Introduction to Nuclear Energy

22.01 – Intro to Radiation

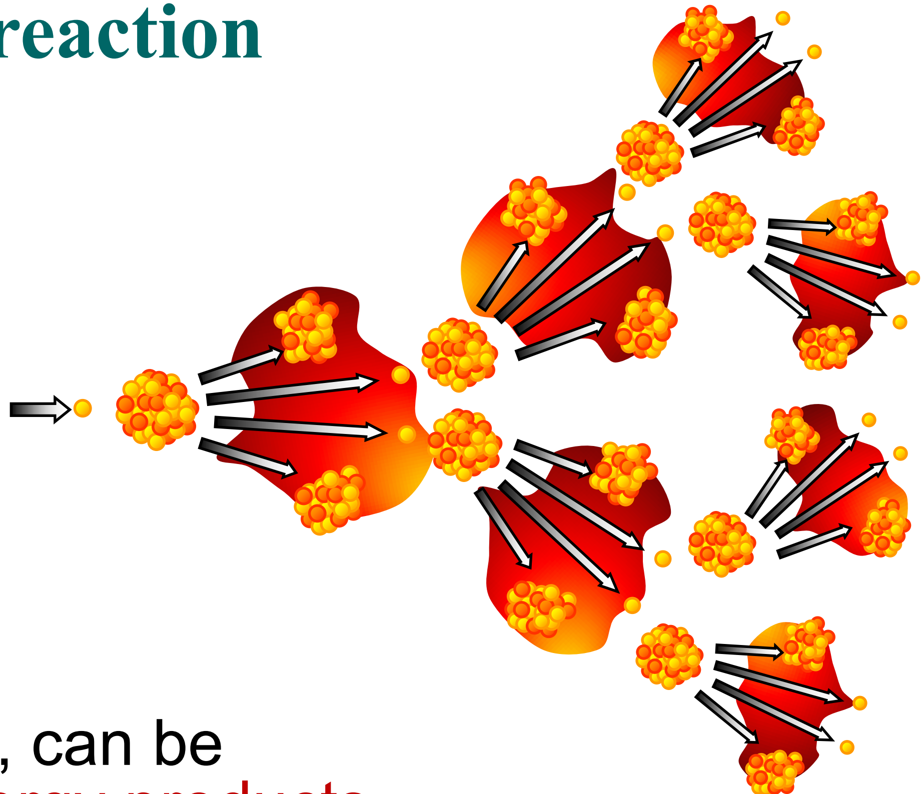
September 16, 2015

*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): $C + O_2 \rightarrow CO_2 +$ **4 eV**

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

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

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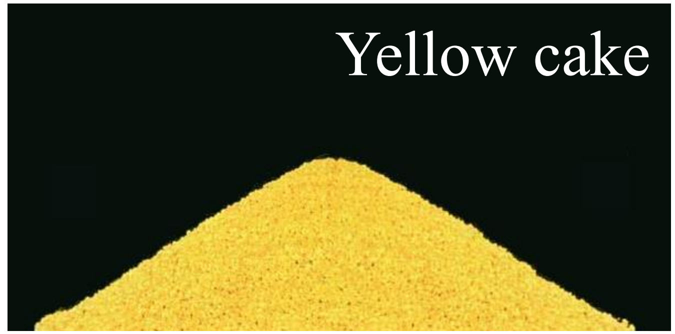
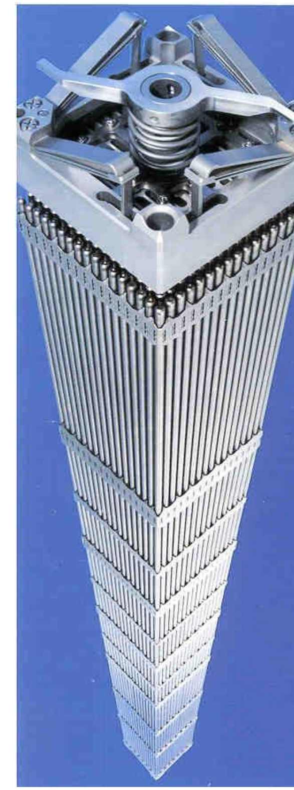
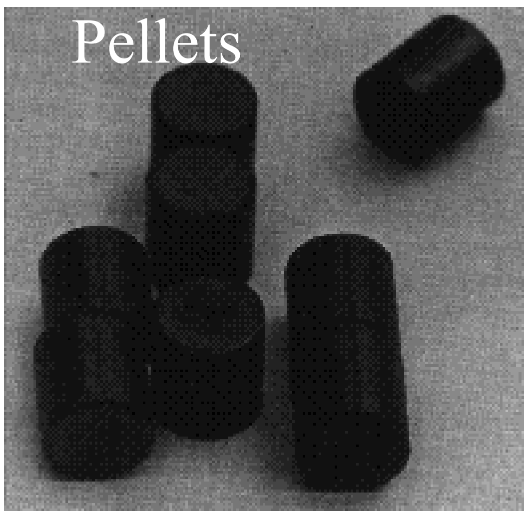
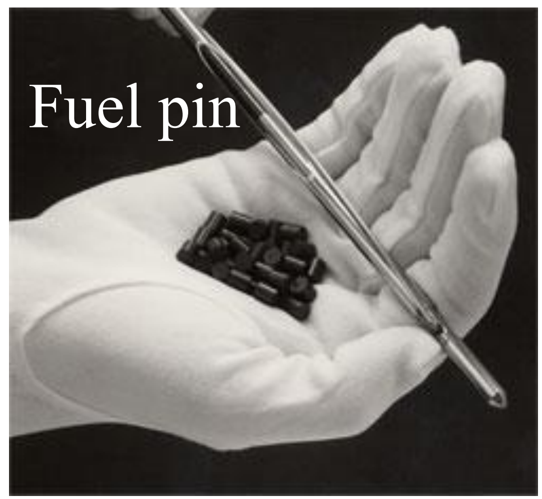
From Rocks to Reactors

U ore









Fuel assembly

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Reactor Intro: Acronyms!!!

LBEFR

RBMK

CANDU

LBE

LFR

IFR

NNFR

PHWR

AGR

MSR

GFR

VHTR

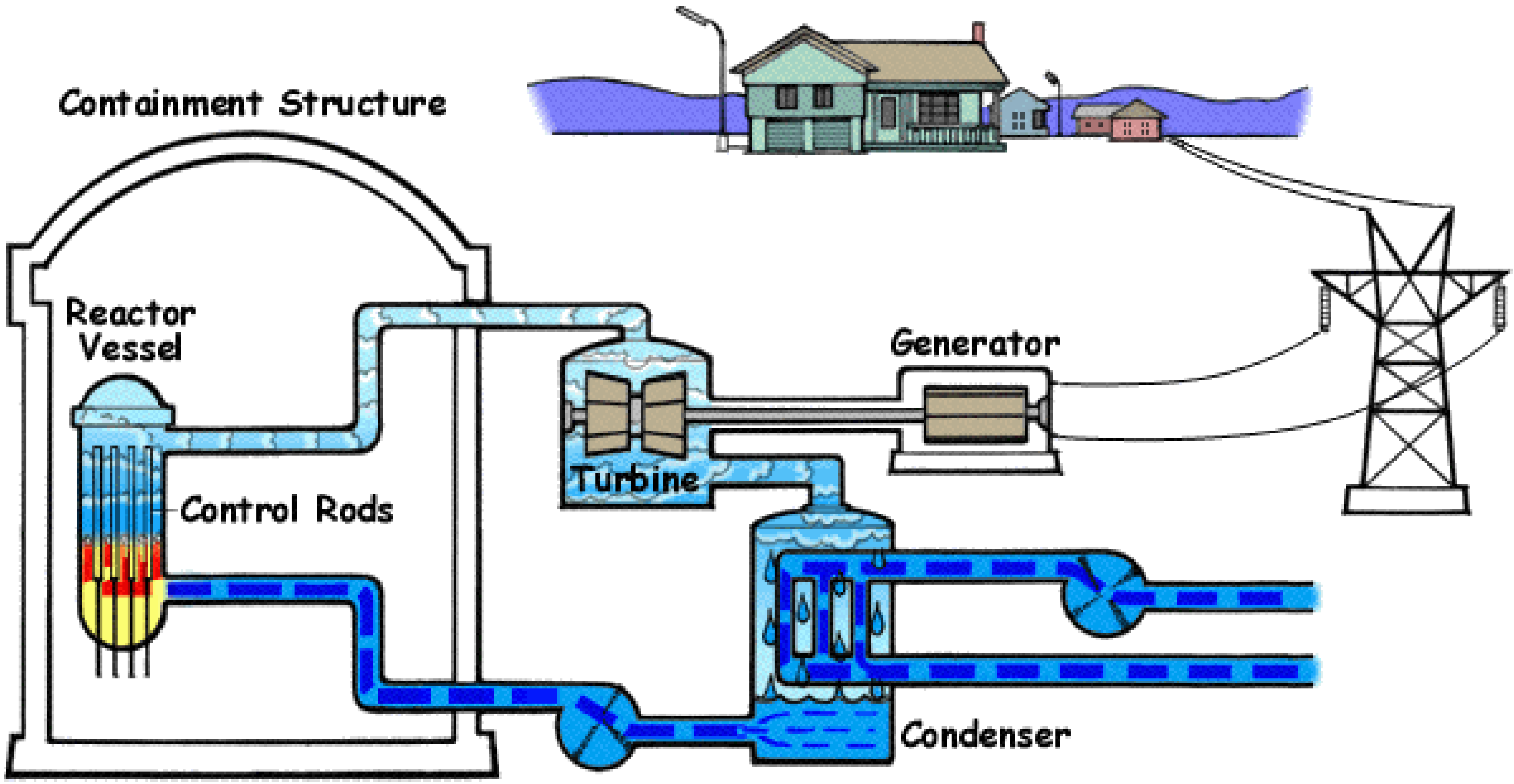
SCWR

SFR

PBMR

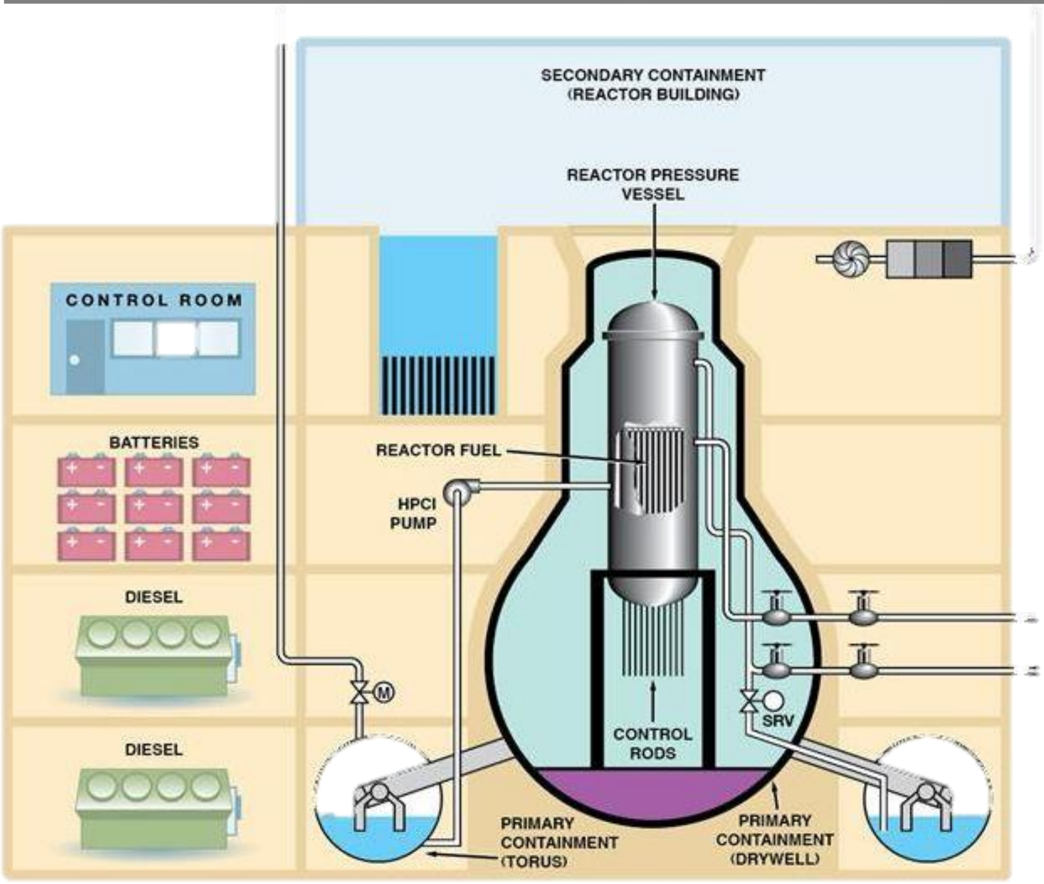
NaK

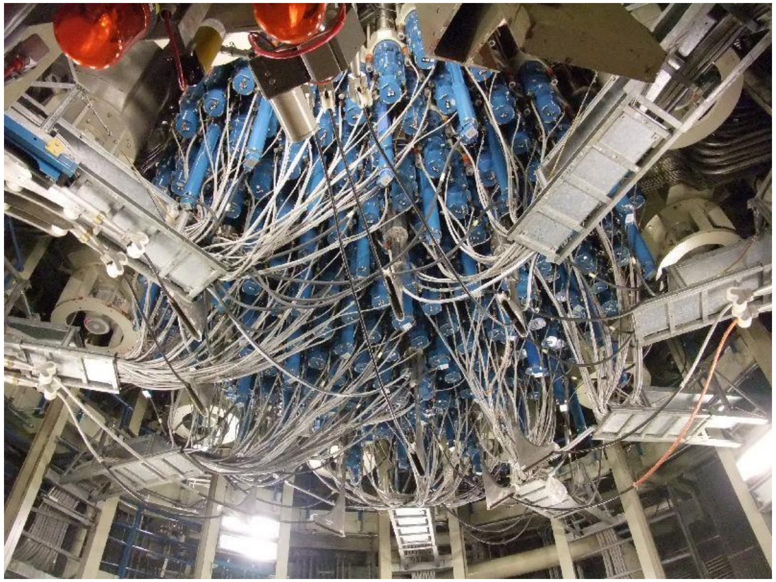
Boiling Water Reactor (BWR)



Public domain image, from U.S. NRC.

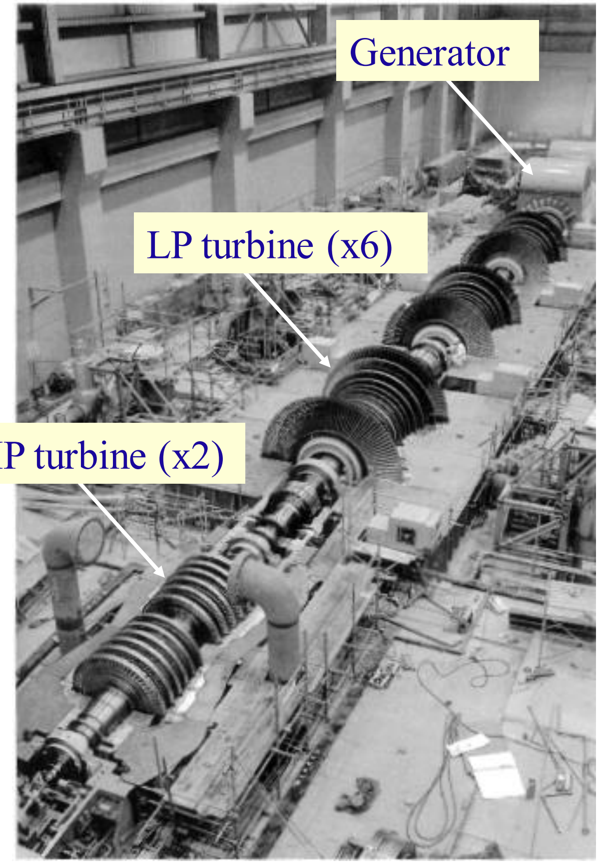
BWR Primary System





BWR Underside

Turbine and Generator



Turbine-generator

turns heat into work, then electricity

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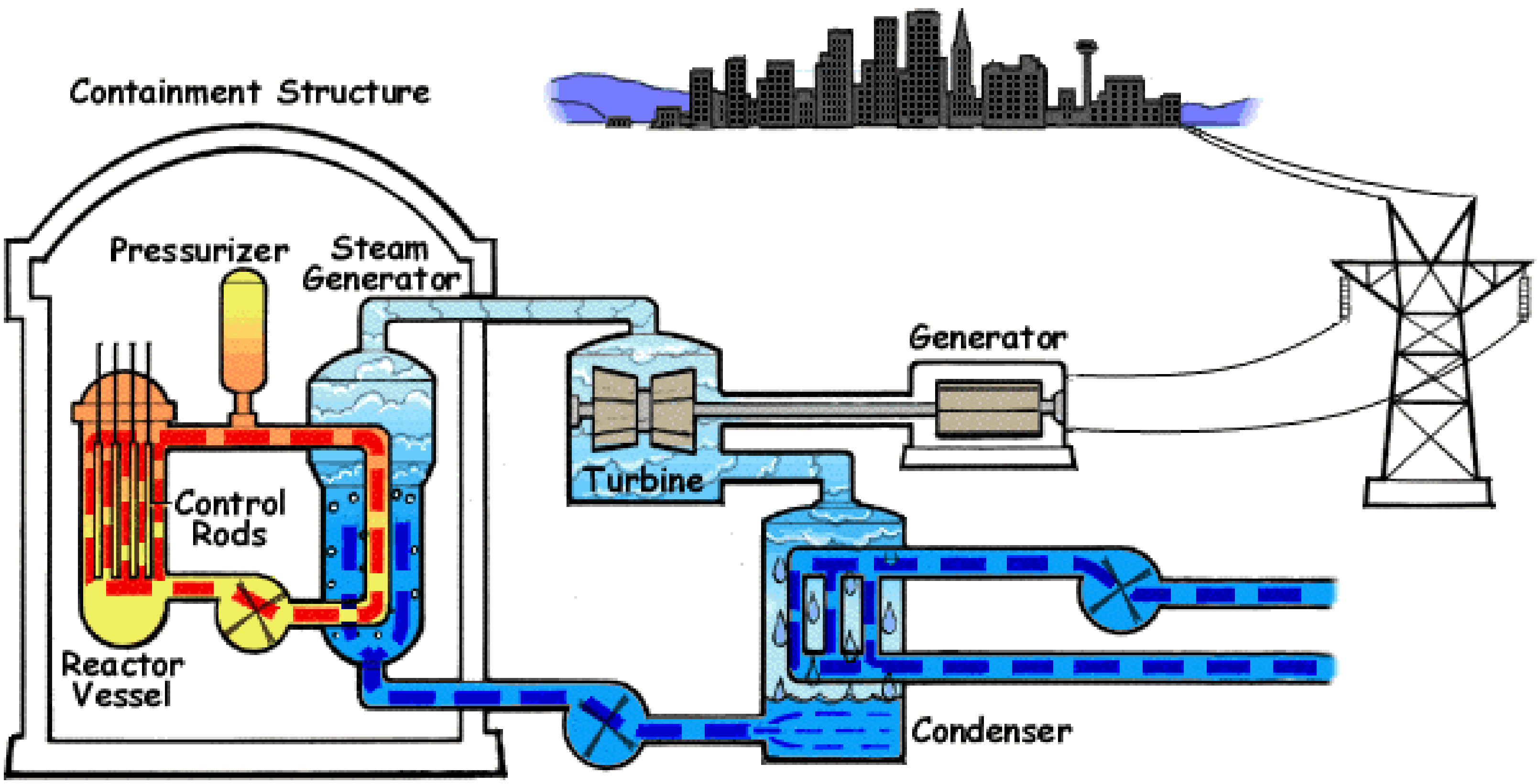
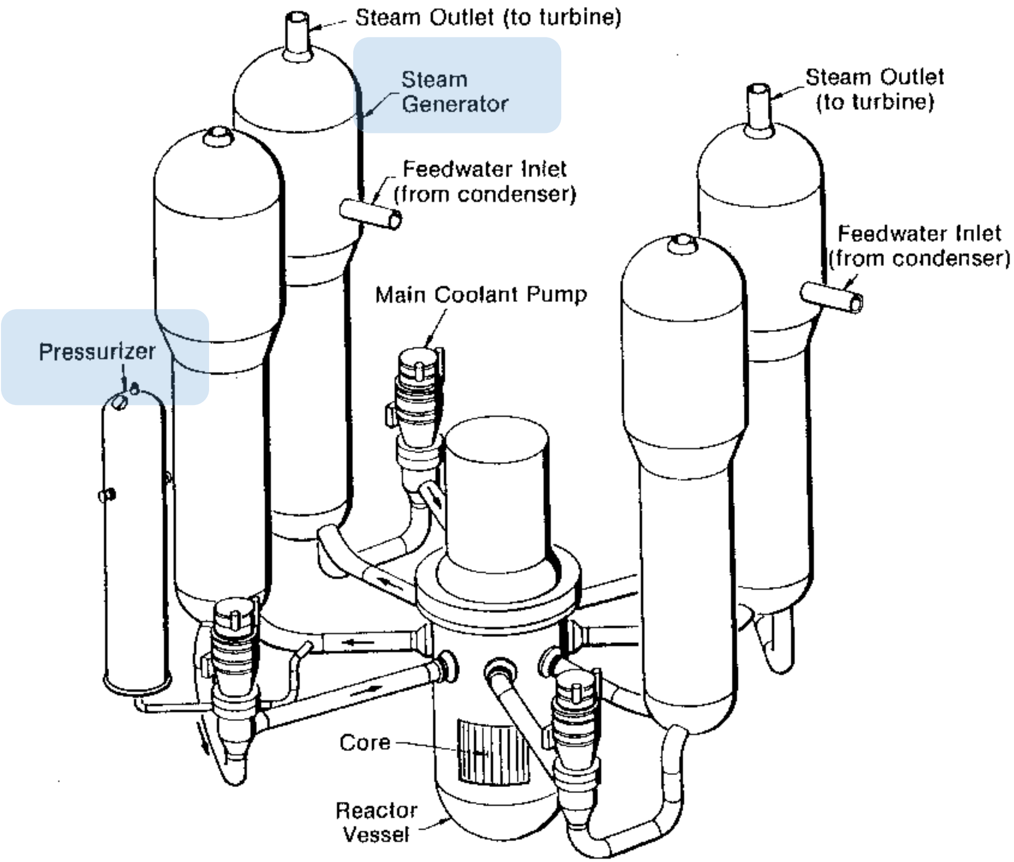
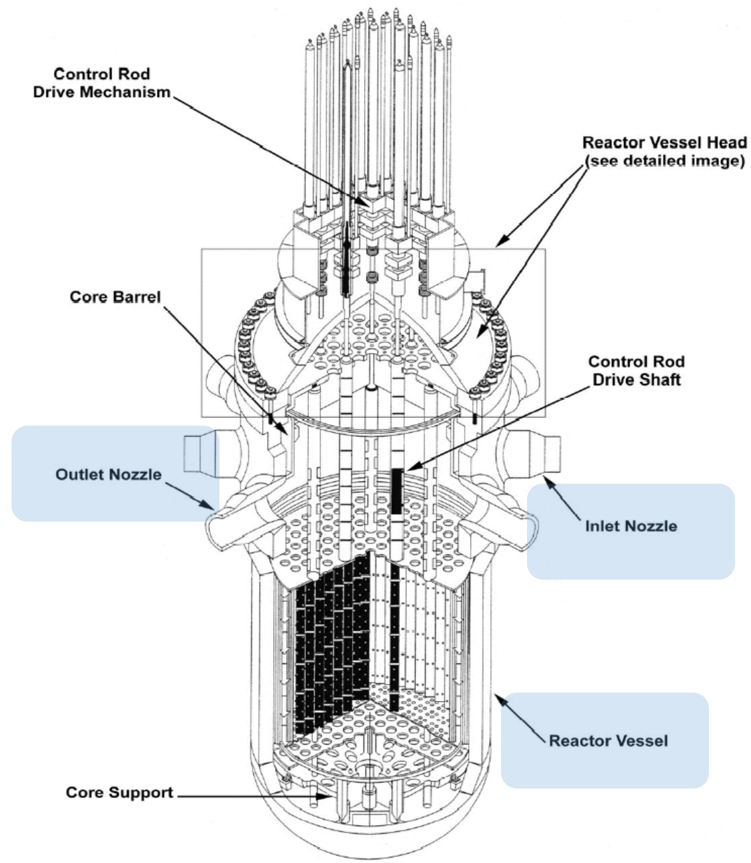
Pressurized Water Reactor (PWR)



Public domain image, from U.S. NRC.

PWR Primary System





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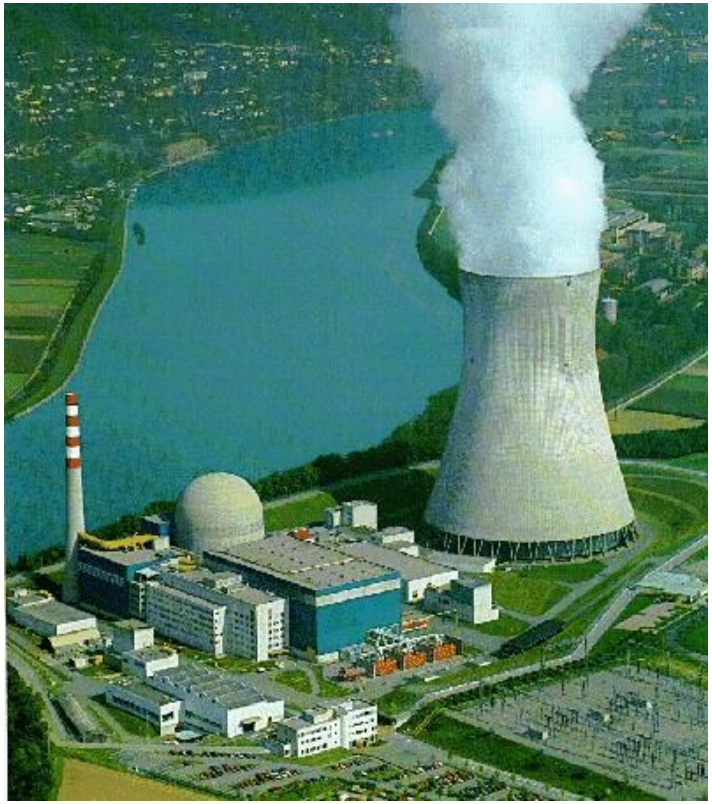
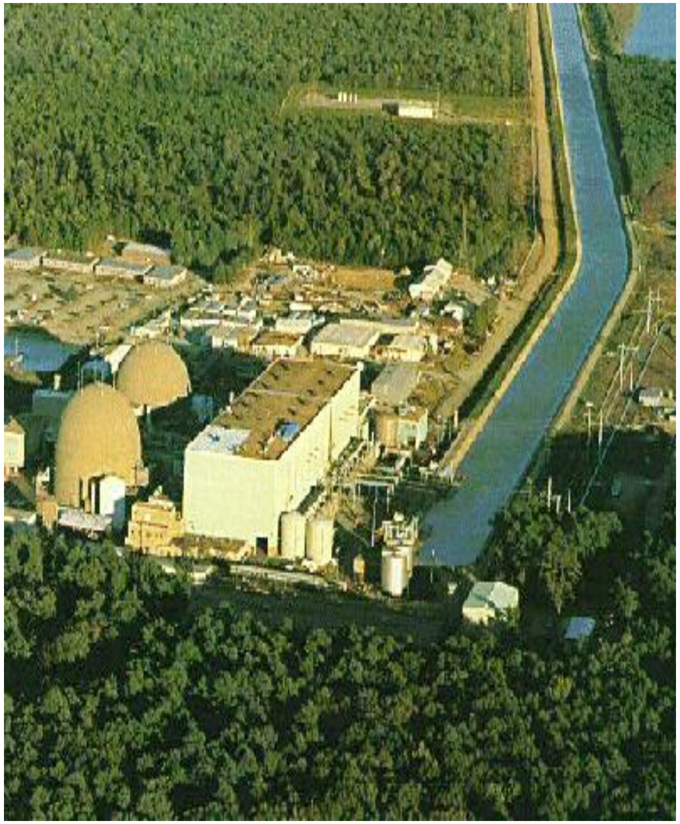
Heat Discharge in Nuclear Plants





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Nuclear Energy Today in the US

- **100 US reactors, 100 GWe is 13% of US installed capacity, which provides about 19% of total electricity.**
- **In 2010 nuclear energy production in the US was the highest ever.**
- **US plants ran at 86.4% capacity in 2012, up from 56% in 1980.**
- **3.1 GWe of uprates were permitted in the last decade.
  1.5 GWe are expected by 2017.**
- **73 reactor licenses extended, from 40 years to 60 years of operation, 27 more reactors in process.**
- **Electricity production costs of nuclear are the lowest in US (1.9-2.9 ¢/kWh), but natural gas costs have come down**

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US Nuclear Plants (LWRs)

Photos of various plants removed due to copyright restrictions.

See map of U.S. nuclear reactor locations, with photos, at
http://www.nrc.gov/info-finder/reactors/

The MIT Research Reactor

- 6 MW power
- Located near NW12, Albany St.
- Operated by MIT students
- In service since 1958!

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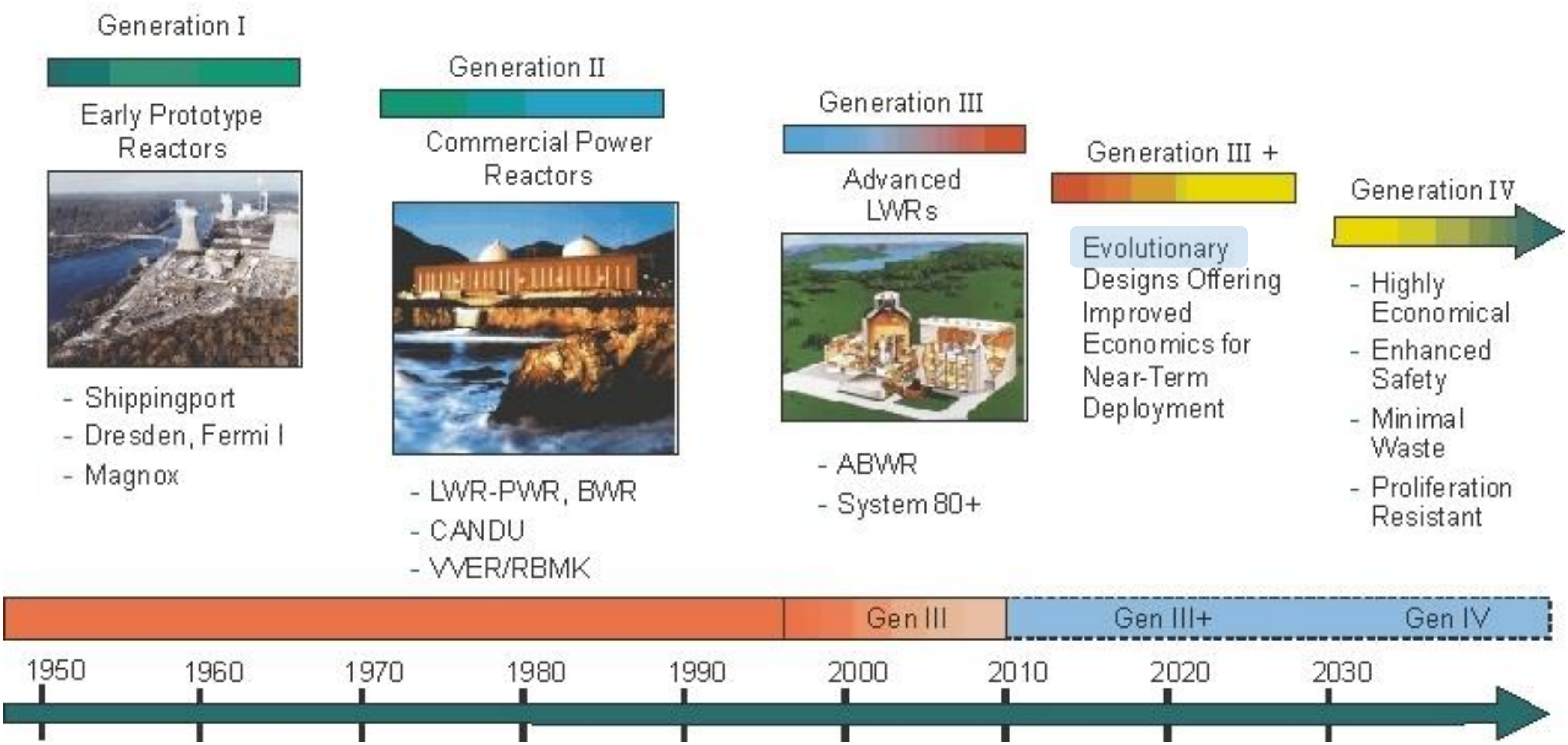
Nuclear Reactor Timeline



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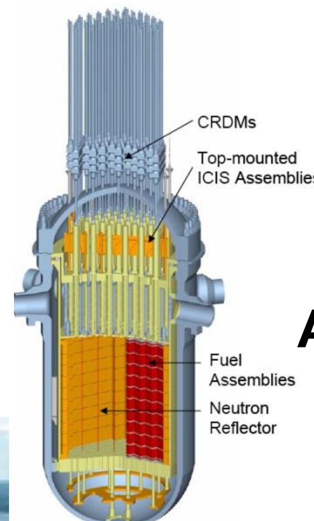
5 Gen III+ Designs Considered for New Construction in the US

Gen III+ Plants: Improved Versions of Existing Plant Designs

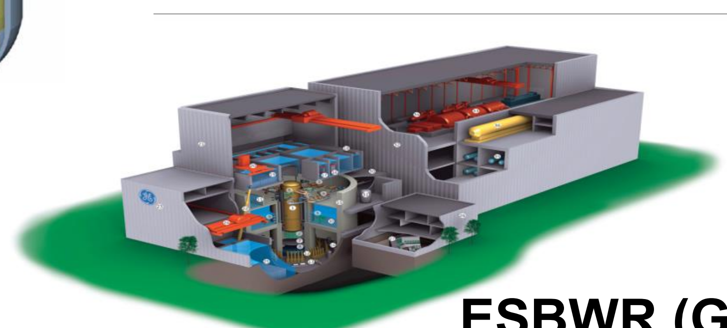
ABWR (GE-Hitachi)

US-APWR (Mitsubishi)



AP1000 (Toshiba: Westinghouse)

US-EPR (AREVA)



ESBWR (GE-Hitachi)

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Gen III+ designs that initiated design certification process with the NRC

Design	Applicant	Type	Status
AP1000	Westinghouse-Toshiba	Advanced Passive PWR 1100 MWe	Certified*
ABWR	GE-Hitachi, Toshiba	Advanced BWR 1350 MWe	Certified, Constructed in Japan/Taiwan
ESBWR	GE-Hitachi	Advanced Passive BWR 1550 MWe	Expected 2013
US-EPR	AREVA	Advanced PWR 1600 MWe	Expected 2014**
US-APWR	Mitsubishi	Advanced PWR 1700 MWe	Expected 2015

U.S. utilities have submitted 18 licensing applications (total 28 units); first license (Vogtle) approved on 2/10/12

* Under construction in China ** Euro version under construction in Finland, France and China

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Mission/Goals for Gen III+

Improved economics:

-Increased plant design life (60 years)

-Shorter construction schedule (36 months*)

-Low overnight capital cost (~$1000/kWe** for NOAK plant)

-Low O&M cost of electricity (~1-2 ¢/kWh)

Improved safety and reliability:

-Reduced need for operator action

-Expected to beat NRC goal of CDF $< 10^{-4}$/yr

-Reduced large release probability

-More redundancy <u>or</u> passive safety

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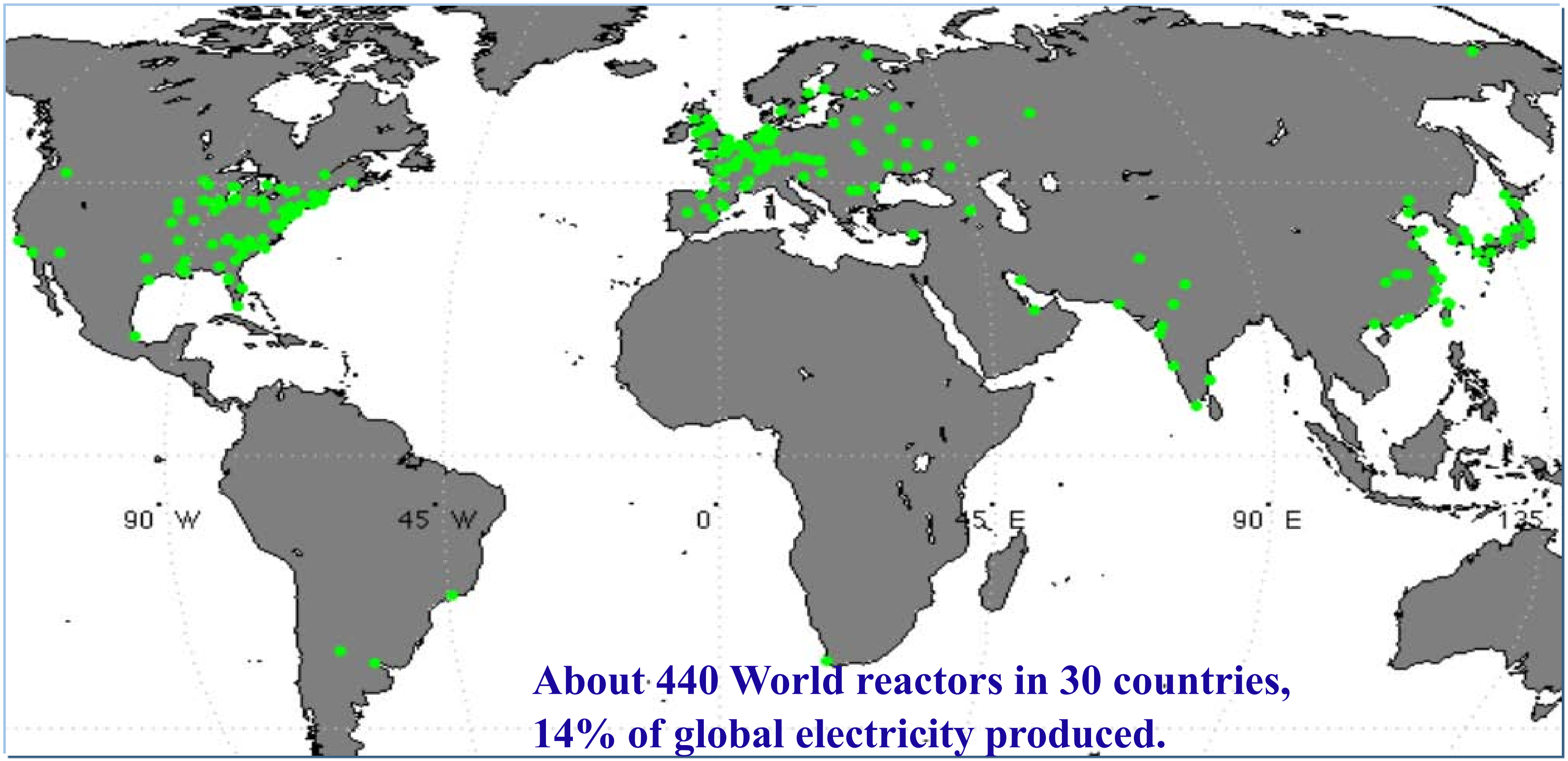
Nuclear Energy in the World Today



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60 new reactors under construction

Olkiluoto – Finland

Lungmen – Taiwan

Kudankulam – India

Flamanville – France

Rostov – Russia

Shin kori – S. Korea

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3 Ongoing in the US!

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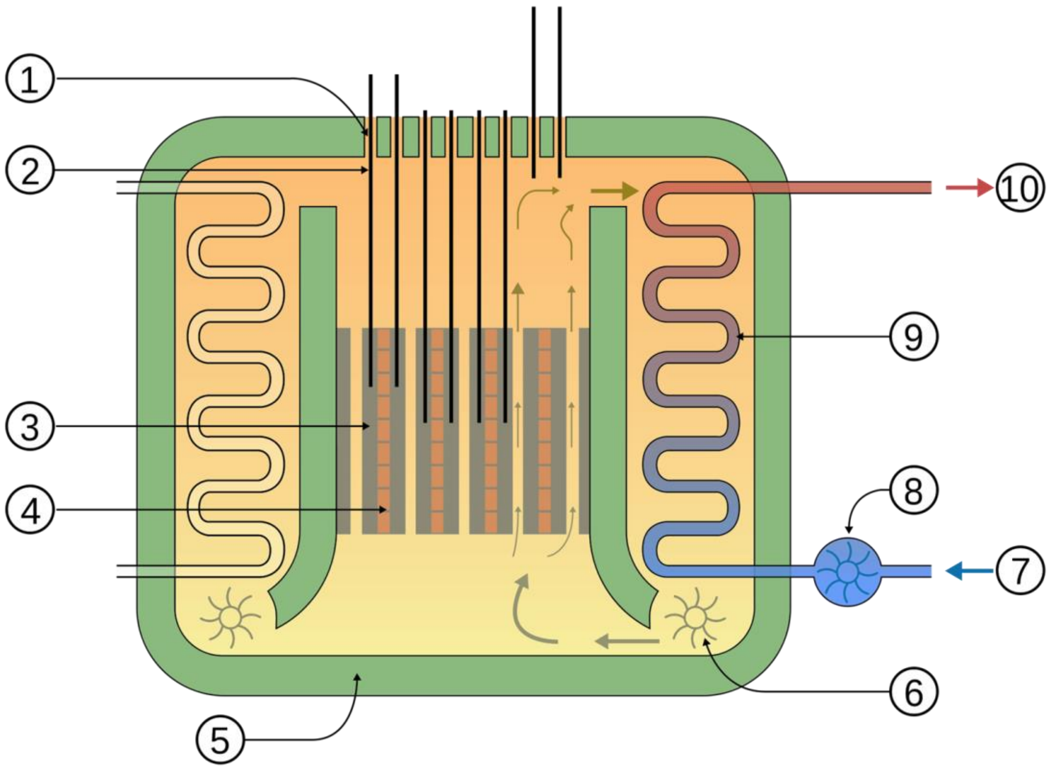
Gas Cooled Reactors

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

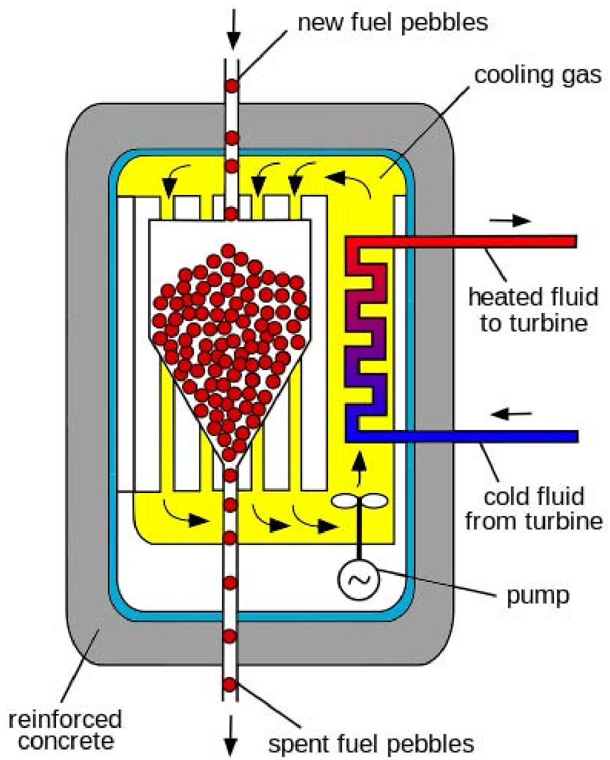
AGR
Special Features, Peculiarities

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

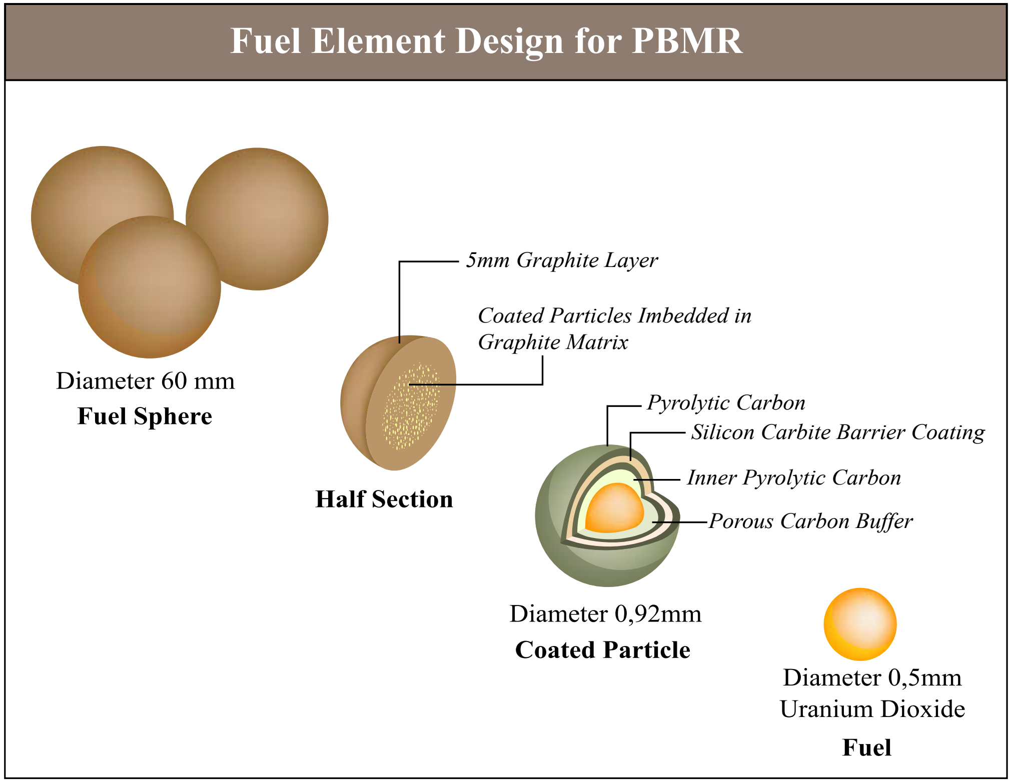
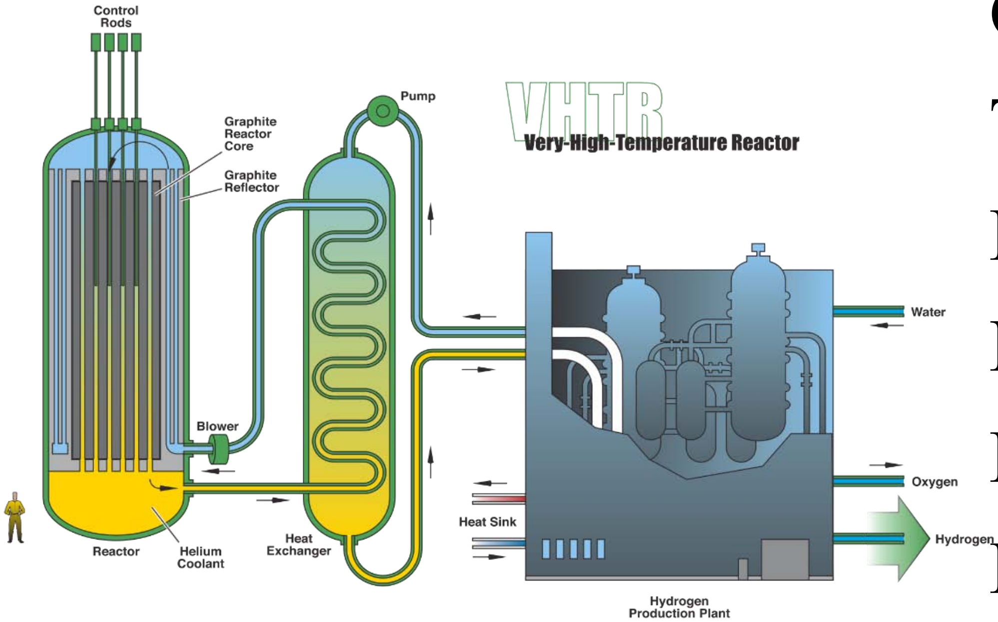


Image by MIT OpenCourseWare.

See "High Temperature Gas Reactors: The Next Generation?" Andrew C. Kadak, MIT, July 14, 2004

- 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

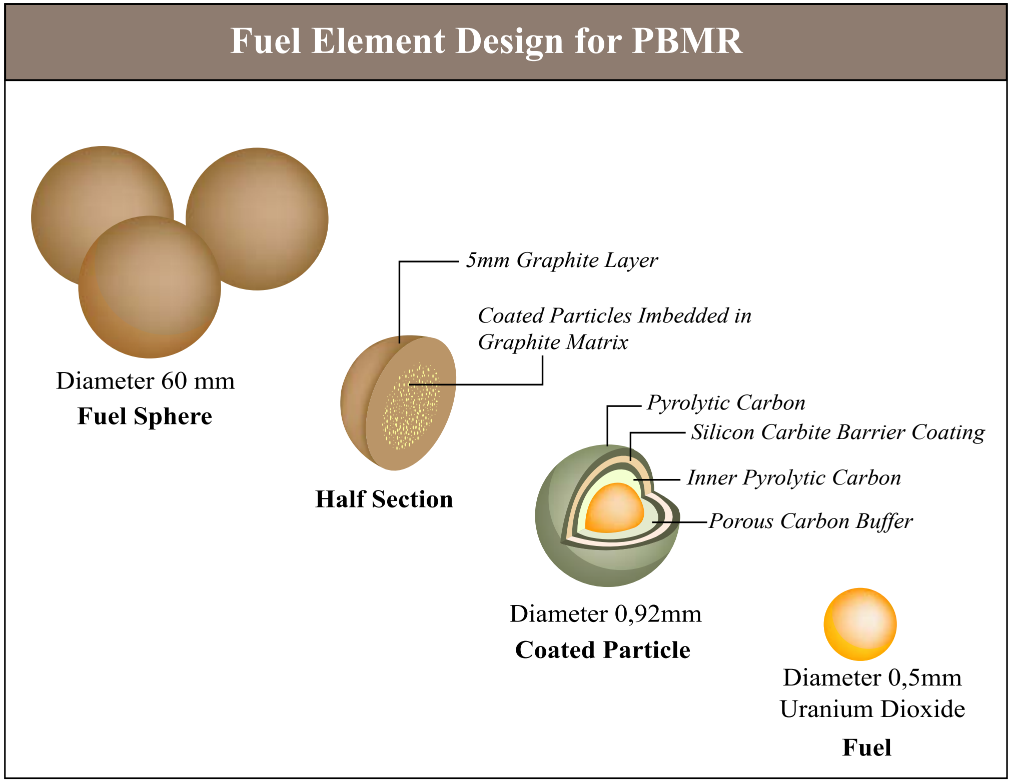


Image by MIT OpenCourseWare.

See "High Temperature Gas Reactors: The Next Generation?" Andrew C. Kadak, MIT, July 14, 2004

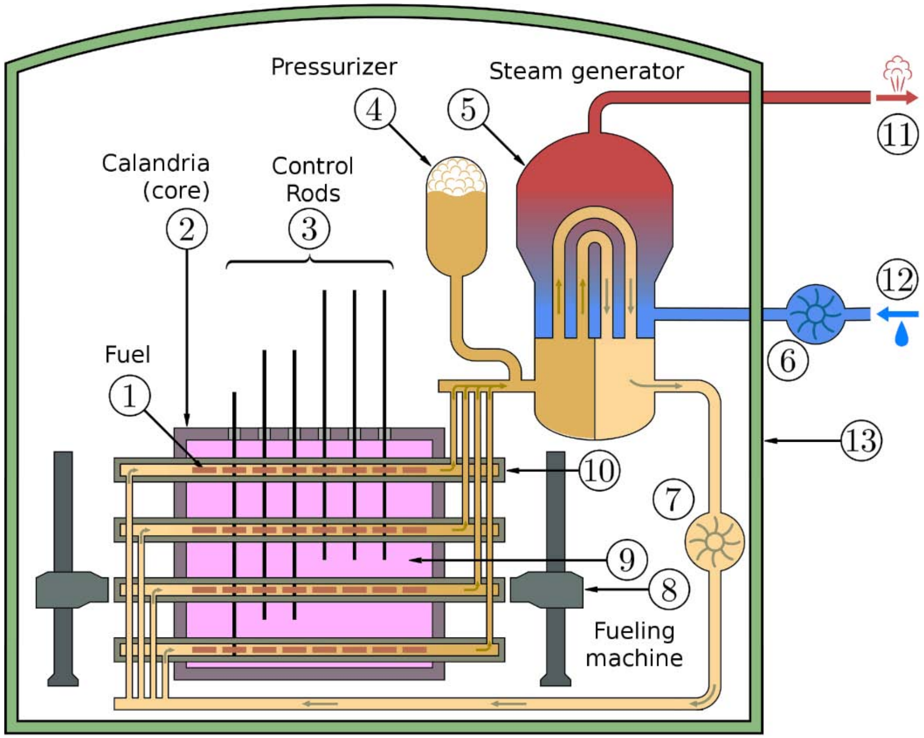
- High T_{out} opens up all doors to hydrogen
- Significant high-T materials concerns
- Molten salt variety can be more corrosive
- Single phase coolant
- TRISO particles, ups & downs

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?)

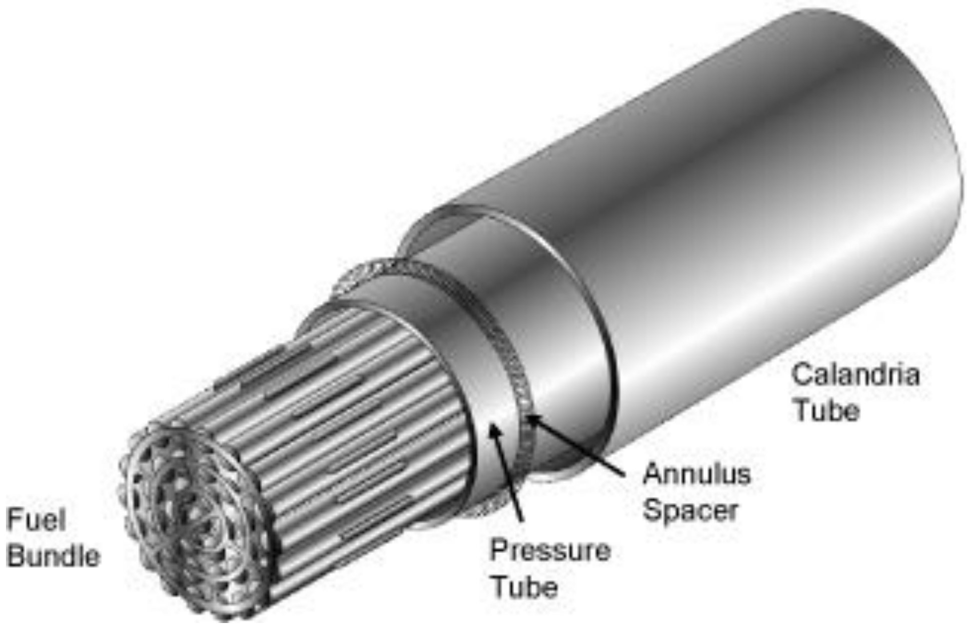
Moderator: D_2O

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

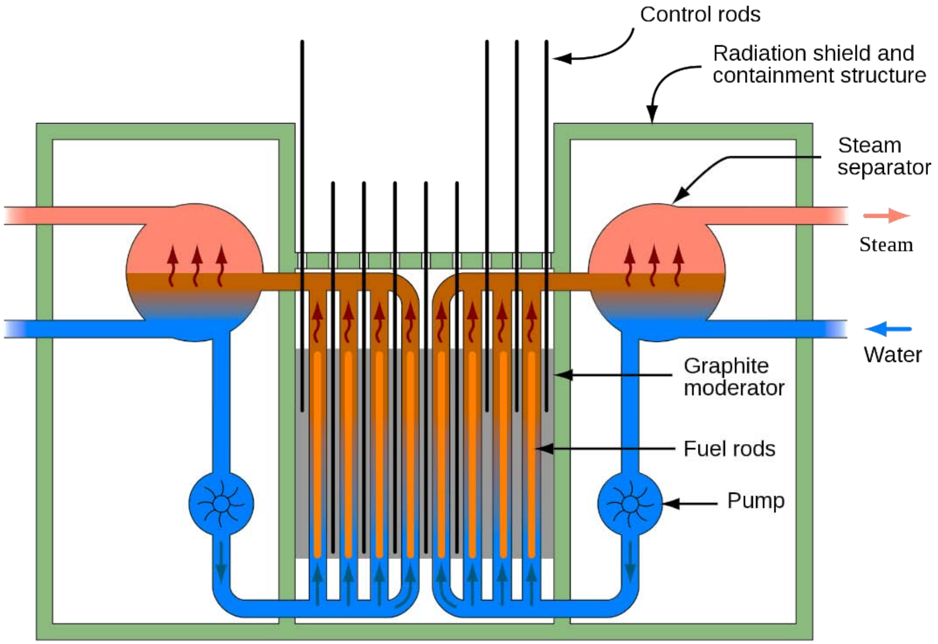


Image source: Wikimedia Commons

Coolant: H_2O

T_{out}: Low

Fuel: NU - LEU

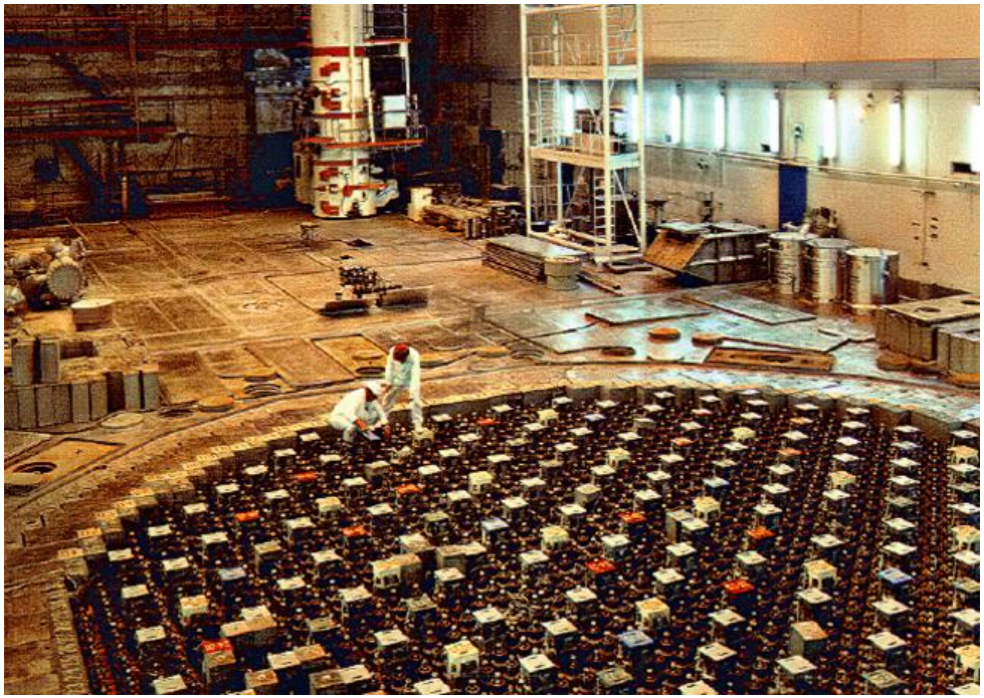
Moderator: Graphite

Power level: High

Power density: Low

Feasibility: Med. (safety)

RBMK
Special Features, Peculiarities



Public domain image. (Source: Wikimedia Commons)

Ignalina RBMK reactor tube tops, from
https://en.wikipedia.org/wiki/Ignalina_Nuclear_Power_Plant

Online refueling possible

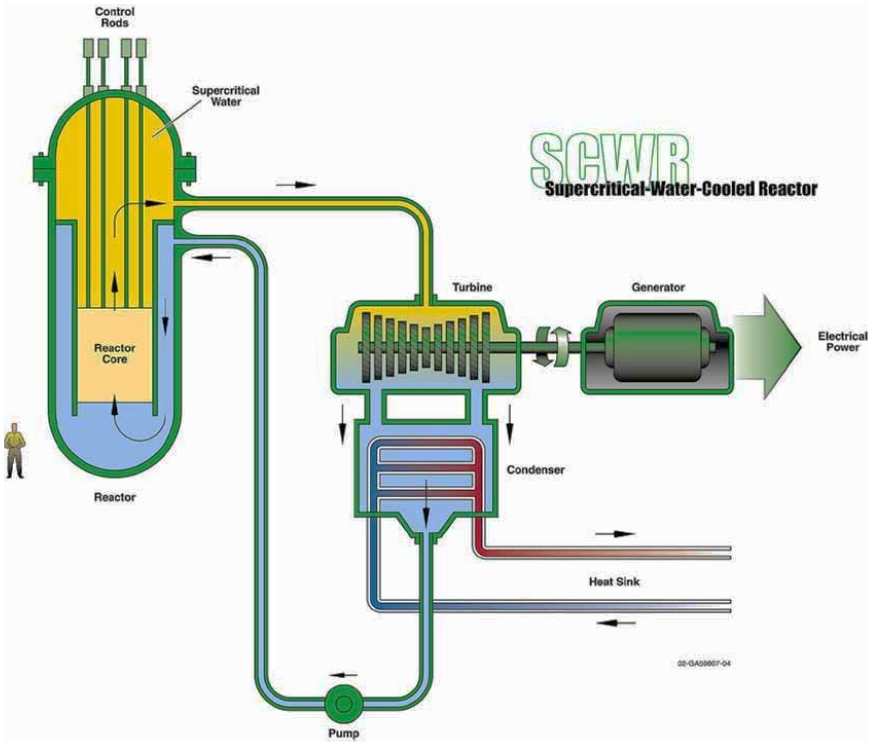
High positive void coefficient – Why?

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

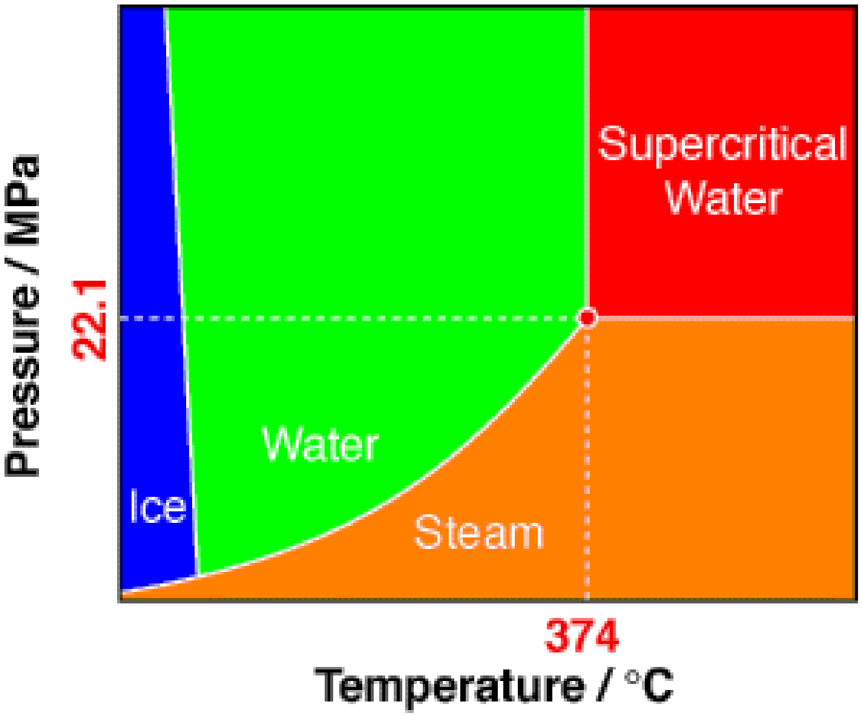
Moderator: SC-H_2O

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

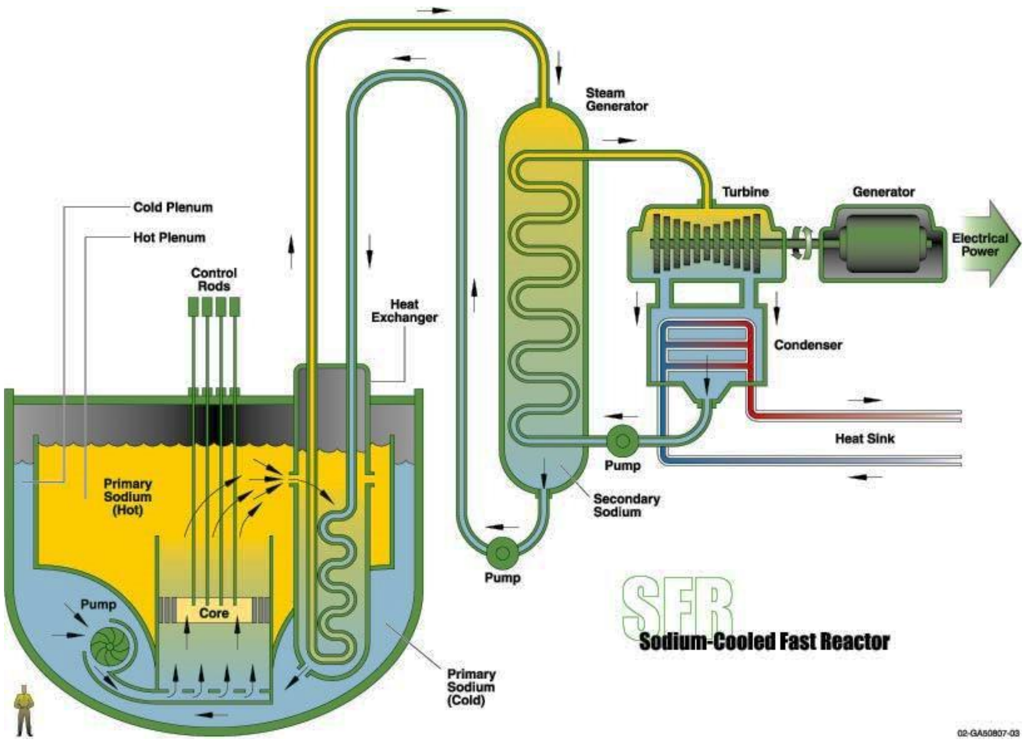
Liquid Metal Cooled Reactors

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

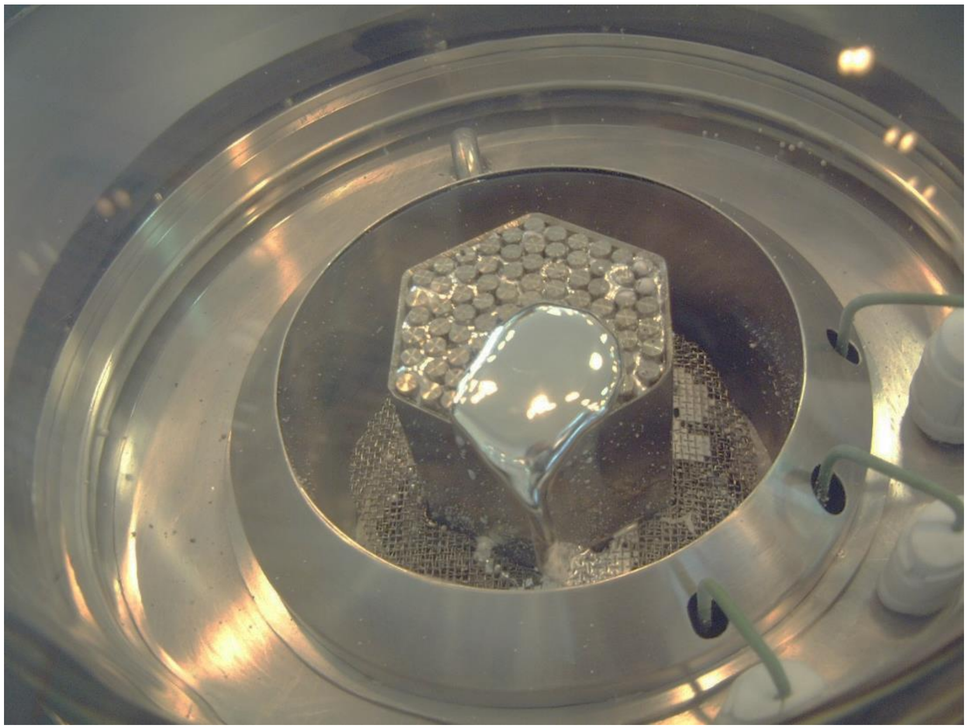
Moderator: None

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

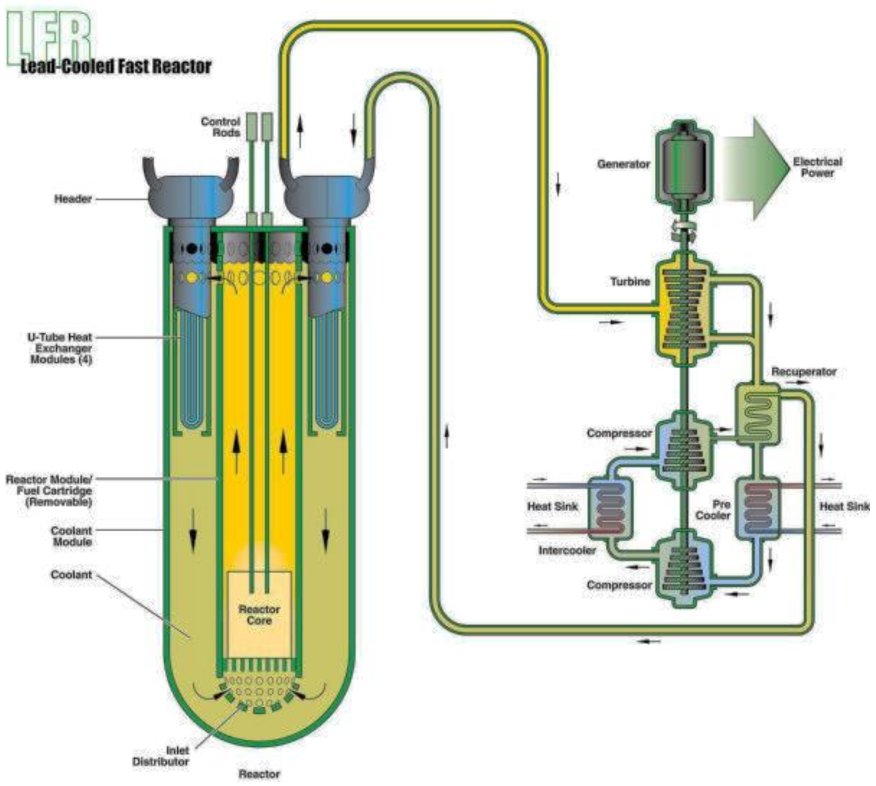
High material compatibility

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

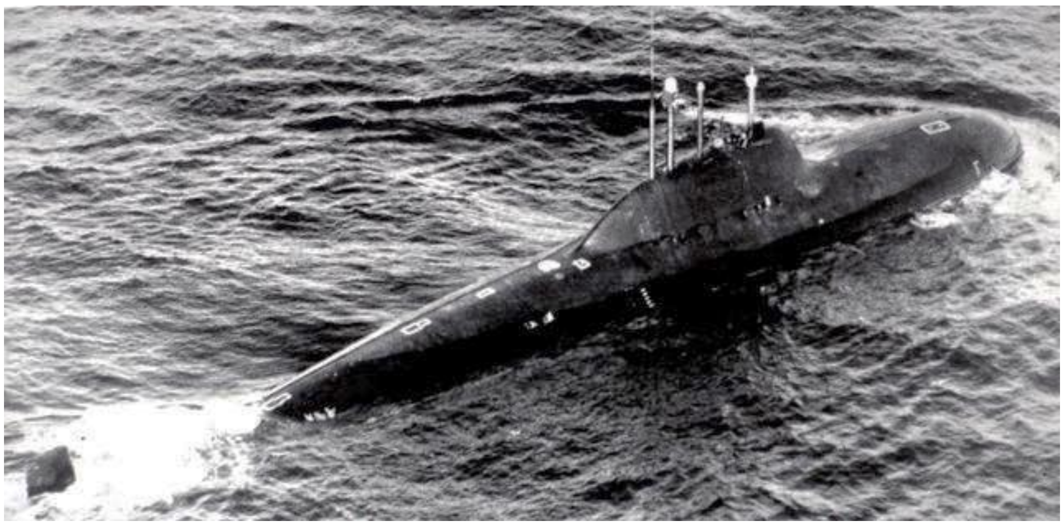
Moderator: None

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

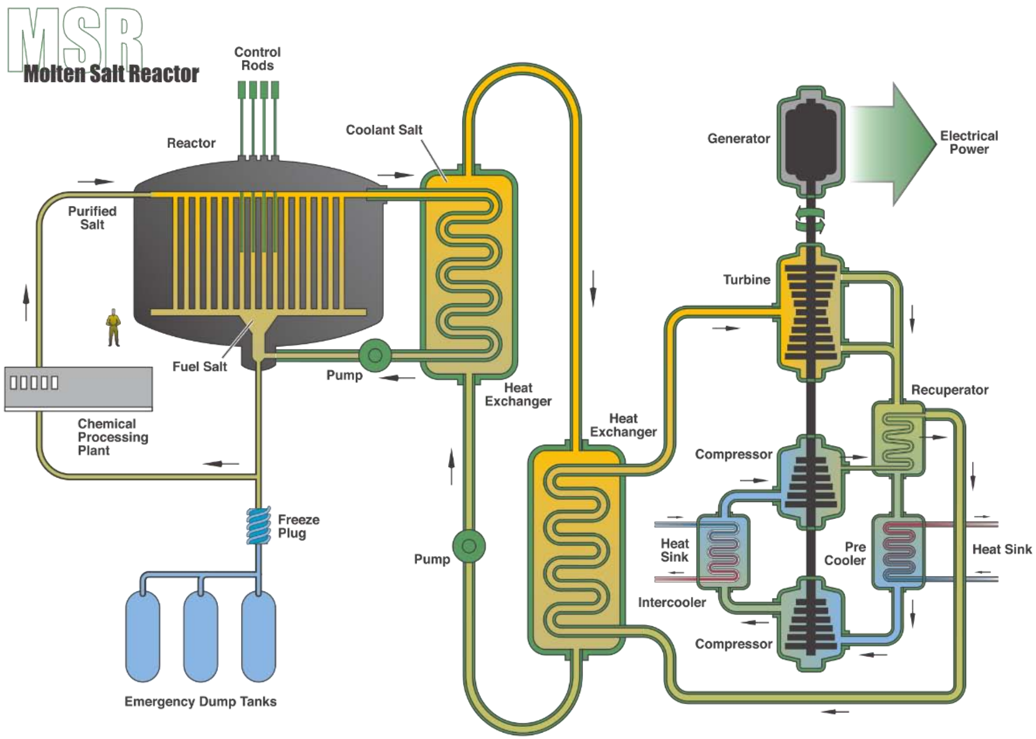
Coolant cost (LBE)

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

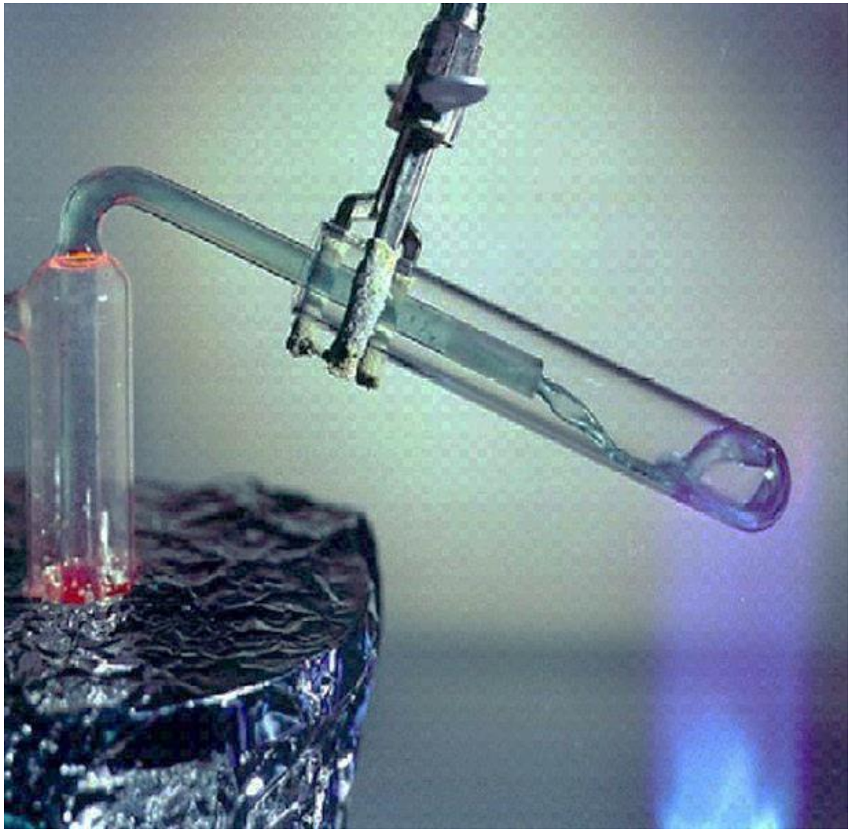
Moderator: Graphite

Power levels: All

Power density: High

Feasibility: Med. (now)

MSR
Special Features, Peculiarities



Public domain image.

Molten FLiBe. Image source: Wikimedia Commons

Unpressurized core

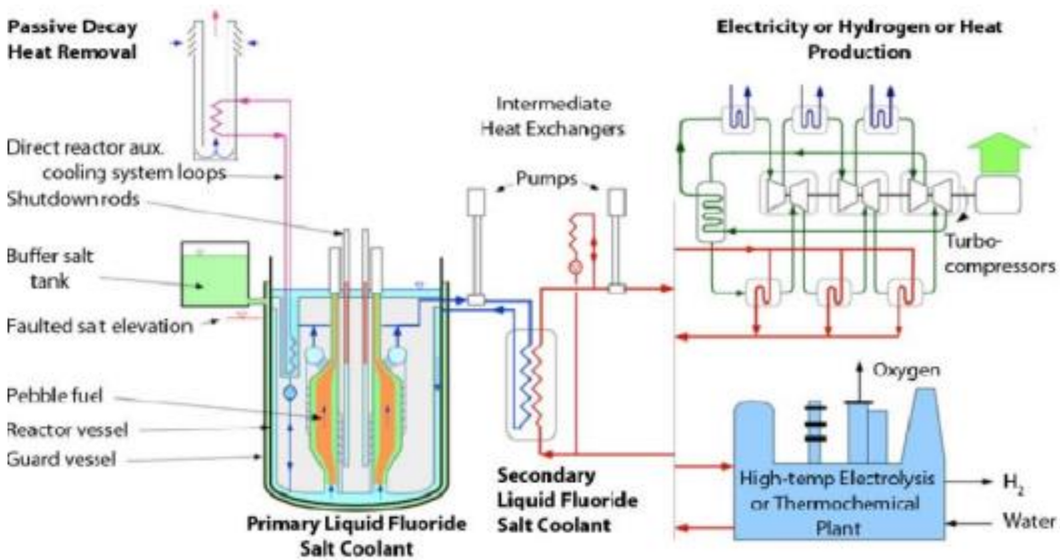
ThF_4/UF_4 fluid can be both fuel & coolant

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

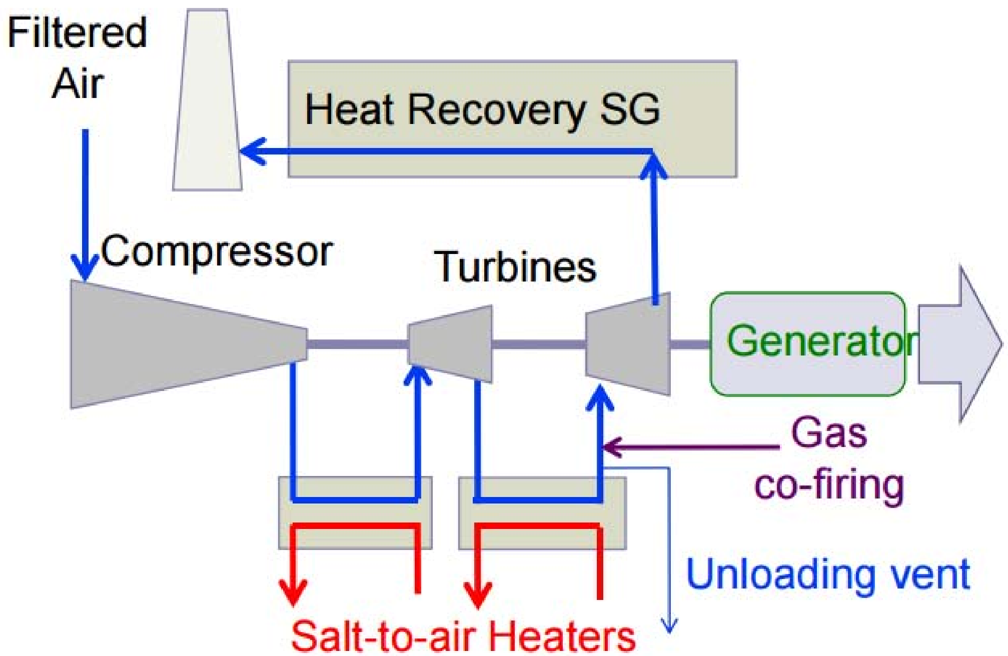
Moderator: Graphite

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**

"Nuclear afterburner"

Allow gas co-firing to meet peak demand

Always meet baseline demand anyway

Fusion Systems

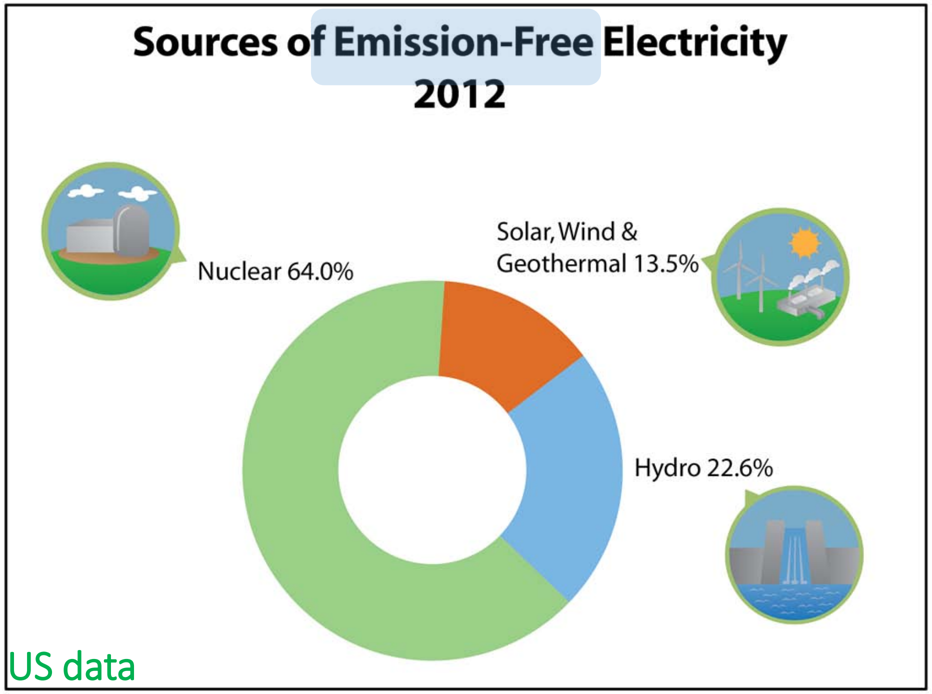
Slides by 2013 student team in 22.033 Design Project course removed due to copyright restrictions. Topics:

- Tokamak
- Stellarator
- Spherical Tokamak
- Spheromak
- Intertial Confinement
- Z-Pinch

The Case for New Nuclear in the US

Concerns for ***climate change…***

Athabasca Glacier (2008), Jasper National Park, Alberta, Canada.
Source: Wikimedia Commons, public domain.



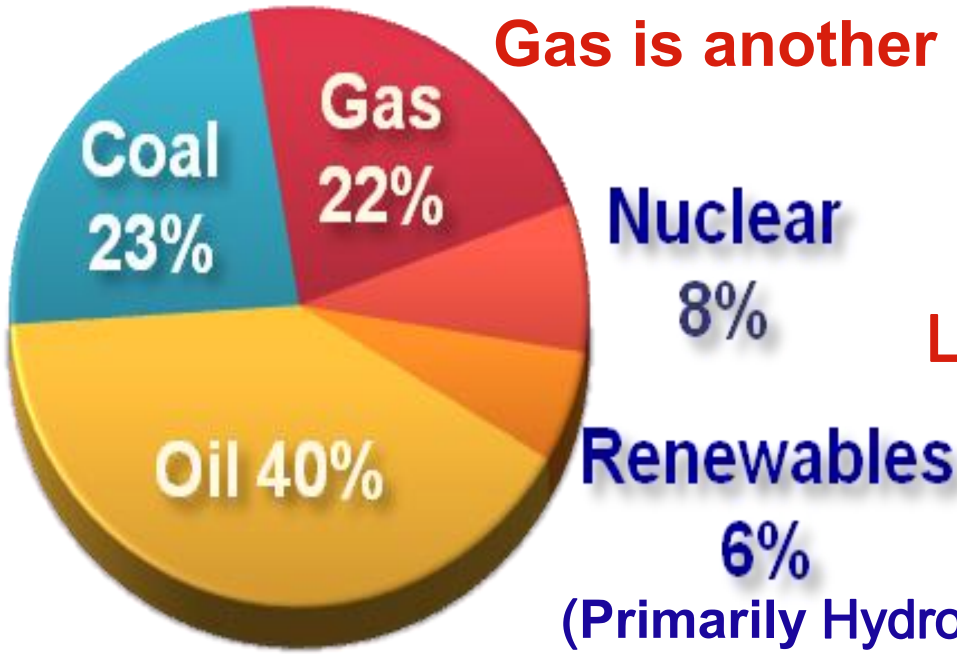
~570,000,000 tons of CO_2 emissions avoided in the US in 2012

The Case for New Nuclear in the US (2)

…and *growing fossil fuel imports and consumption*

Total U.S. Energy Consumption

Gas is another challenge



↑
Low Carbon
↓

Oil is one Challenge

U.S. data from EIA, Annual Energy Outlook 2008 Early Release, years 2006 and 2030; world data from IEA, World Energy Outlook 2007, years 2005 and 2030

Can nuclear displace coal?

Yes, as they are both used for baseload electricity generation.

What about oil?

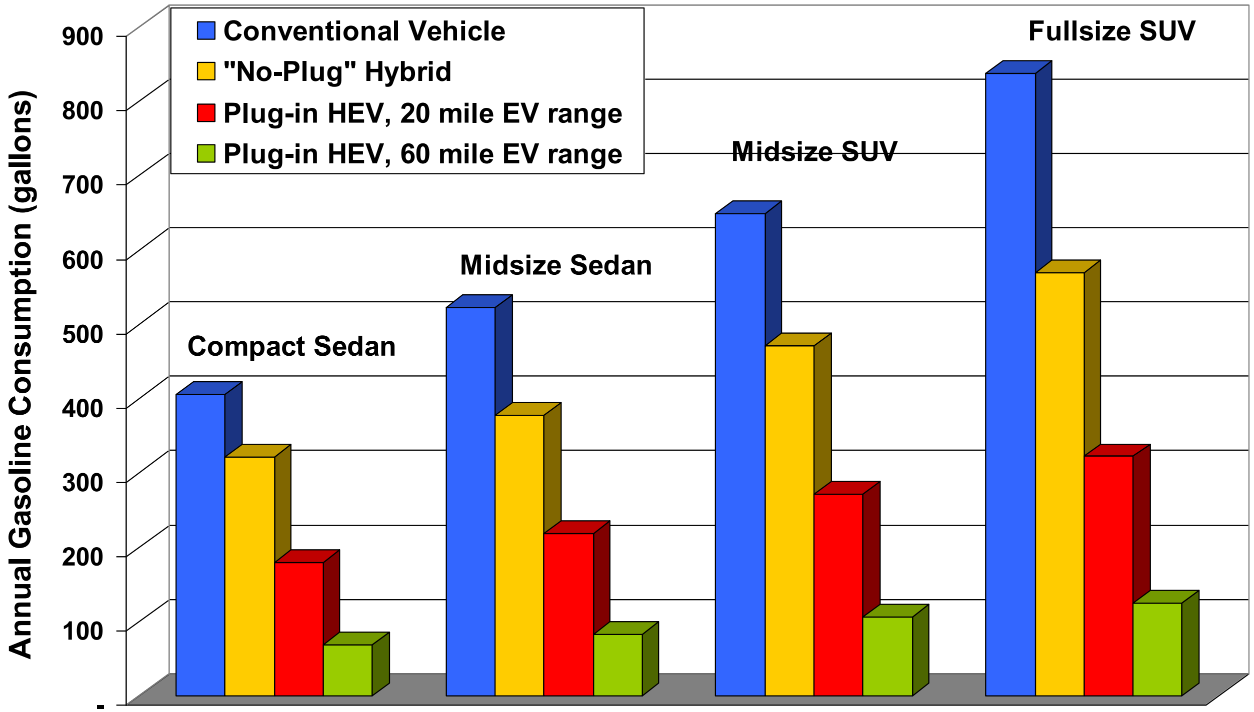
Oil Is Used for Transportation. What Are the Other Options?

- Plug-in hybrid electric vehicles (PHEVs)
- Liquid fuels from fossil sources (oil, natural gas and coal)
- Liquid fuels from biomass
- Hydrogen
- Long term option
- Depends upon hydrogen on-board-vehicle storage breakthrough

PHEVs: Recharge Batteries from the Electric Grid Plus Use of Gasoline

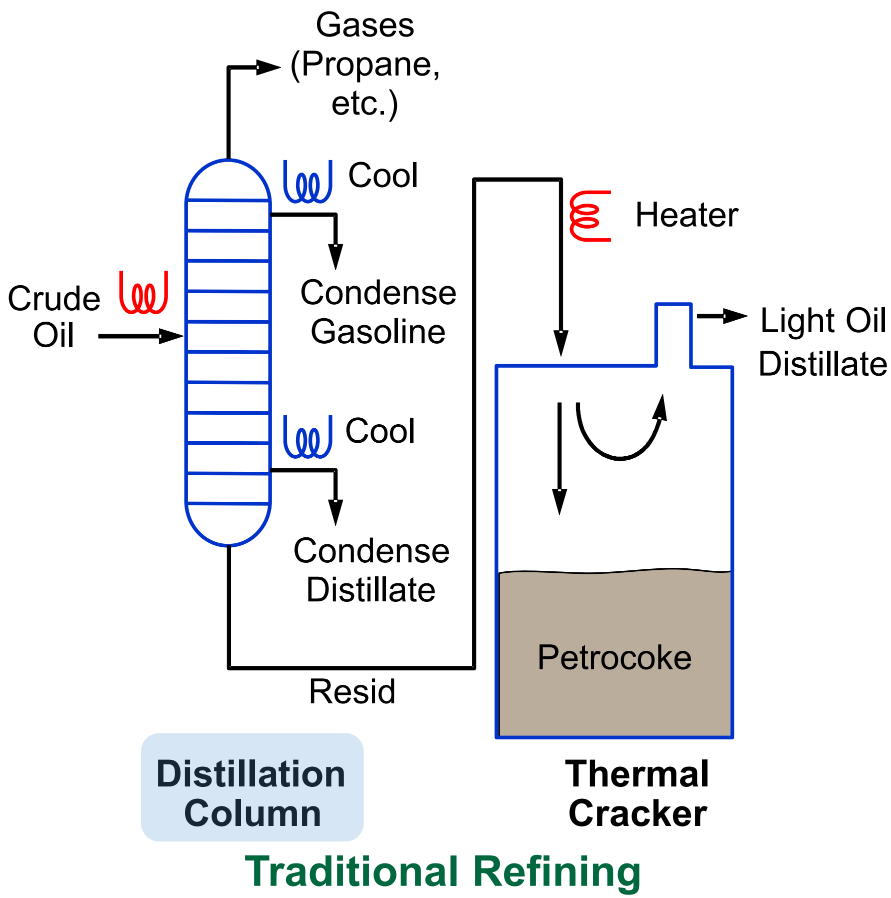
- Electric car limitations
  - Limited range
  - Recharge time (Gasoline/Diesel refueling rate is ~10 MW)
- Plug-in hybrid electric vehicle
  - Electric drive for short trips
  - Recharge battery overnight to avoid rapid recharge requirement
  - Hybrid engine with gasoline or diesel engine for longer trips
- Connects cars and light trucks to the electrical grid

PHEVs: Annual Gasoline Consumption Substituting Electricity for Gasoline



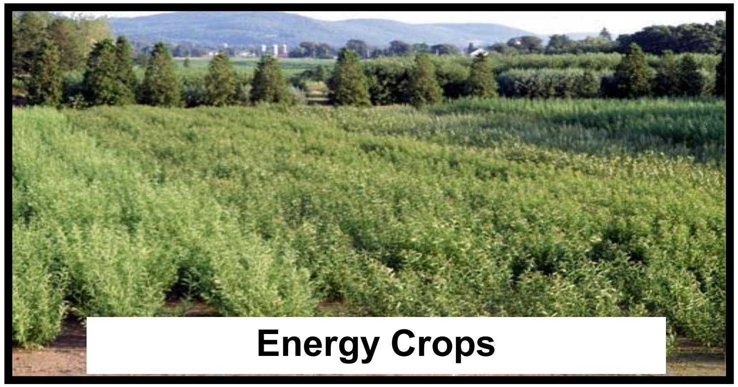
Need 150 to 200 Nuclear Plants Each Producing 1000 MW(e)

Refineries Consume ~5% of the Total U.S. Energy Demand



- Energy inputs
  - Heat at 550°C
  - Some hydrogen
- <u>High-temperature gas reactors could supply heat and H_2</u>
  - Market size equals existing nuclear enterprise

Biomass: 1.3 Billion Tons per Year, Available without Significantly Impacting U.S. Food, Fiber, and Timber



Conversion of Biomass to Liquid Fuels Requires Energy

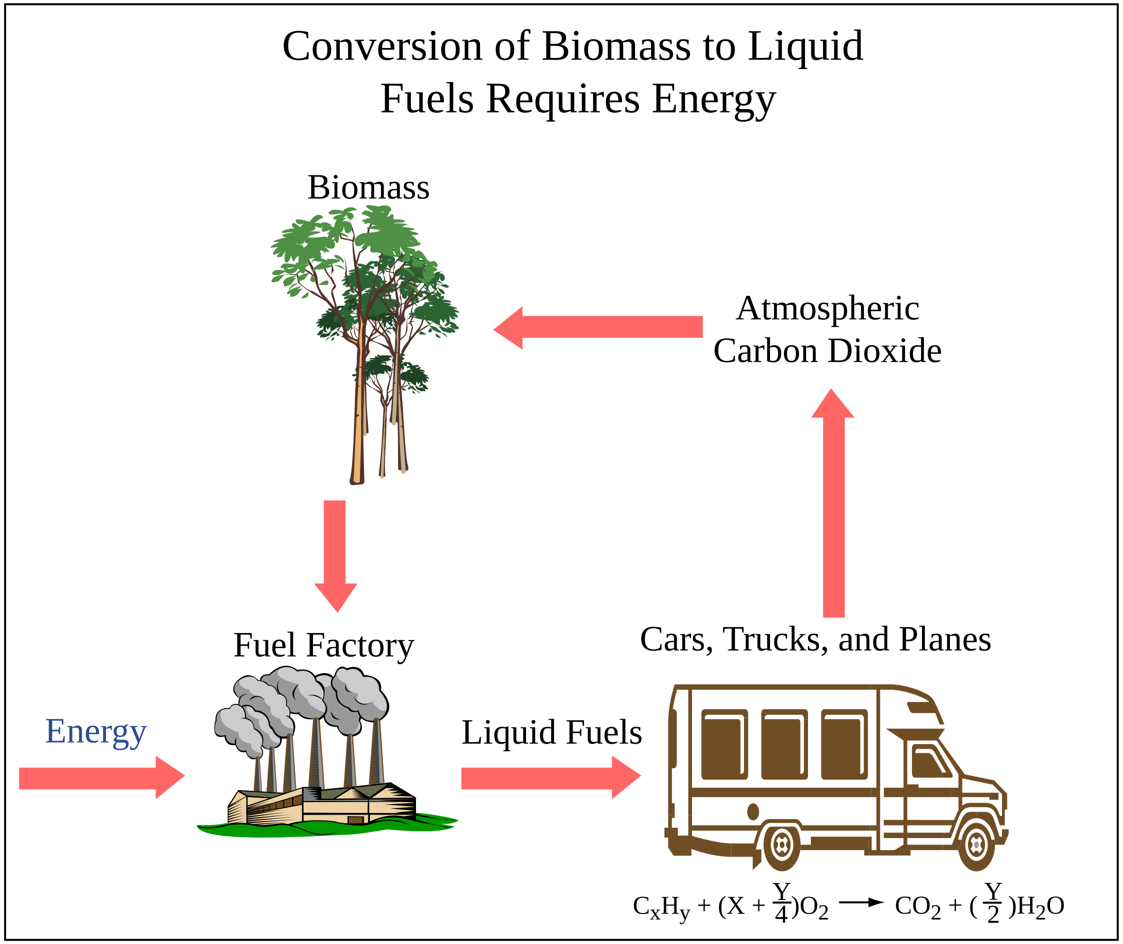


Image by MIT OpenCourseWare.

<u>One Option:</u> Steam From Existing Nuclear Plants to Starch-Ethanol Plants

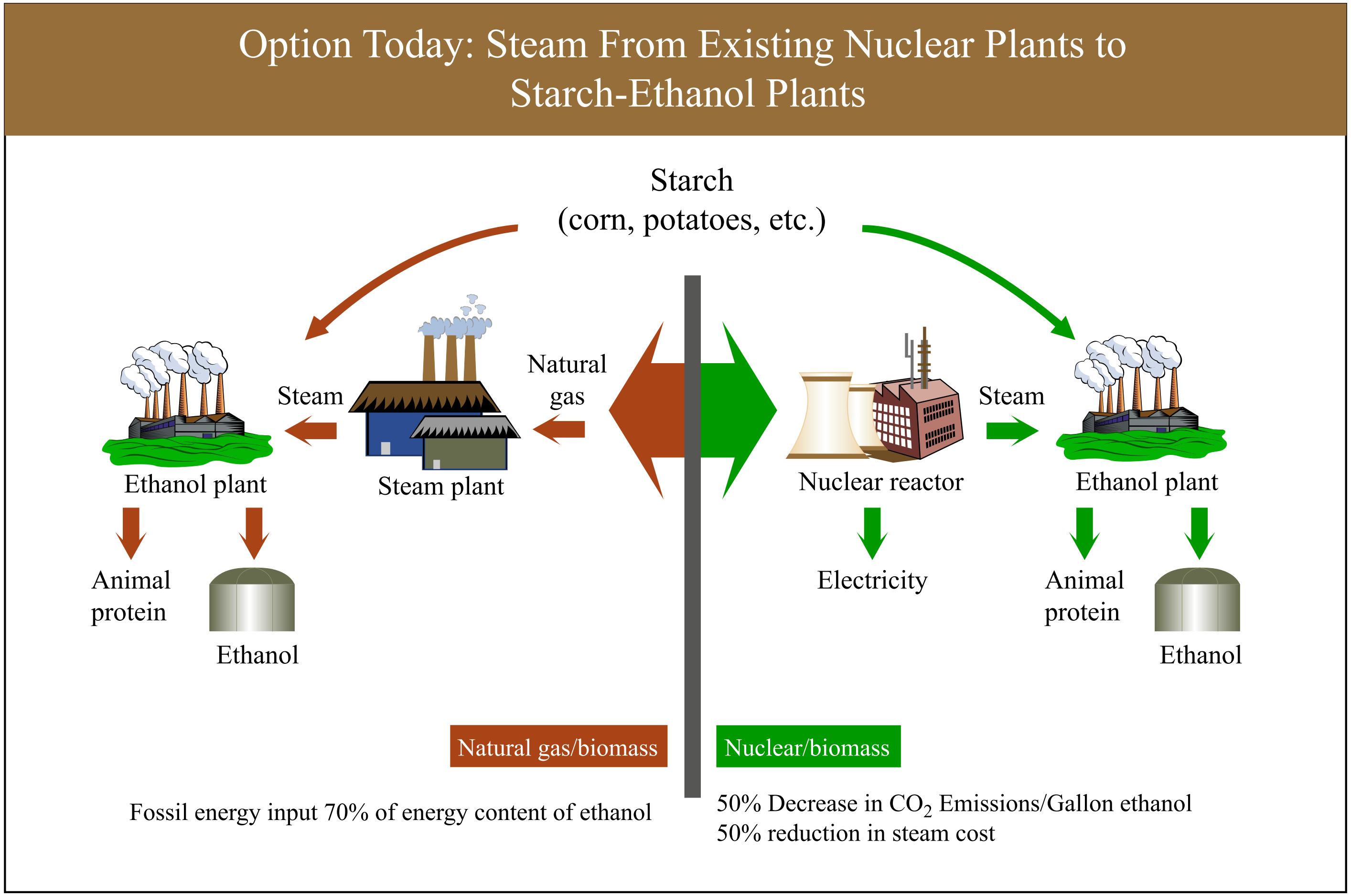


Image by MIT OpenCourseWare.

Nuclear Safety Primer

Hazard (1): fission products are highly radioactive

Objective (1): prevent release of radioactivity into environment

Hazard (2): nuclear fuel never completely shuts down (decay heat)

Objective (2): heat must be removed from nuclear fuel at all times

Safety Pillars:

-*Defense-in-depth*: multiple, independent physical barriers (i.e., fuel pin + vessel + containment)

-*Safety systems*: prevent overheating of the core when normal cooling is lost

[JB]

Some interesting safety-related features of the Gen III+ reactors…

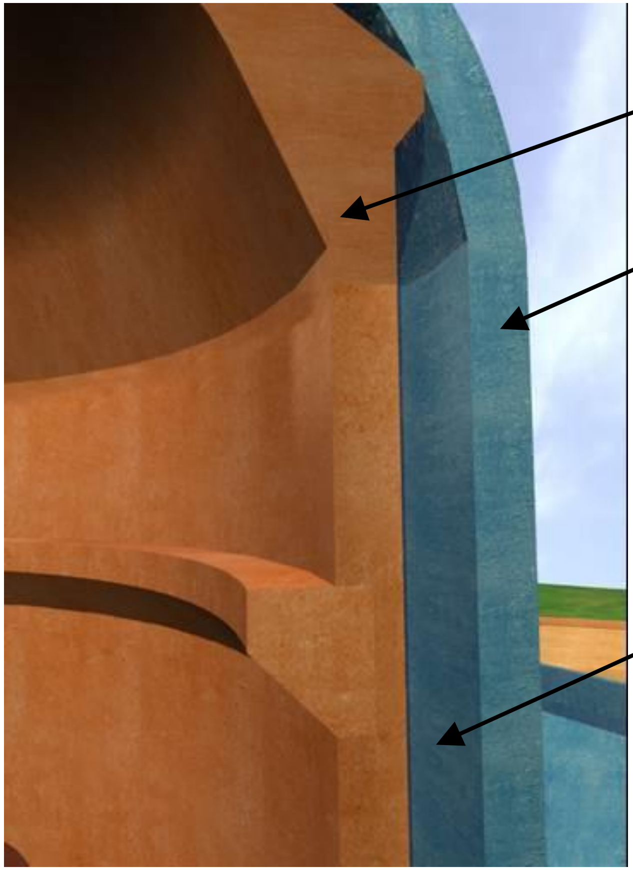
[JB]

Higher redundancy (US-EPR ECCS)

- **Four** identical diesel-driven trains, each 100%, provide redundancy for maintenance or single-failure criterion (N+2)
- Physical separation against internal hazards (e.g. fire)

[JB]

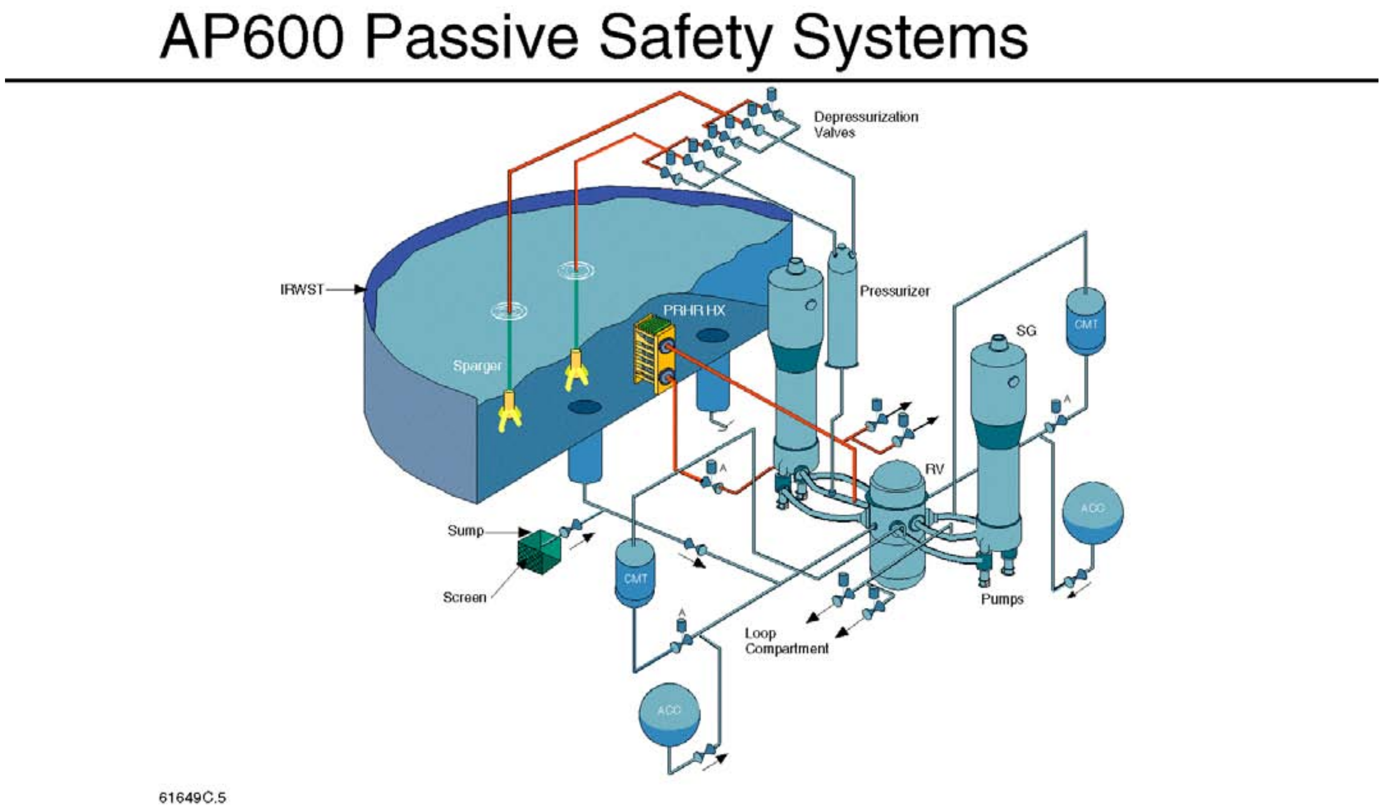
Higher redundancy (US-EPR Containment)



- **Inner wall pre-stressed concrete with steel liner**
- **Outer wall reinforced concrete**
- **Protection against airplane crash**
- **Protection against external explosions**
- **Annulus sub-atmospheric and filtered to reduce radioisotope release**

[JB]

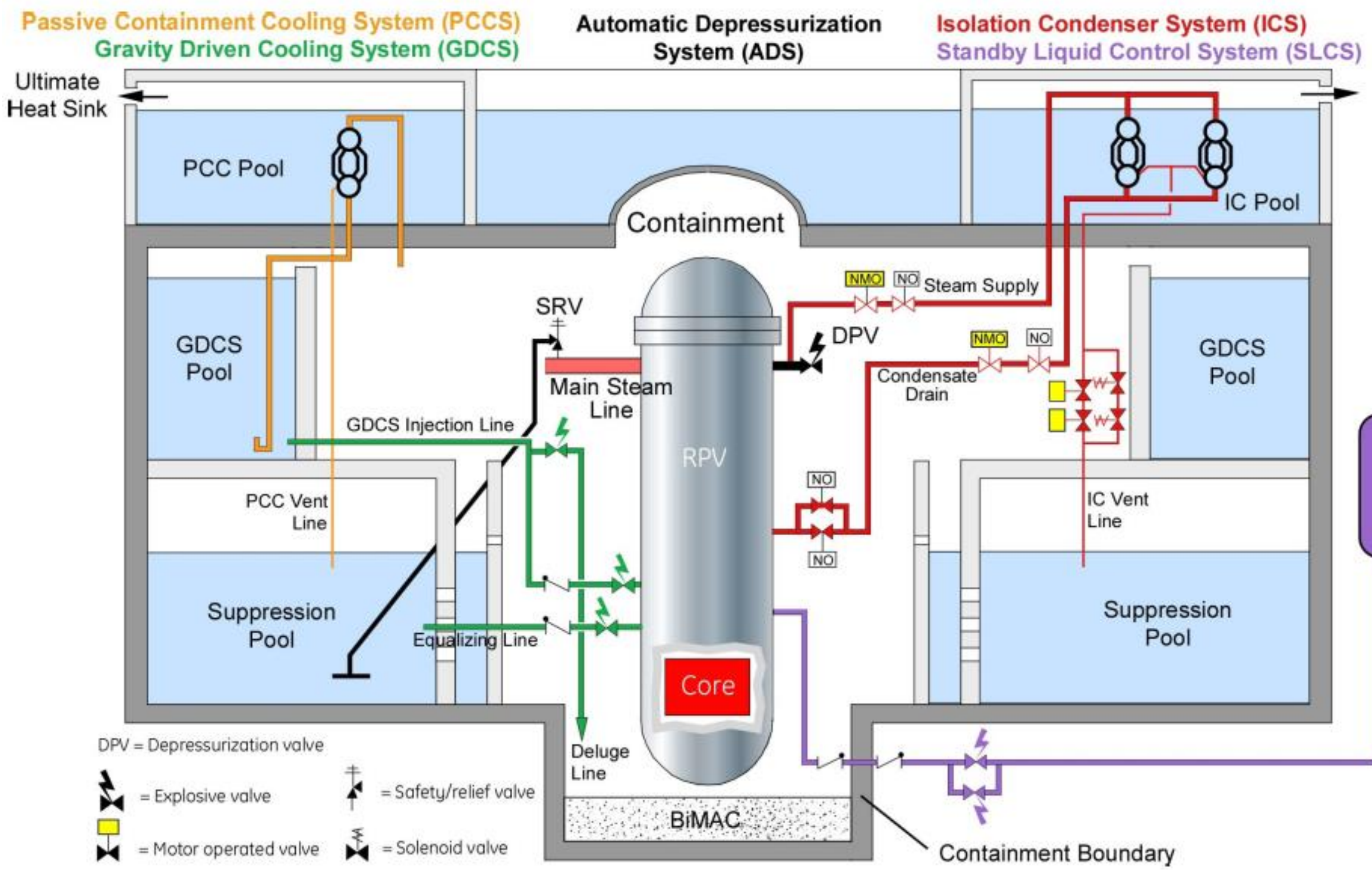
Passive safety systems (AP1000 ECCS)



Courtesy of Westinghouse. Used with permission.

[JB]

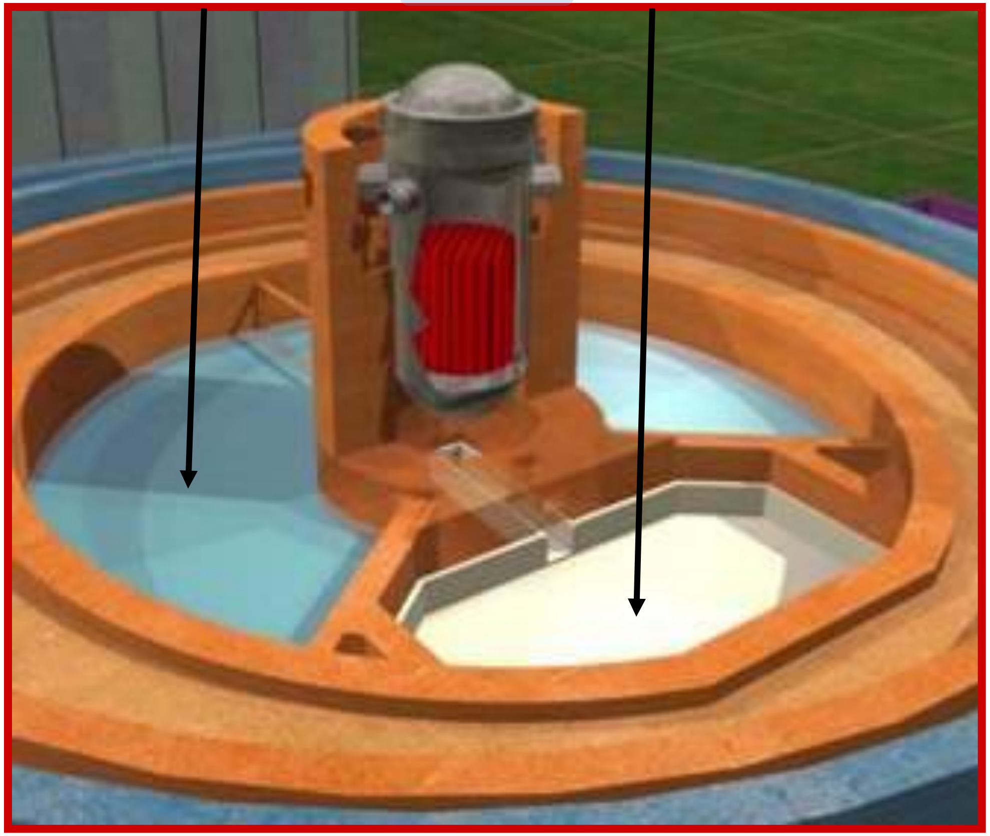
Passive safety systems (ESBWR ECCS and PCCS)



Courtesy of GE Hitachi Nuclear Systems. Used with permission.

[JB]

Severe accidents mitigation (EPR core catcher)



Ex-vessel core catcher concept (passive)

- Molten core assumed to breach vessel

- Molten core flows into spreading area and is cooled by IRWST water

- Hydrogen recombiners ensure no detonation within container

[JB]

Nuclear energy economics

[JB]

Nuclear Energy Economics

Financial risk for new plants is high

–**Initial investment is large** (~$3,480/kW ⇒ G$/unit)

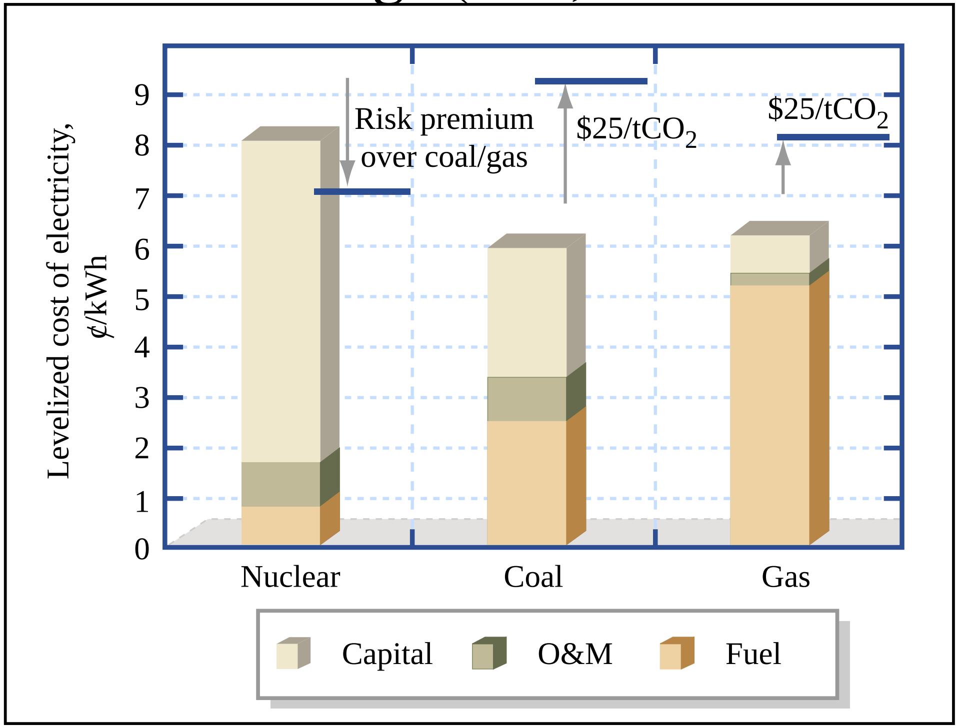
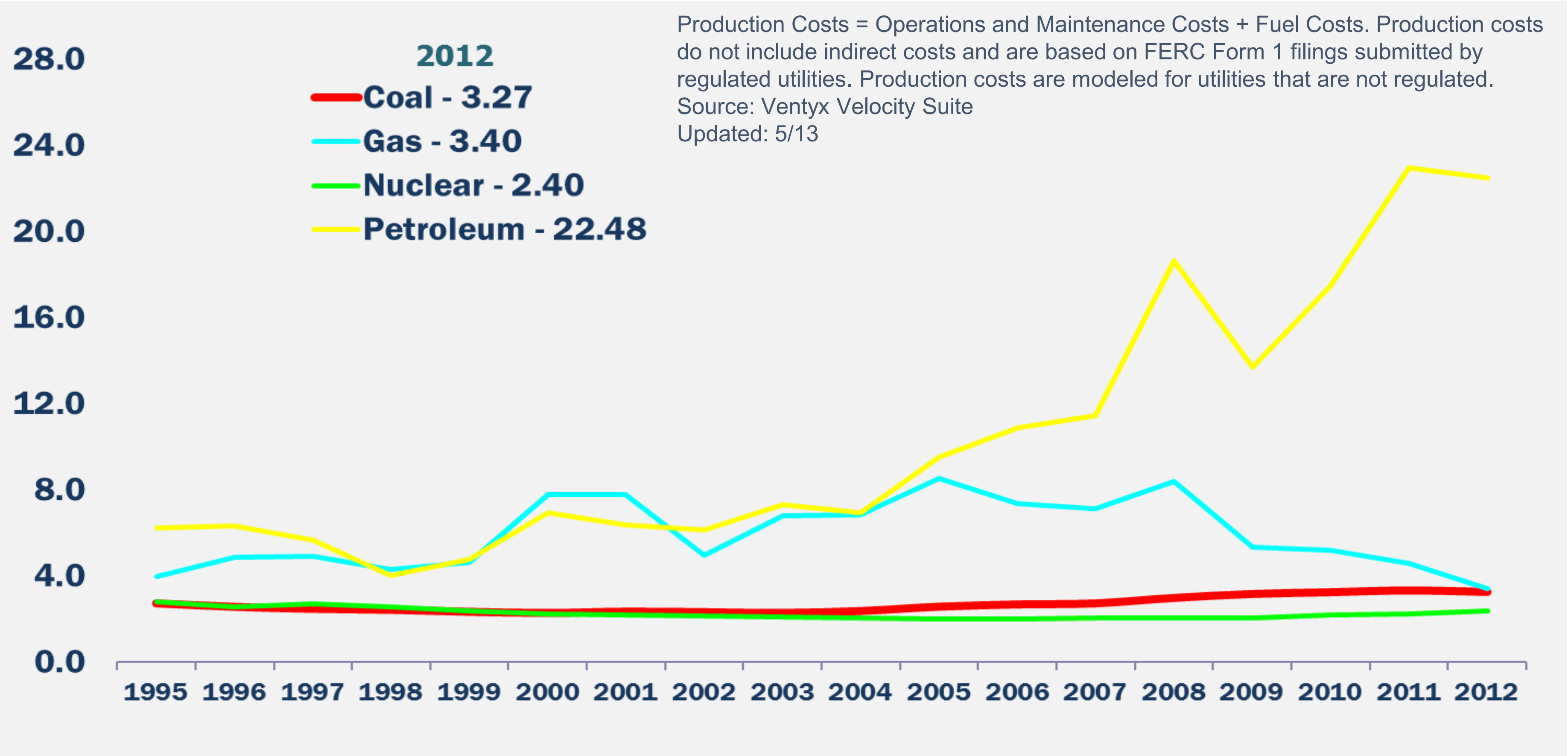


Image by MIT OpenCourseWare.

[JB]

U.S. Electricity Production Costs

1995-2012, *In 2012 cents per kilowatt-hour*



[JB]

Nuclear Fuel - Compact & Economic

Nuclear fuel cycle has made up less than 15% of the cost of nuclear electricity. In 2006 that was about 6 $/MWhr, out of a total electricity cost of 50 $/MWhr

This covers the following steps

–Uranium ore extraction and conversion to U_3O_8, at $48/kg

–Enrichment in U235, typically by centrifugal forces spinning gaseous UF_6, to about 4% (Japan Rakashu plant in side pictures)

–Manufacturing of UO_2 pellets, and placing them in Zr tubes (cladding) thus producing fuel rods. The rods (or pins) are arranged in square lattices called assemblies.

–Removal of spent fuel assemblies to temporary storage in fuel pools, then to interim dry storage

–1 $/MWhr for spent fuel disposal fees

[JB]

Nuclear fuel cycle

[JB]

Fuel Cycle Scenarios (1)

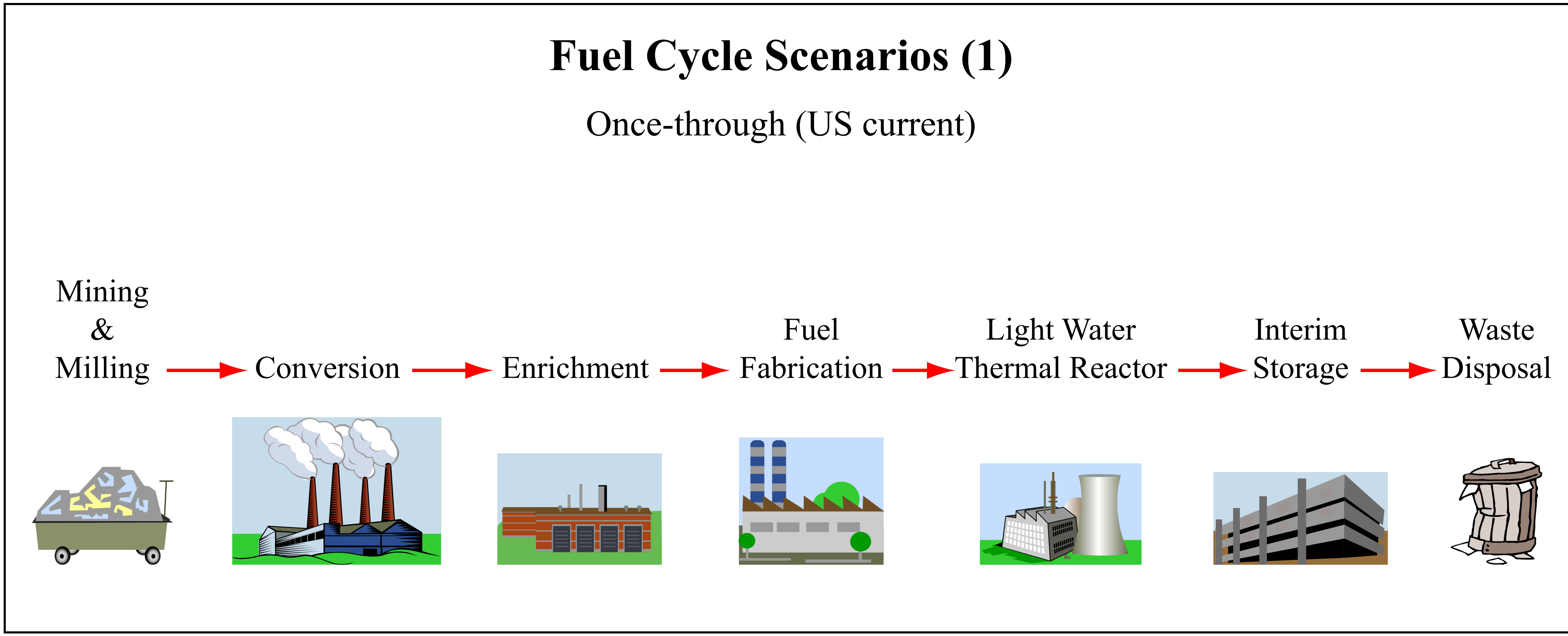


Image by MIT OpenCourseWare.

[JB]

Milling & Mining Process

1MT ore = 2-3 lb (1-2 kg) uranium

End product is U_3O_8 powder ("yellowcake")

Major suppliers:

–Canada

–Australia

–Kazakhstan

–Africa

–Former Soviet Union [FSU]

Large secondary ("already mined") market dominates supplies

[JB]

Bellezane, France Site (open pit mine)

[JB]

Bellezane Site: After Reclaimation

[JB]

Beverley, South Australia – (In situ leaching)

[JB]

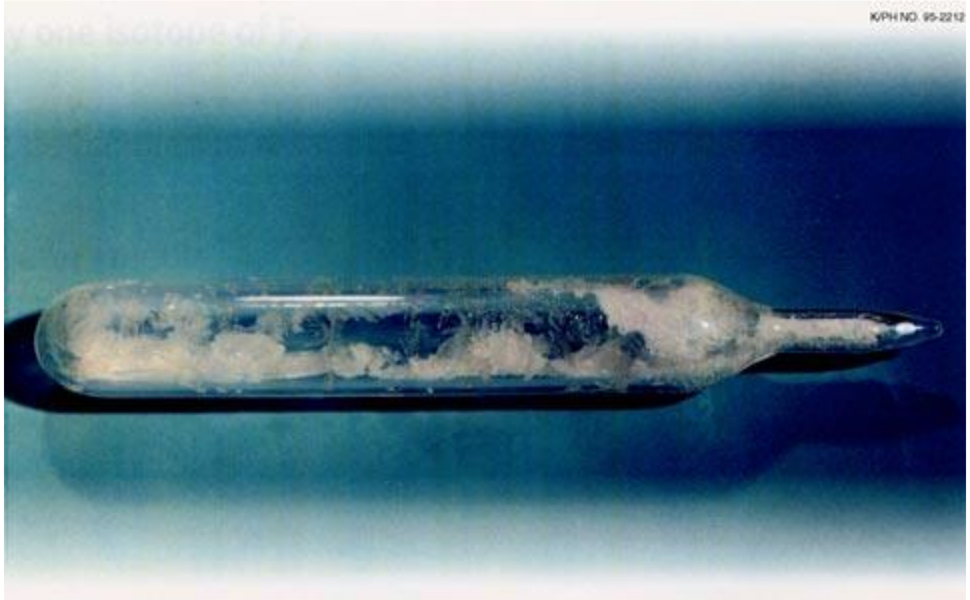
Conversion Process

U_3O_8 converted to UF_6 for enrichment process

UF_6: only form of uranium that is gaseous at “industrial” temperatures

–Gaseous at 133° F (56.1° C)

–In solid form at room temperature



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[JB]

Uranium Enrichment

Two major commercial processes:

–Gaseous Diffusion

–Gas Centrifuging

Can also blend down weapons-grade HEU

–U.S.-Russian HEU Agreement ("Megatons to Megawatts") – was ~50% of U.S. fuel supply

Upward price pressure driven by projected demand

Recent downturn in price due to Fukushima

Priced in Separative Work Units (SWU)

[JB]

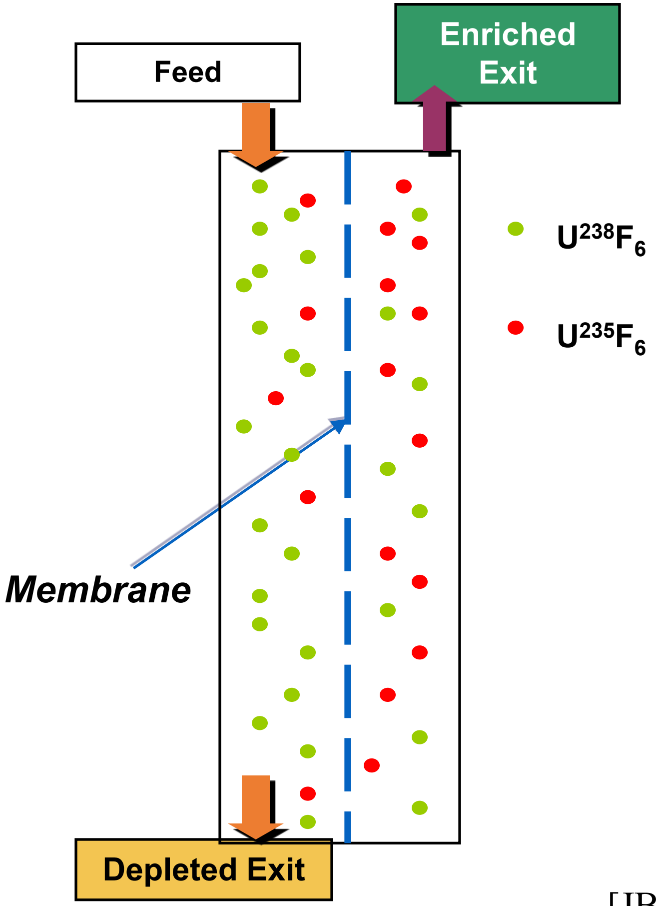
Enrichment: Gaseous Diffusion

- The UF_6 gas diffuses across a membrane (filter):
  - $U^{235}F_6$ molecules are smaller, faster: they cross the membrane more often, statistically

    This gas is enriched in U^{235}

  - $U^{238}F_6$ molecules are bigger, slower: they cross the membrane less often, statistically

    ➡ This gas is depleted in U^{235}



[JB]

Gaseous Diffusion Enrichment Facility

[JB]

Tricastin Site: EURODIF Gas Diffusion Enrichment Plant (now being decommissioned)

[JB]

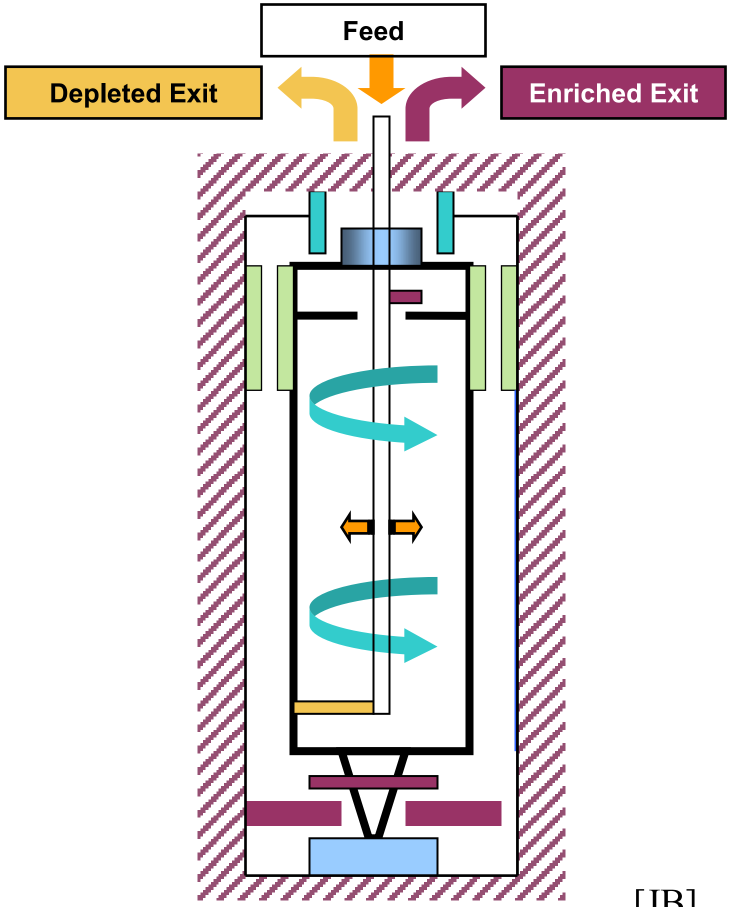
Enrichment: Gas Centrifuging

- The UF_6 gas is centrifuged:
  - $U^{235}F_6$ molecules are lighter and move preferentially toward the center of the rotor

    Red Bale/Gas enriched in U^{235}

  - $U^{238}F_6$ molecules are heavier and move preferentially toward the periphery of the rotor

    ➡ Yellow Bale/Gas depleted in U^{235}



[JB]

Gas Centrifuge Enrichment Facility

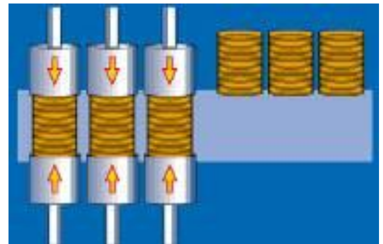
[JB]

Fuel Fabrication Process

« De-Conversion »

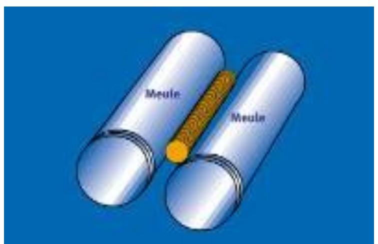
$UF_6 \Rightarrow UO_2$

1 *Powder Production*

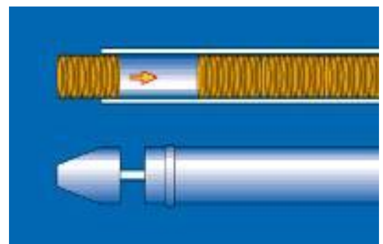


2 *Pressing or pelletizing*

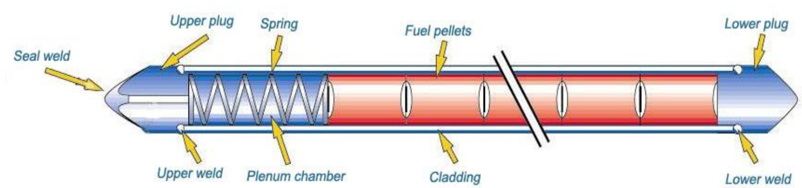
3 *Sintering*



4 *Grinding*



5 *Rod cladding*



Light water reactor fuel rod

6 *Assembly fabrication*

[JB]

Fuel Fabricator Consolidations

<u>Toshiba</u>

–Westinghouse (PWR)

–Nuclear Fuel Industries, Ltd., ABB-CE (PWR, BWR)

<u>AREVA NP</u>

–Framatome (PWR), Siemens Nuclear (PWR, BWR)

<u>GNF (Global Nuclear Fuels)</u>

–GE Nuclear Fuel, JNF: Hitachi/Toshiba (BWR)

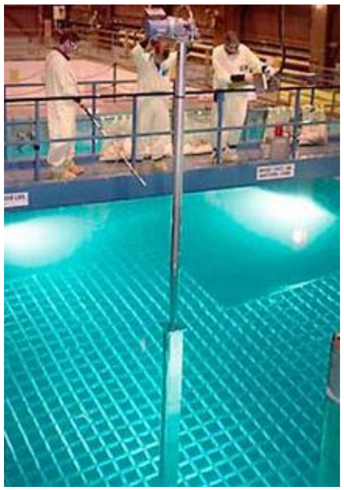
<u>AECL (CANDU)</u>

<u>Atomenergoexport (VVER)</u>

[JB]

Spent Fuel Management (waste disposal)

In the US all spent fuel is currently stored at the plants



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- In the spent fuel storage pools for about 10 years …
  - … then transferred to sealed dry casks; cooled by air; heavily shielded; internal temp and press monitored; can last for decades with minimal maintenance and cost.
  - A 1000-MW reactor requires about 80 dry casks for all the spent fuel it produces in 60 years of operation (about 3 acres of land).
  - Dry cask storing of all US nuclear fleet spent fuel would require only 300 acres of land. (The volumes are small !!!)

[JB]

Spent Fuel Management (waste disposal) (2)

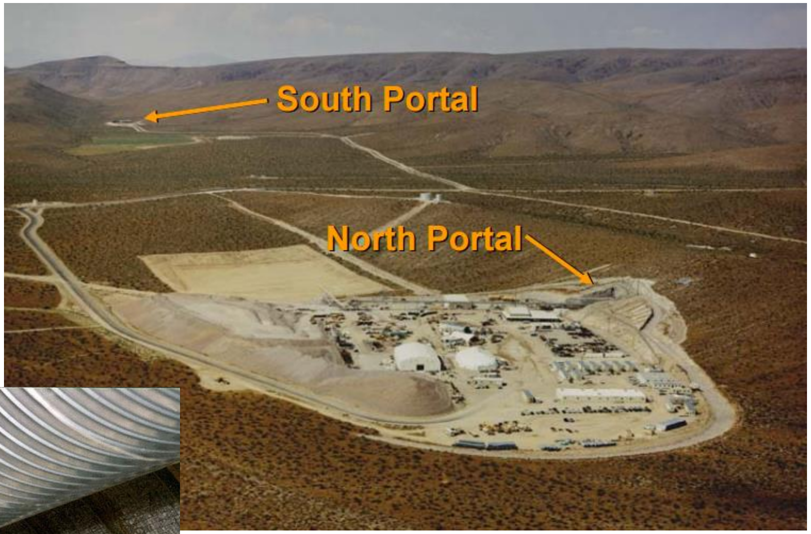
In the long-term the spent fuel can be stored in deep geological repository

- The Yucca Mountain site was selected for the US, authorized by then-President Bush, the license application received by NRC in 2008
- The project is strongly opposed by the State of Nevada

The current administration has shut down the Yucca Mountain project; A committee has recommended interim storage facility and search for alternative long-term geological repository site

[JB]

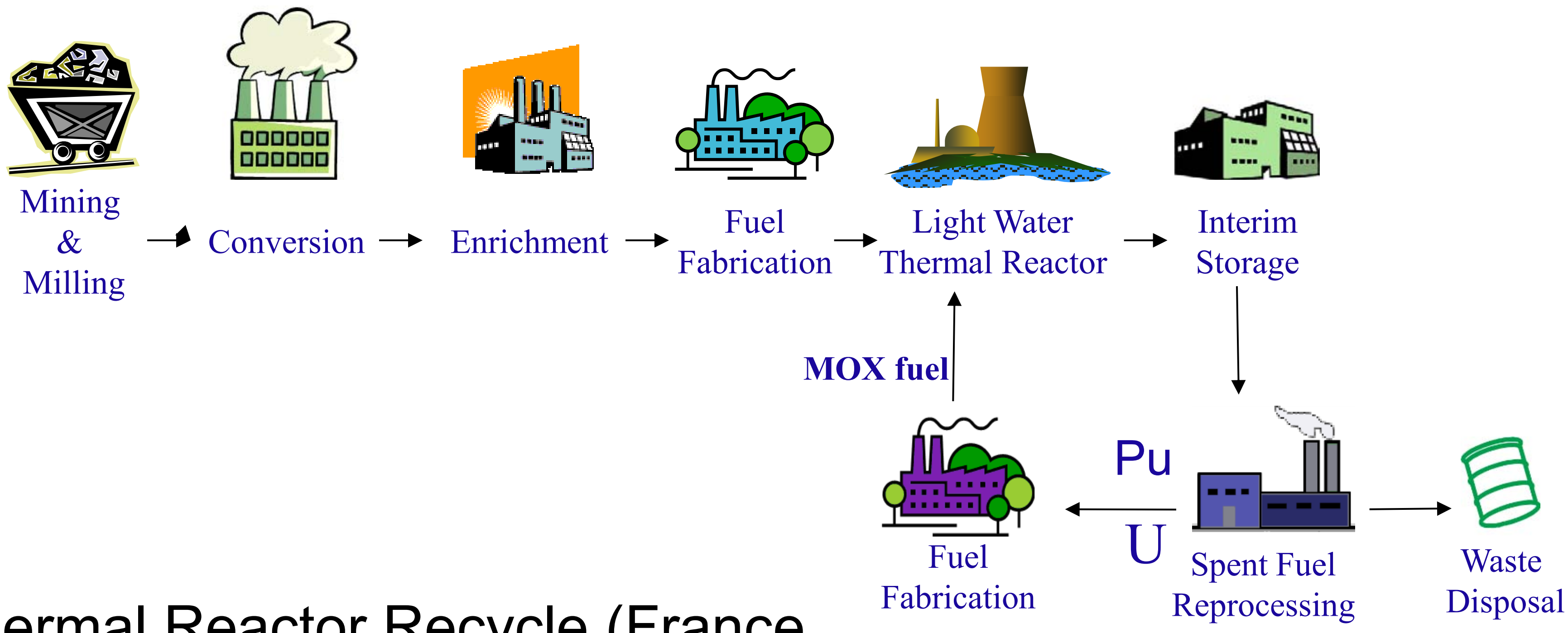
Yucca Mountain Spent Nuclear Fuel Repository



Public domain photos.

[JB]

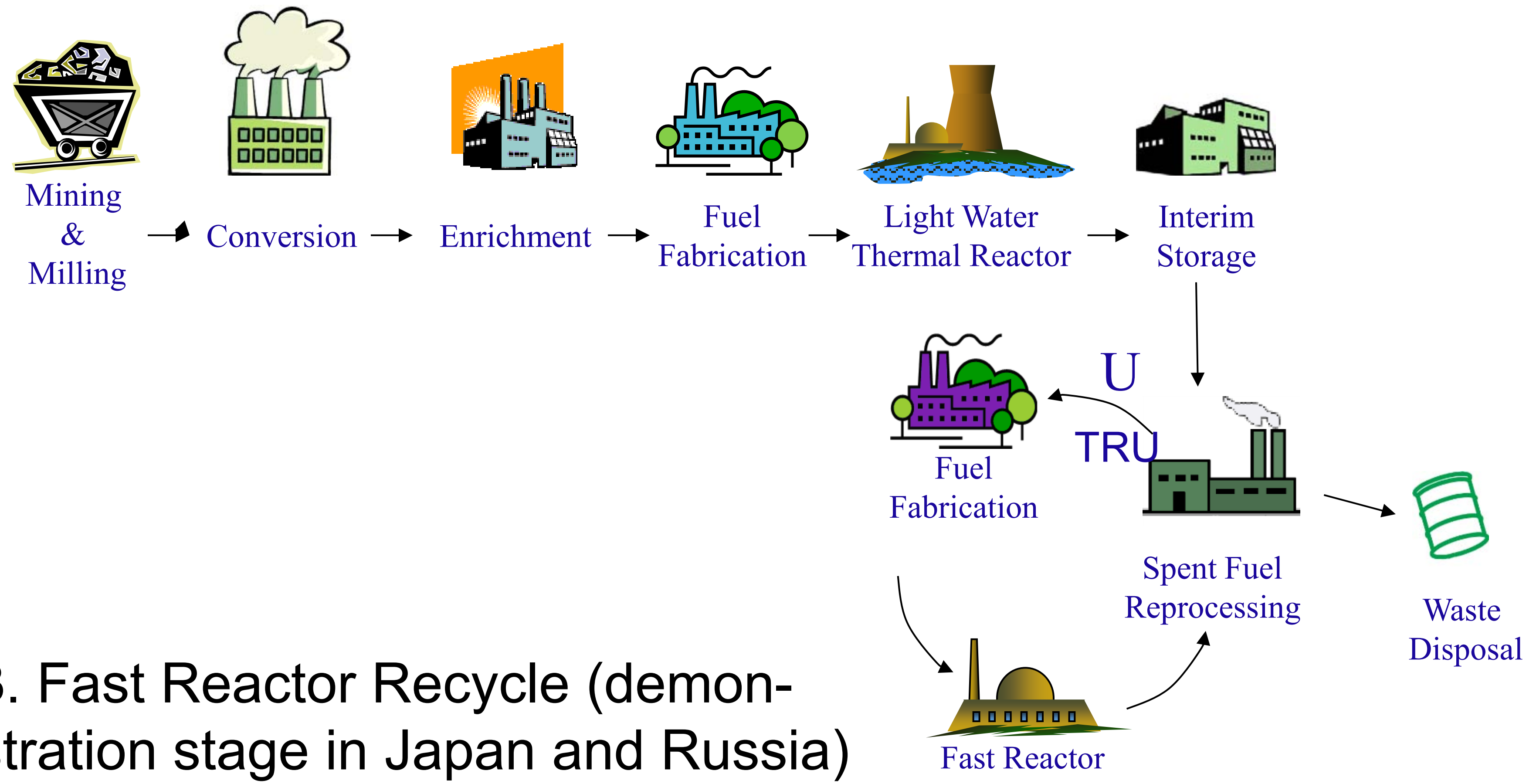
Fuel Cycle Scenarios (2)



Thermal Reactor Recycle (France, Germany, Switzerland, Belgium and Japan current, soon in the US)

[JB]

Fuel Cycle Scenarios (3)

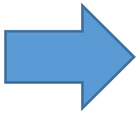


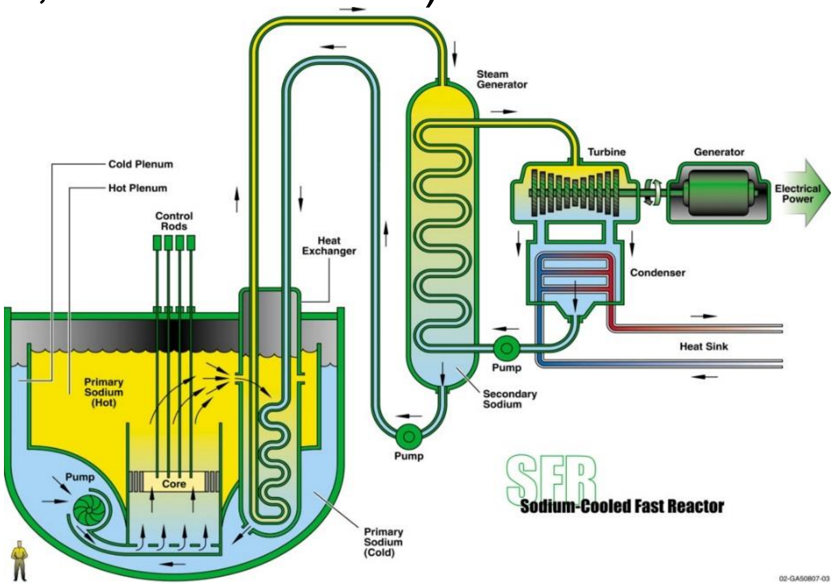
3. Fast Reactor Recycle (demon-stration stage in Japan and Russia)

[JB]

Spent fuel management (recycling)

- Separated Pu is recycled in LWRs (MOX approach, done in France and Japan, soon US)
- Pu+U recycled in (Na-cooled) fast reactors (being reconsidered in Russia, Japan, France and US)





[JB]

96% of a used fuel assembly is recyclable

- **Composition of used light water reactor fuel**
  - 1 LWR fuel assembly = 500 kg uranium before irradiation in the reactor

Recyclable materials | Waste

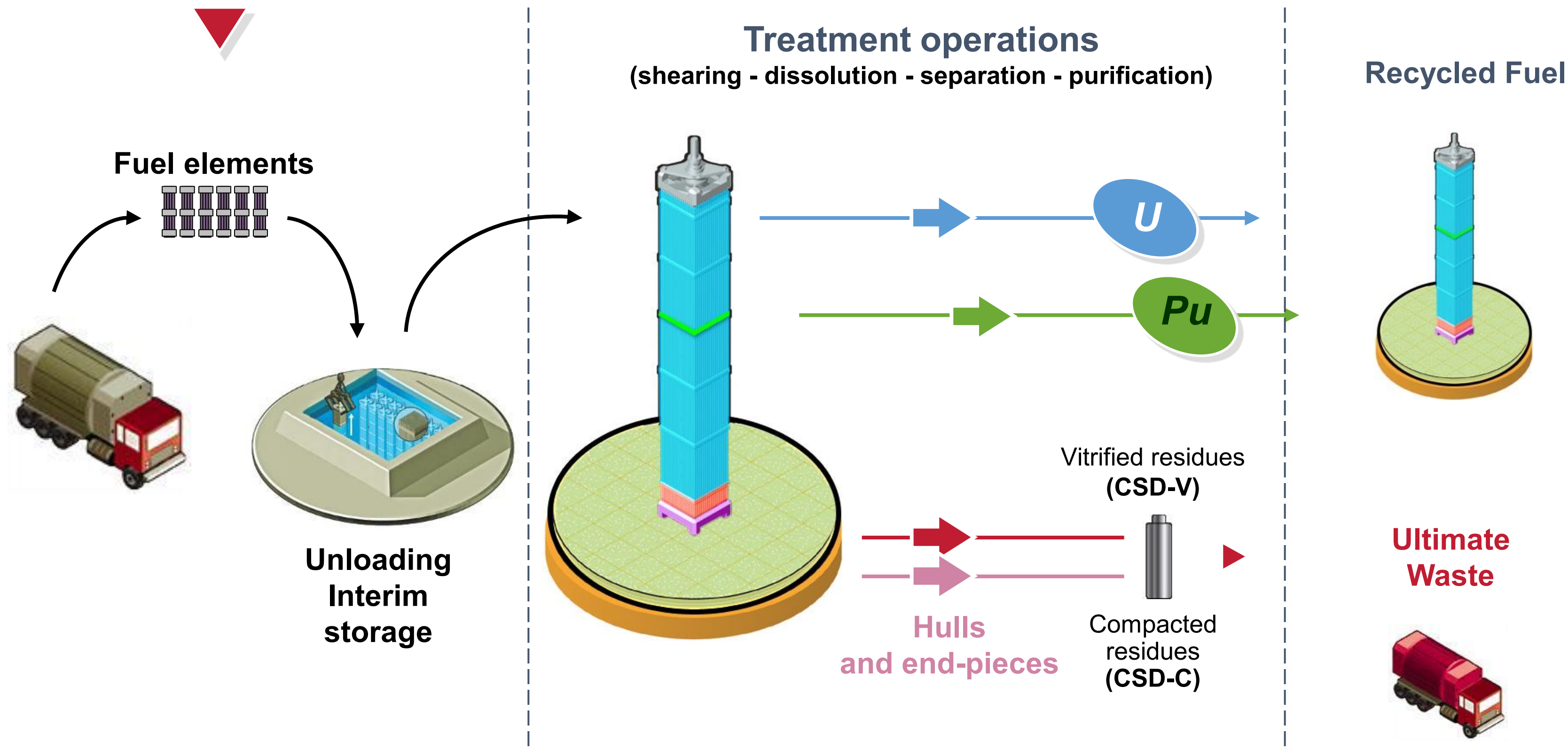
After irradiation*

U 475 to 480 kg (94 to 96 %)	Pu 5 kg (1 %)	FP 15 to 20 kg (3 to 5 %)
RECYCLING	RECYCLING	FINAL WASTE

* Percentages may vary based on fuel burnup

[JB]

The Main Stages in Recycling

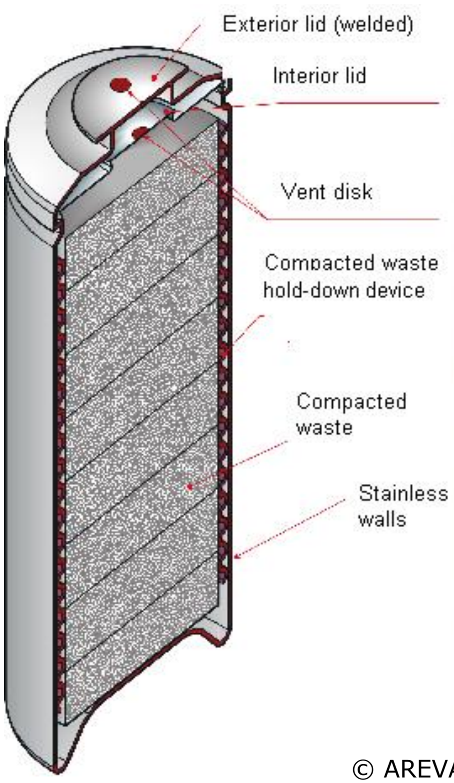


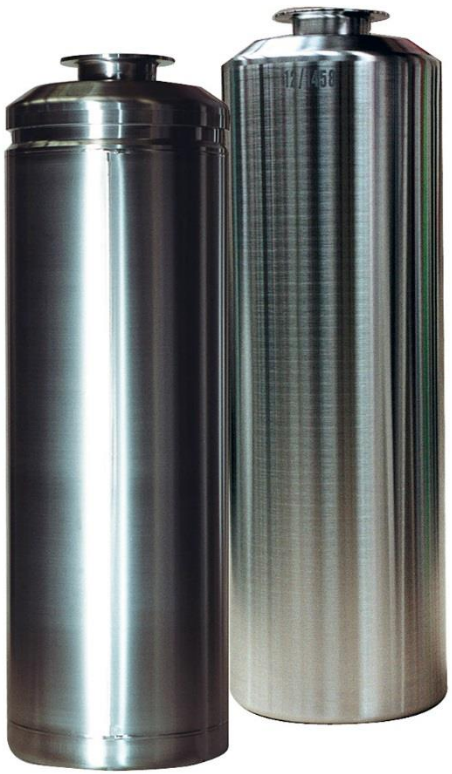
At each stage, nuclear material accounting occurs under IAEA safeguards

[JB]

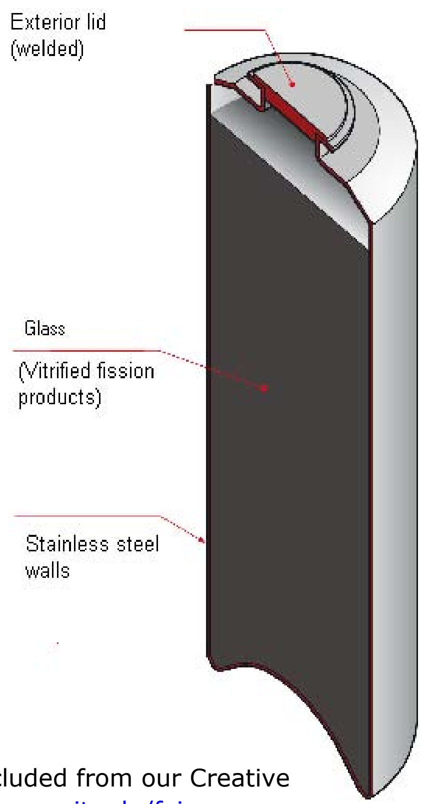
Standard packaging for long-term management

Compacted waste





Vitrified waste



[JB]

Proliferation Risk

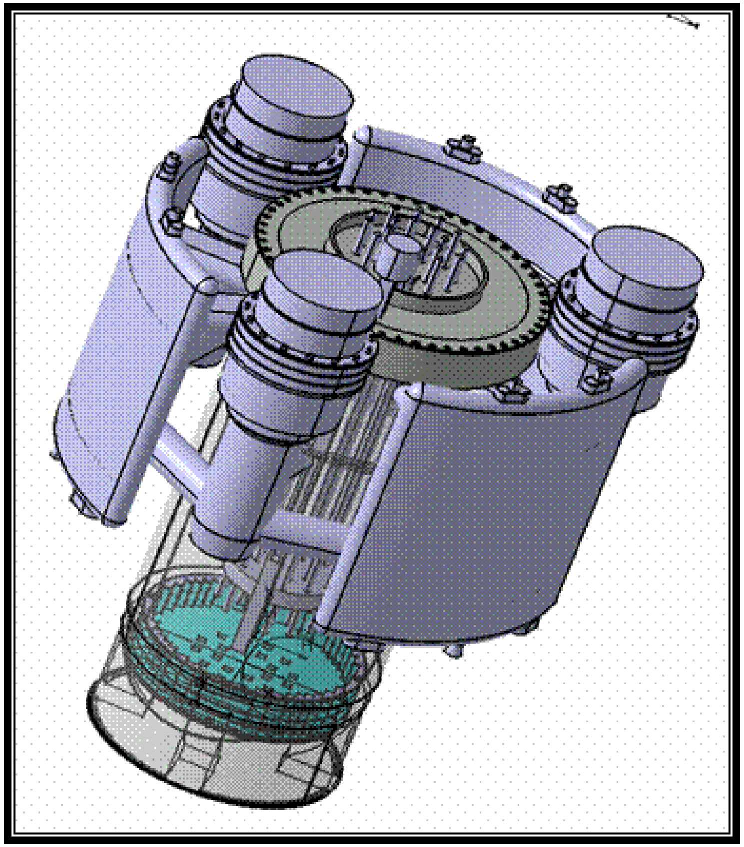
–Some technical characteristics of the fuel cycle (high burnup, no Pu separation, use of Th) can alleviate (but not completely eliminate) the proliferation risk

–For the US the problem is minimal, as the fuel cycle is well safeguarded

–For developing countries it is mostly a political problem, perhaps best handled through multilateral and/or bilateral inspections

[JB]

Possible Solutions – PEACER

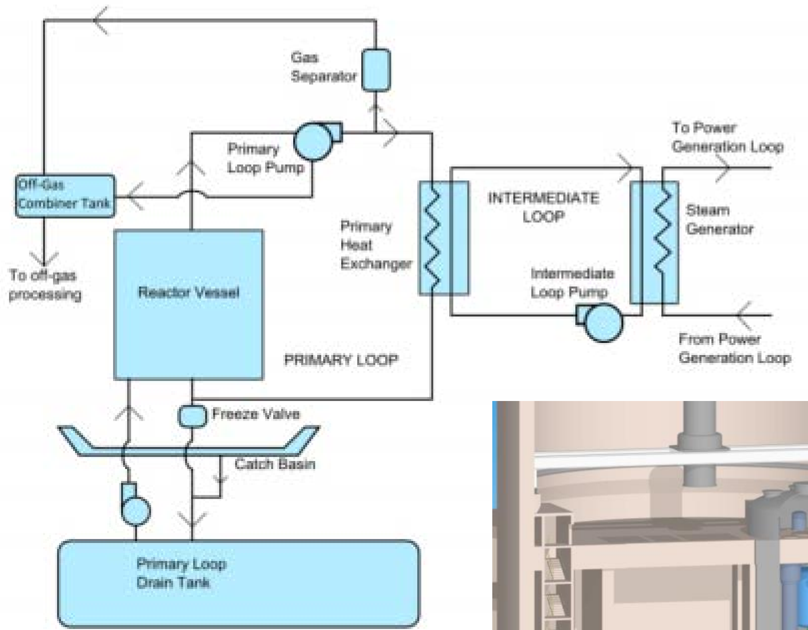


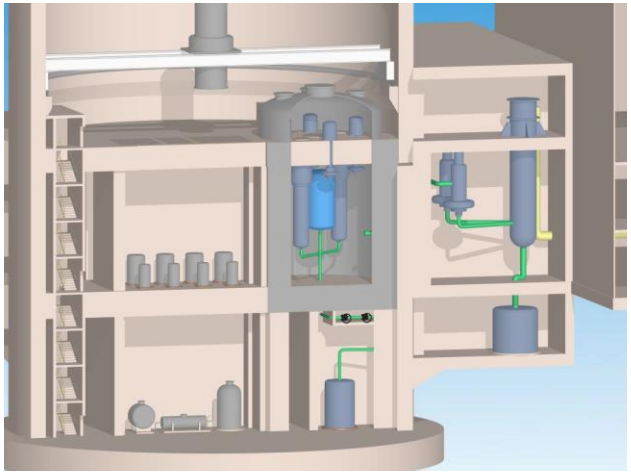
High-level waste burning reactor by Seoul National University

Leaves no high-level waste at all

http://peacer.org/new/bbs/zboard.php?id=peacer

Possible Solutions – Transatomic Power





Courtesy of Transatomic Power Corporation. Used with permission.

http://transatomicpower.com/white_papers/TAP_White_Paper.pdf

Fueled by mix of fresh and spent LWR fuel in molten salt form

Started by MIT NSE alums!

Conclusions

Nuclear produces ~19% of US electricity today

Interest due to climate change, fossil fuel imports

Displaces coal (electricity) sector, oil (transportation)

New reactor technologies offer superior safety via increased redundancy and/or passive safety systems

Various nuclear fuel cycle options are available

Challenge is capital cost of new plants (not safety… and not waste)

22.01 Introduction to Nuclear Engineering and Ionizing Radiation
Fall 2015