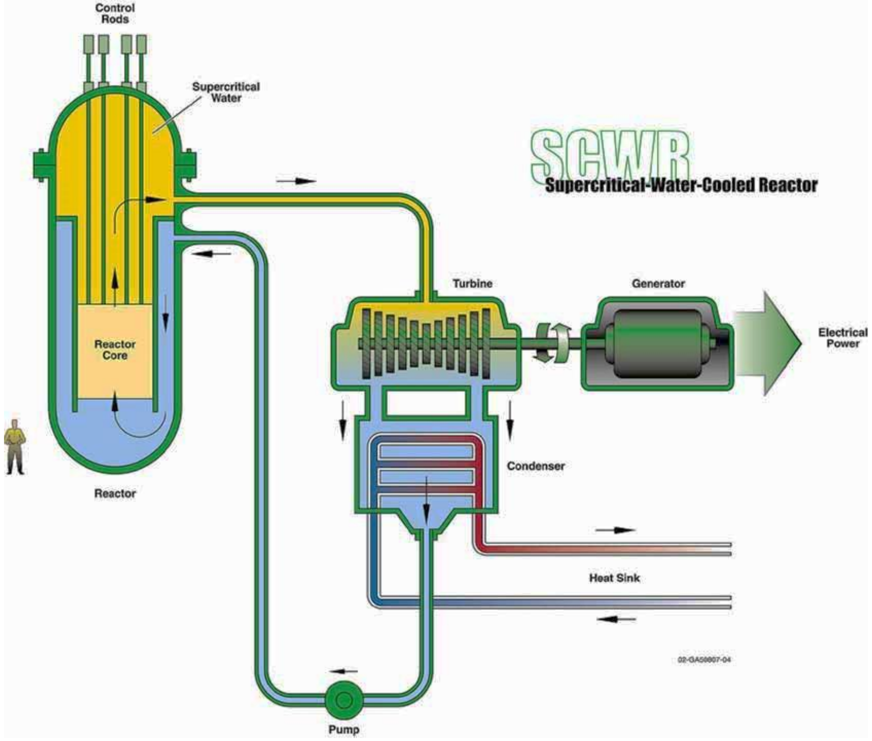
High positive void coefficient – Why?

Improvements in design

-No more graphite-tipped control rods

-More control rods

SCWR
Supercritial Water Reactor



Courtesy of Idaho National Laboratory. Used with permission.

Image source:
http://www.ornl.gov/info/news/pulse/pulse_v120_02.htm

Coolant: SC-H_2O

T_{out}: Med.

Fuel: NU - LEU

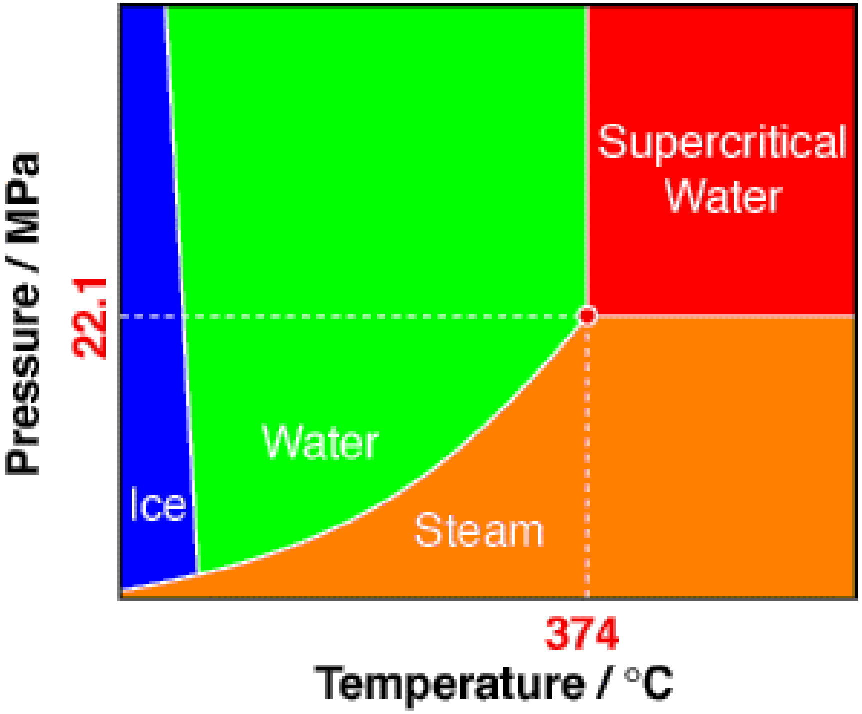
Moderator: SC-H_2O

Power level: High

Power density: High

Feasibility: Low (now)

SCWR
Special Features, Peculiarities



Phase diagram for water. Image source: http://geothermania.blogspot.com/2011/05/research-of-supercritical-water-may.html

- Very simple design
- Significant materials concerns
- Coolant/moderator voiding a non-issue
- High efficiency
- Start-up procedures (pre-heating) to bring coolant supercritial

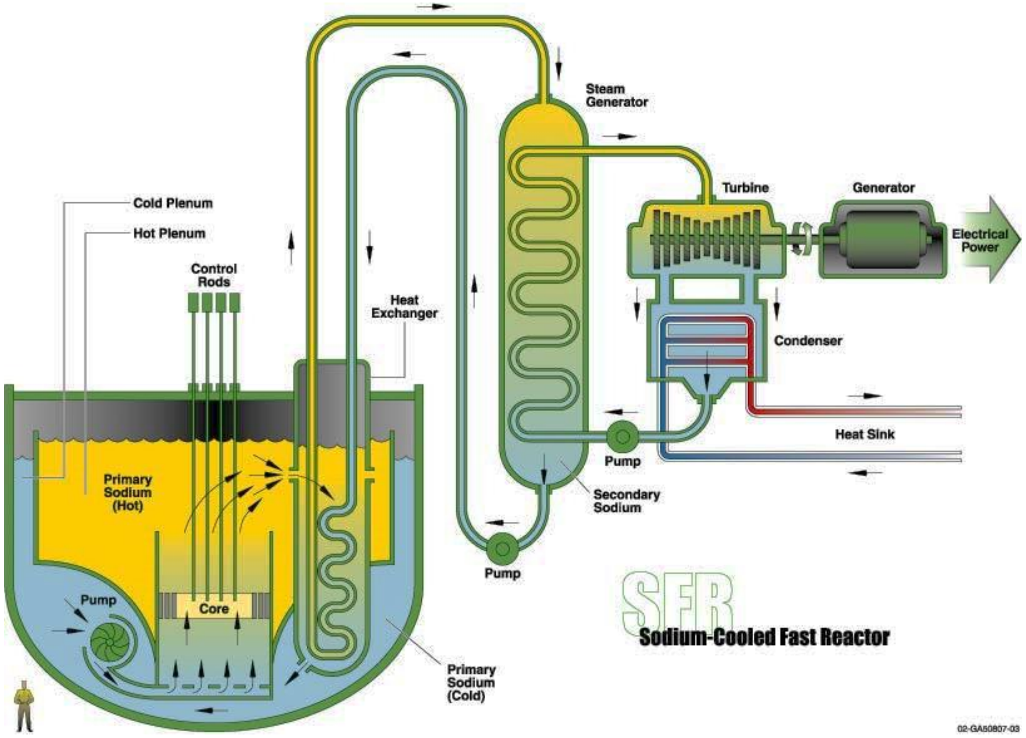
Liquid Metal Cooled Reactors

More acronyms/symbols:

-LBE – Lead-bismuth eutectic

-NaK – Sodium-potassium alloy

SFR (or NaK-FR) Sodium Fast Reactor



Courtesy of Idaho National Laboratory. Used with permission.

Coolant: Liquid sodium

T_{out}: Med.

Fuel: NEU - HEU

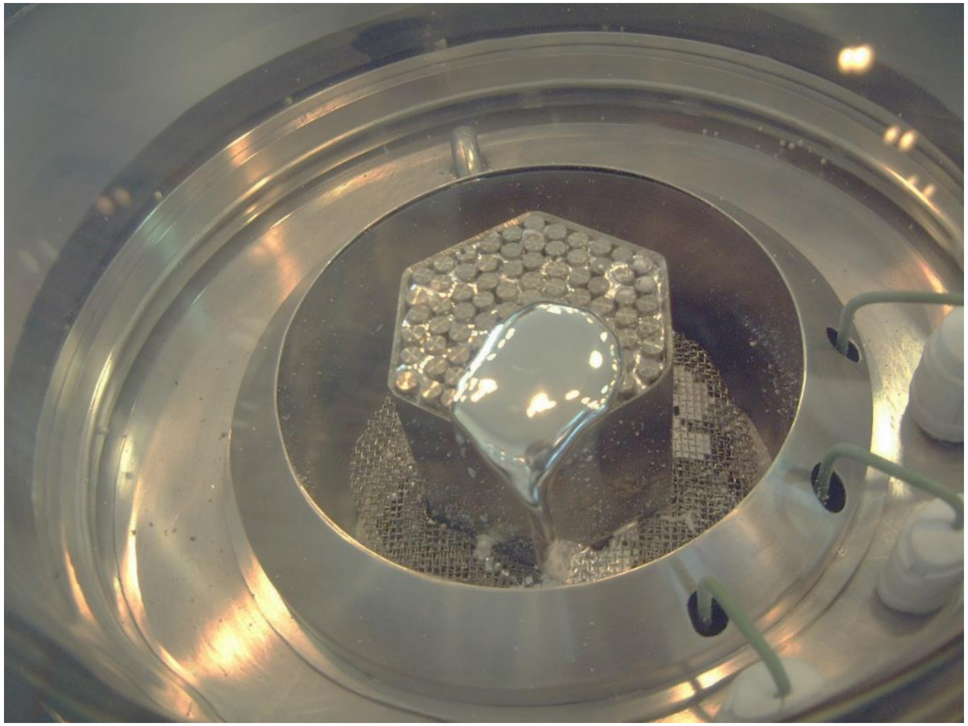
Moderator: None

Power levels: All

Power density: High

Feasibility: Low-Med. (now)

SFR
Special Features, Peculiarities



Courtesy of and copyright Bruno Comby / EFN - Environmentalists For Nuclear Energy. Used with permission.

Molten sodium at MONJU, Japan. Image source: http://www.ecolo.org/photos/visite/monju_02/monju.sodium.hot.melted.jpg

No pressurization

Very high k, c_P

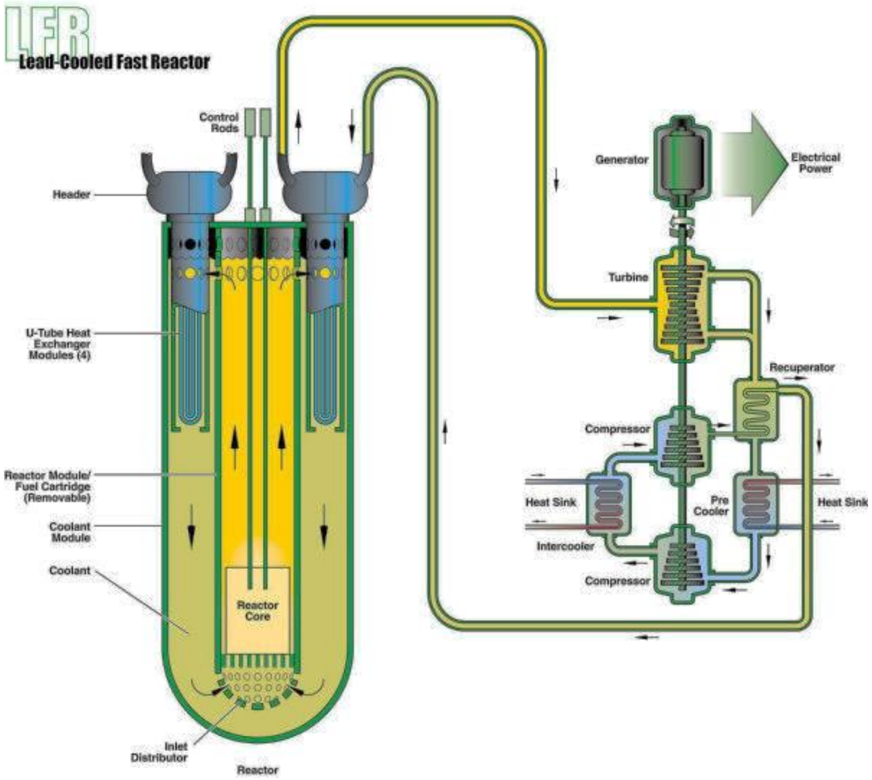
High material compatibility

High boiling margin

Neutron activation – worker dose concerns

$Na + H_2O$ = RUN AWAY

LFR (or LBEFR)
Lead Fast Reactor



Courtesy of Idaho National Laboratory. Used with permission.

Coolant: Lead (or LBE)

T_{out}: Med. (higher soon...)

Fuel: MEU

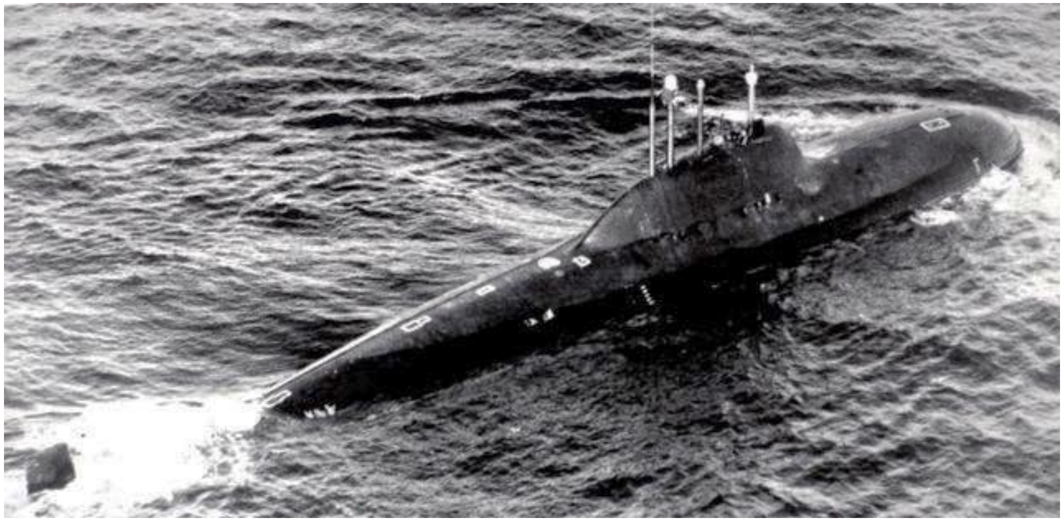
Moderator: None

Power levels: All

Power density: High

Feasibility: Low-Med. (now)

LFR
Special Features, Peculiarities



Public domain image. (Source: Wikimedia Commons)

Alfa-class Russian submarine, using a LFR as its propulsion system.

High heat capacity

Self-shielding

Must melt coolant first

Essentially no coolant voiding possible

Polonium creation

Material corrosion

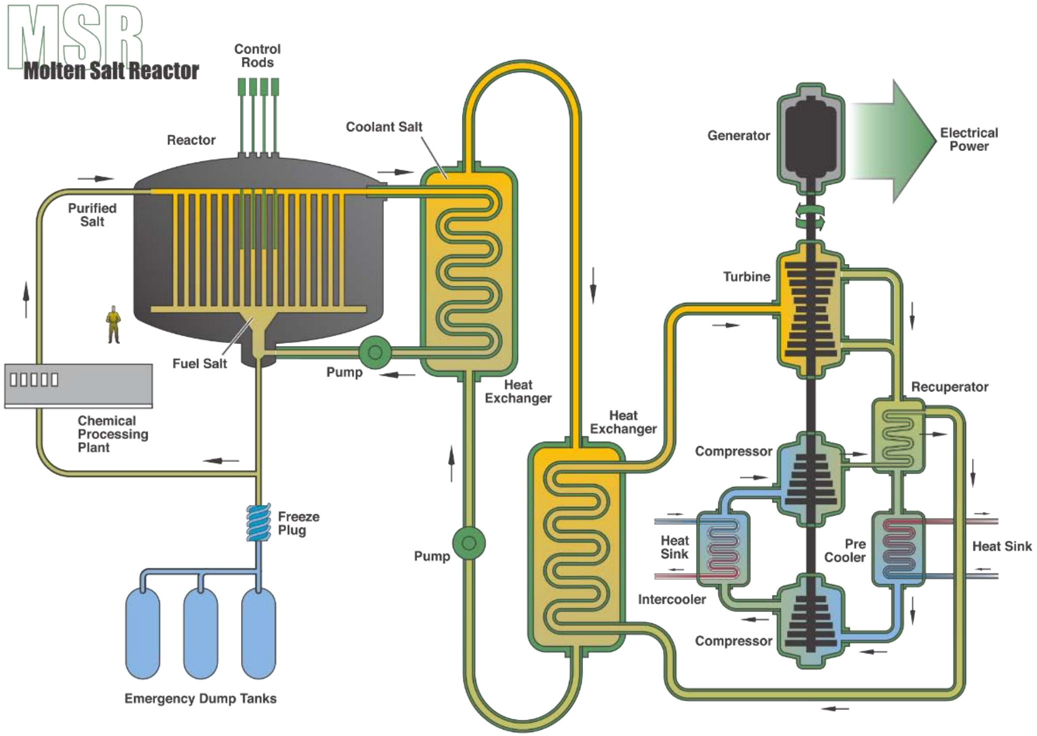
Coolant cost (LBE)

Molten Salt Cooled Reactors

More acronyms/symbols:

-FLiBe – Lithium & beryllium fluoride salts

MSR
Molten Salt Reactor



Courtesy of Idaho National Laboratory. Used with permission.

Coolant: FLiBe, UF_4

T_{out}: Med. - High

Fuel: MEU

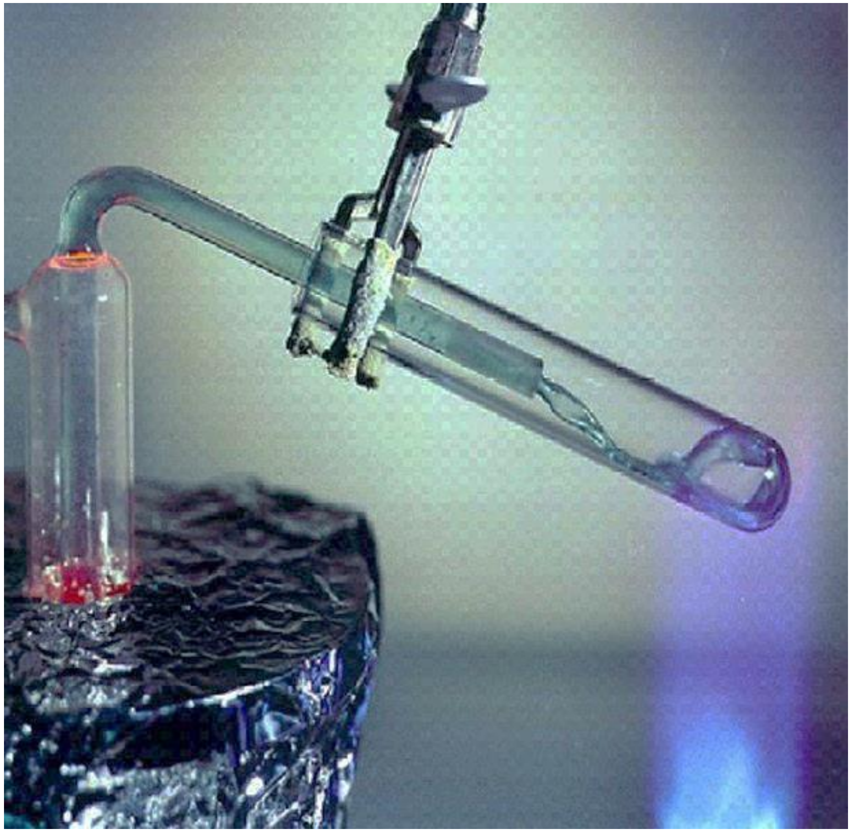
Moderator: Graphite

Power levels: All

Power density: High

Feasibility: Med. (now)

MSR
Special Features, Peculiarities



Public domain image.

Molten FLiBe. Image source: Wikimedia Commons

Unpressurized core

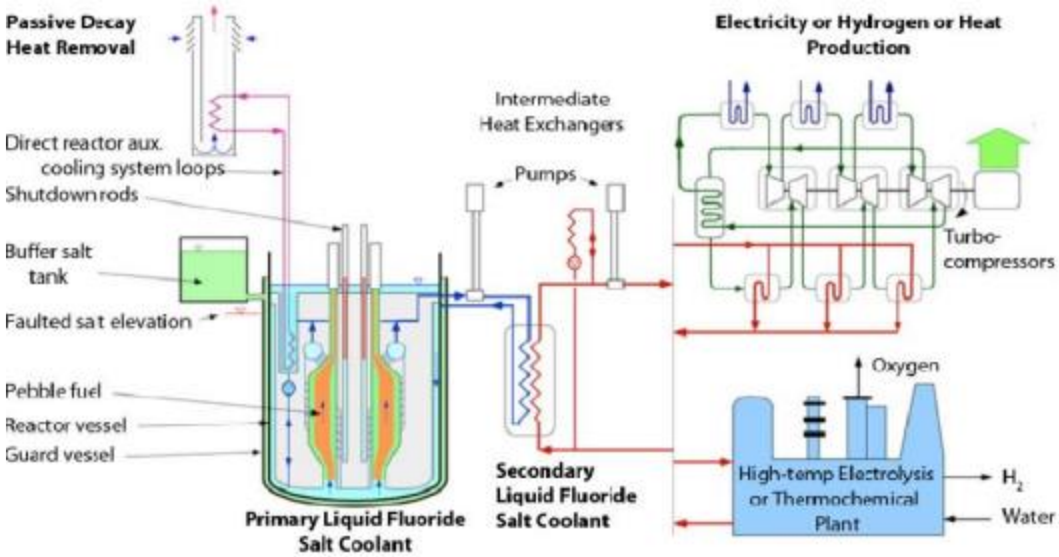
ThF_4/UF_4 fluid can be both fuel & coolant

Very negative temperature coeff.

High neutron flux causes $Li \rightarrow {}^3H$, ${}^3H + F^- \rightarrow HF$ (hydrofluoric acid)

On-site salt reprocessing

FHR: Fluoride-salt-cooled High-temperature Reactor



See K. Sridrahan, "Fluoride Salt-Cooled High-Temperature Reactor (FHR) – Materials and Corrosion." Presentation, IAEA, Vienna, Austria, June 10-13, 2004.

Coolant: FLiBe

T_{out}: Med. - High

Fuel: MEU

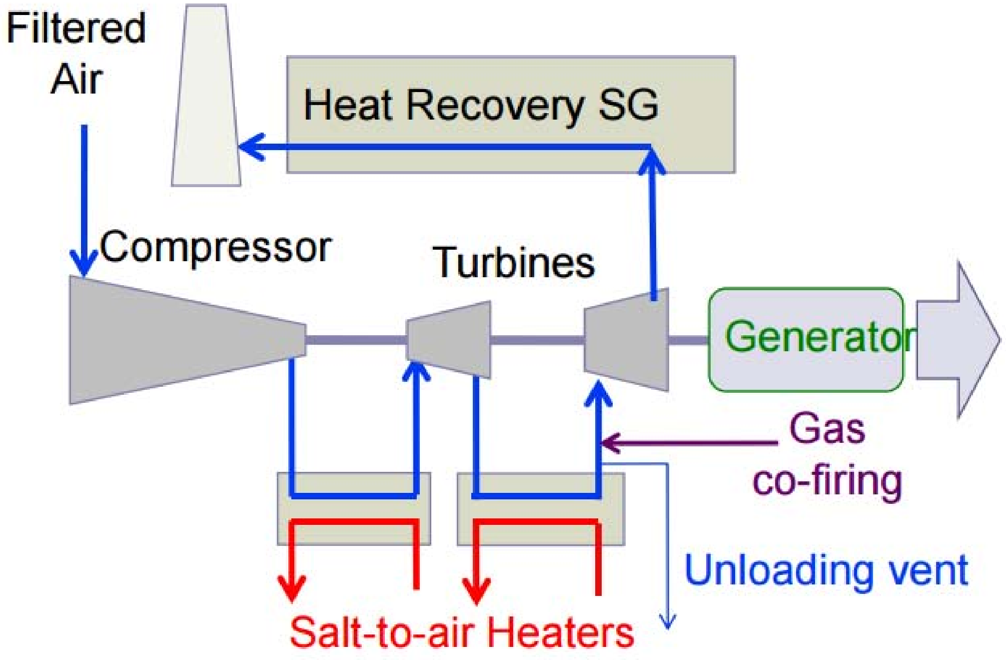
Moderator: Graphite

Power levels: All

Power density: High

Feasibility: Med. (now)

FHR: Nuclear & Air Brayton Combined Cycle



Public domain image.

Image source: P. Peterson et al., "Integrated Research Project FHR Overview for DOE Nuclear Energy Advisory Committee." [**http://energy.gov/sites/prod/files/2013/06/f1/FHRIRPPerPeterson_0.pdf**](http://energy.gov/sites/prod/files/2013/06/f1/FHRIRPPerPeterson_0.pdf)

"Nuclear afterburner"

Allow gas co-firing to meet peak demand

Always meet baseline demand anyway

Fusion Systems: Tokamak

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

$$^{2}H + ^{3}H \rightarrow \alpha + n + 17.59\,MeV$$

- Magnetic Confinement
- 800 million degrees Kelvin
- ~14 MeV neutrons
- Alpha heating
- Scaling
- Stability Issues
- 27 tokamaks in operation

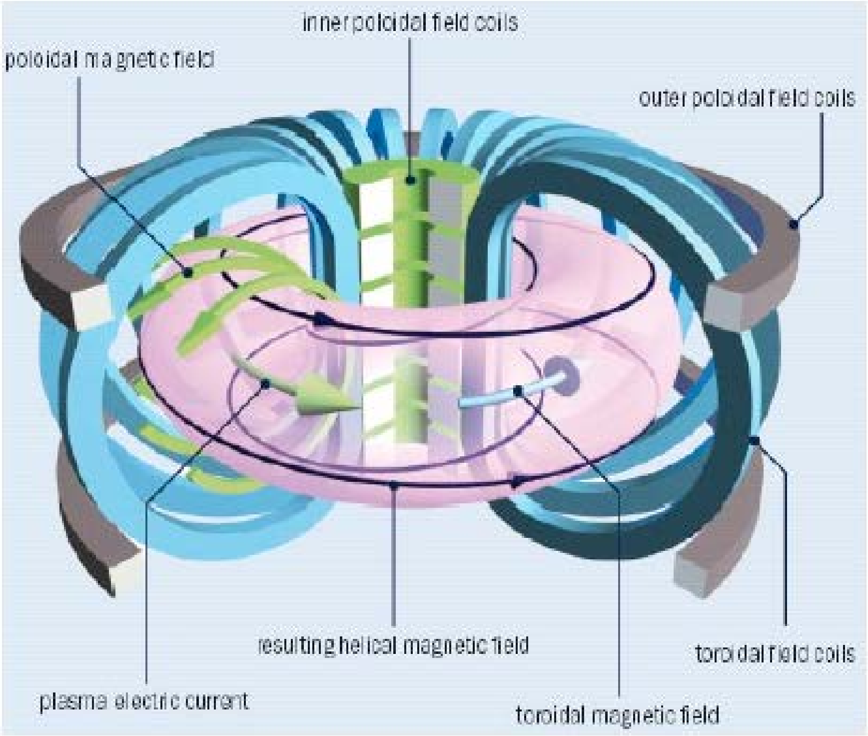
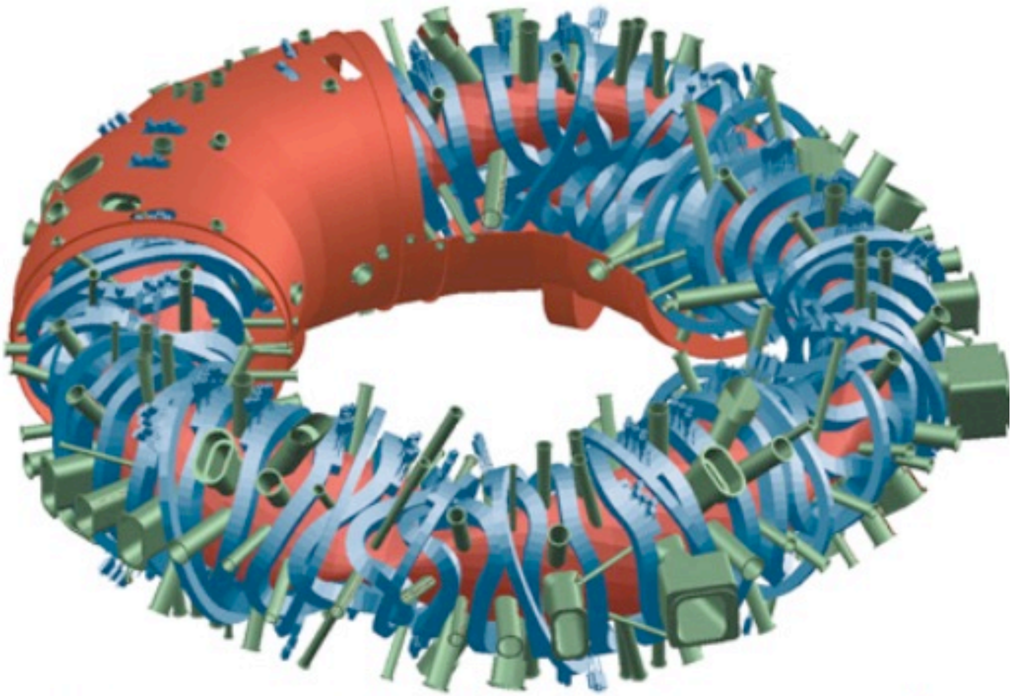


Figure above: The electromagnetic coil set-up of JET (Joint European Torus). **Source:** http://www.efda.org/2011/09/tokamak-principle-2

Fusion Systems: Stellarator

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

- Complicated magnetic configuration
  - Difficult maintenance, expensive
- No large externally driven current
  - Inherently steady state
  - Resistant to disruptions
- Comparable in size to Tokamak power plant



Above: A conceptual view of the W7-X stellarator, set to make its first plasma in 2014. Shown in blue is the magnetic field coils. **Source**: http://newenergyandfuel.com/wp-content/uploads/2008/03/stellarator-cutaway-view.jpeg

Fusion Systems: Spherical Tokamak

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

- Similar to tokamak, but low aspect ratio
- Allows for more energy generation in a compact size (R=3.4m vs. $R_{tokamak}$=9.55m)
- Material concerns
- Not as well understood-poorer performance
- Central solenoid can be removed for maintenance [2]

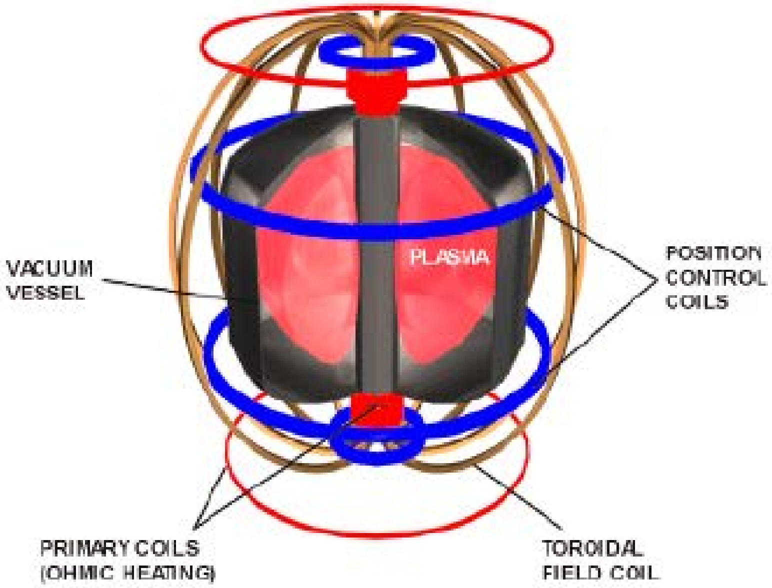
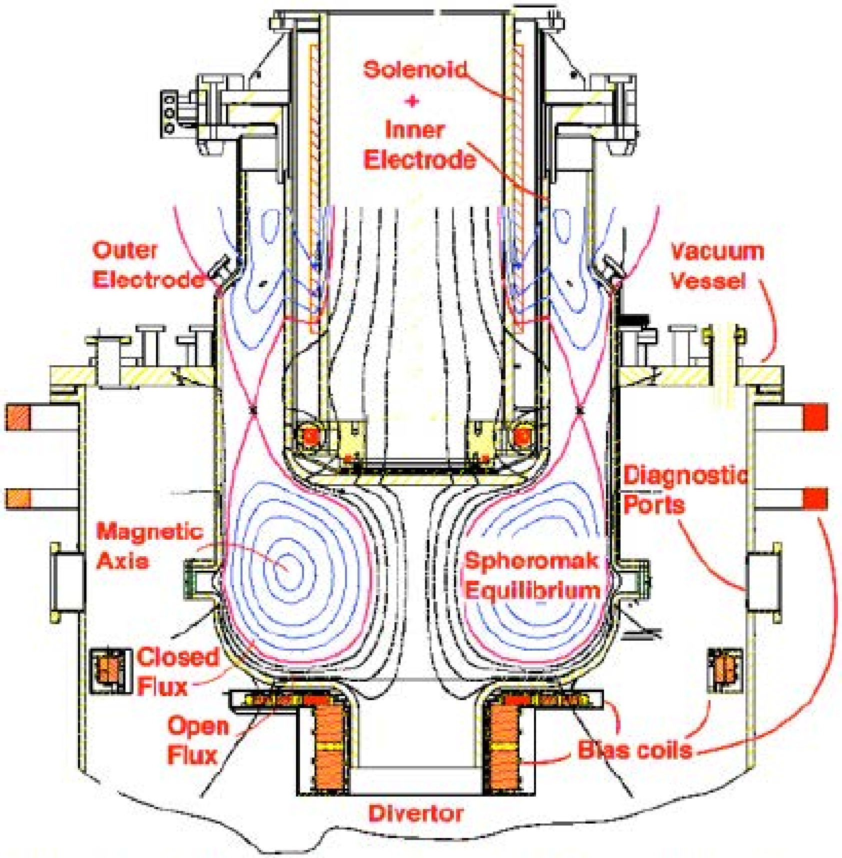


Figure above: A basic design of the spherical tokamak system. **Source:** http://www.plasma.inpe.br/LAP_Portal/LAP_Site/Figures/ETE_3D_Schematic.gif

Fusion Systems: Spheromak

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

- No external magnetic coils required to link fusion plasma through central axis
- Confinement fields generated primarily by plasma current
- High power density
- Simply connected geometry
  - Order of magnitude lower volume and area than the Tokamak



Above: Schematic of the Spheromak design. **Source:** http://icc2006.ph.utexas.edu/uploads/177/icc2006_reconnection.pdf

Fusion Systems: Inertial Confinement

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

- Great power performance- closest to ignition
- Takes up large area because of powerful lasers and remanufacturing plant
- More activated material to dispose of
- Remanufacturing plant will take away some of potential electrical energy

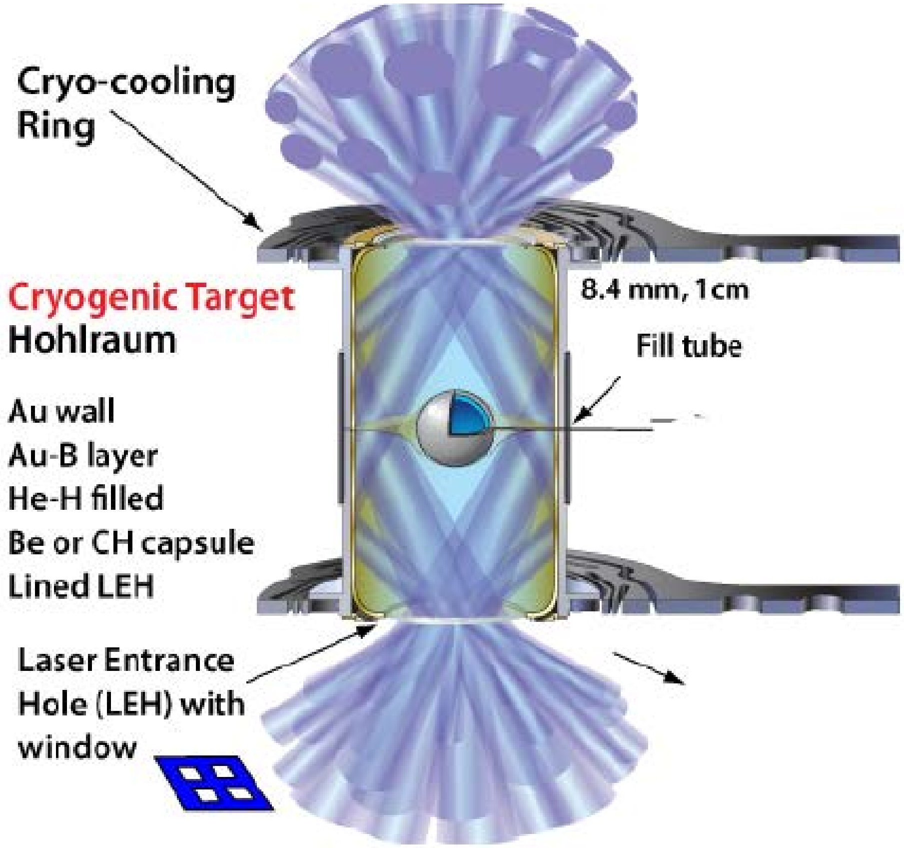


Figure above: Schematic of how to heat up fuel pellet. Lasers reflect of walls of hohlraum for even heating. **Source:** https://lasers.llnl.gov/for_users/images/energetics_01.jpg

Fusion Systems: Z-Pinch

Slide courtesy of C. French, E. Sykora, V. Winters. 22.033 Design Project. 27 September 2013

- Inertial Confinement
- Application of Lorentz Force
- Large capacitor dumps energy into plasma
- Billions of kelvin
- Reloading time
- Few produced

courtesy of NASA.

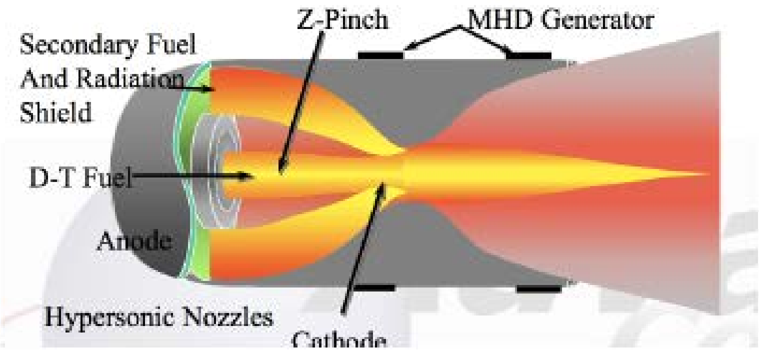


Figure above: Advanced space propulsion on a flow stabilized Z-Pinch device **Source:** FUSION PROPULSION Z-PINCH ENGINE CONCEPT , J. Miernik et al., Advanced Concepts Office, Marshall Space Flight Center

Courtesy of DOE.

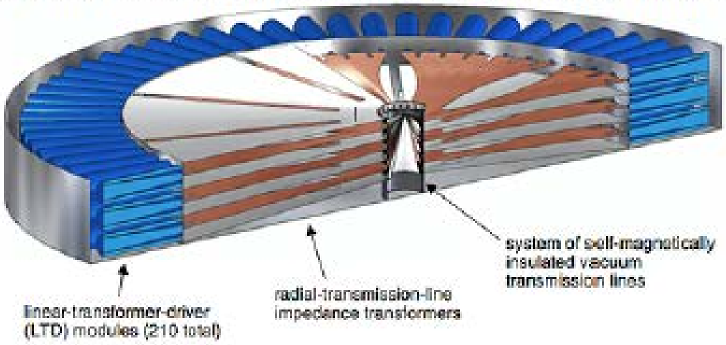


Figure above: 1000 TW LTD-based z-pinch accelerator **Source:** http://en.wikipedia.org/wiki/File:Petawatt_LTD_z_pinch.png

22.01 Introduction to Nuclear Engineering and Ionizing Radiation
Spring 2024