NE301
Fundamentals of Nuclear Engineering

Reactor Types
Part 2

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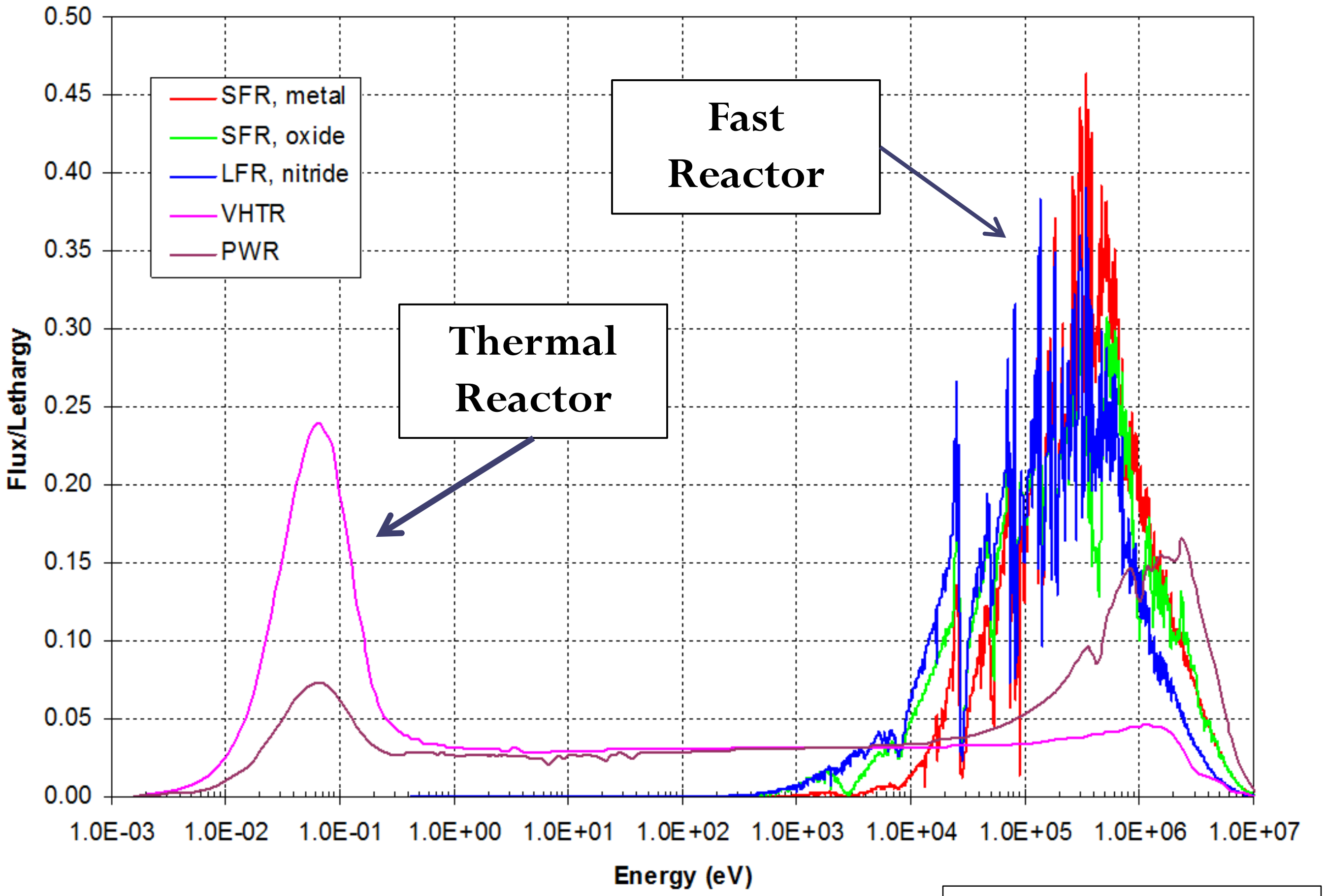
Dr. Scott Palmtag
sppalmta@ncsu.edu

Fast Reactors

Fast Breeder Reactors

- Use a fast neutron spectrum (not thermal)
- Do not want the neutrons to slow down (unlike thermal reactors)
- Need to minimize moderation, so they typically use a metal coolant, such as sodium or lead
- There are many different FBR designs!
- Fuel can be an oxide or a metallic fuel
- Reactors tend to be much smaller (higher power density)
- Increased number density requires close packed fuel, hence a hexagonal geometry (lower cross section → higher number den)
- Mean-free paths are much larger in the fast spectrum and the cores have much more leakage

Fast Spectrum



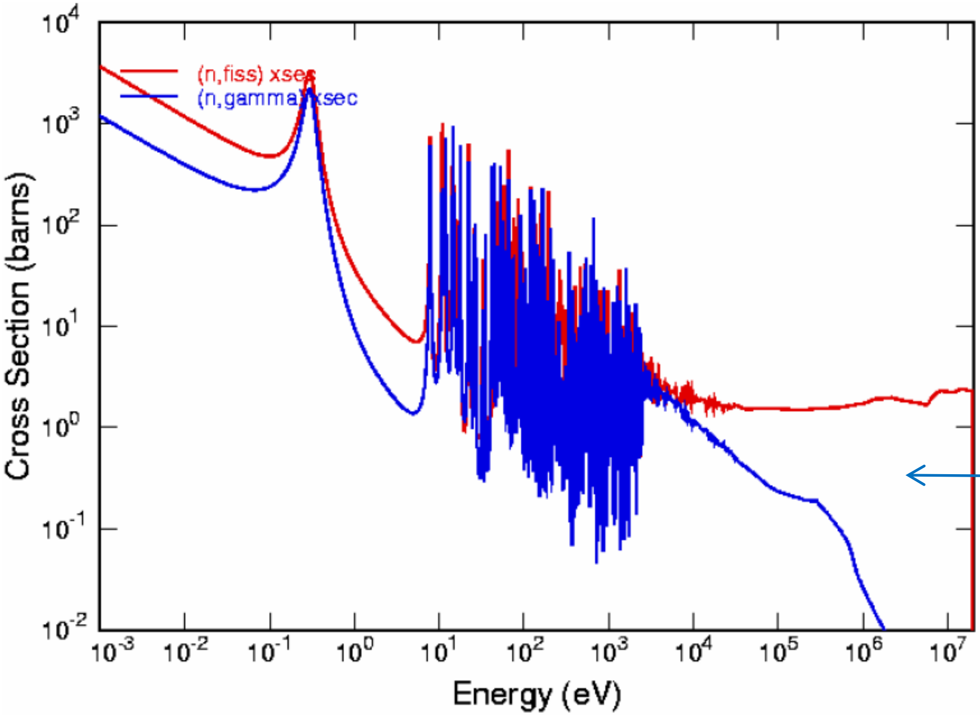
Fast Reactor

Thermal Reactor

[Lewis Figure 3.6]

Neutrons are not thermalized

Pu-239 Cross Sections



Larger fission to capture ratio at high energies

- Overall cross section is much lower in the fast region
- Requires larger number densities to compensate (more fuel volume fraction and higher enrichment)
- However, fission to capture ratio is much higher in the fast region

Nuclear Conversion

- Conversion is the process to convert fertile material into fissile material
- If we can use fertile isotopes in the fuel cycle, we have a near limitless supply of nuclear fuel
- 99.3% of natural uranium is U-238
- Thorium abundance in the earths crust is about three times greater than uranium abundance

U-238 (non-fissile) + n → U-239 → Np-239 → Pu-239 (fissile)

Th-232 (non-fissile) + n → Th-233 → Pa-233 → U-233 (fissile)

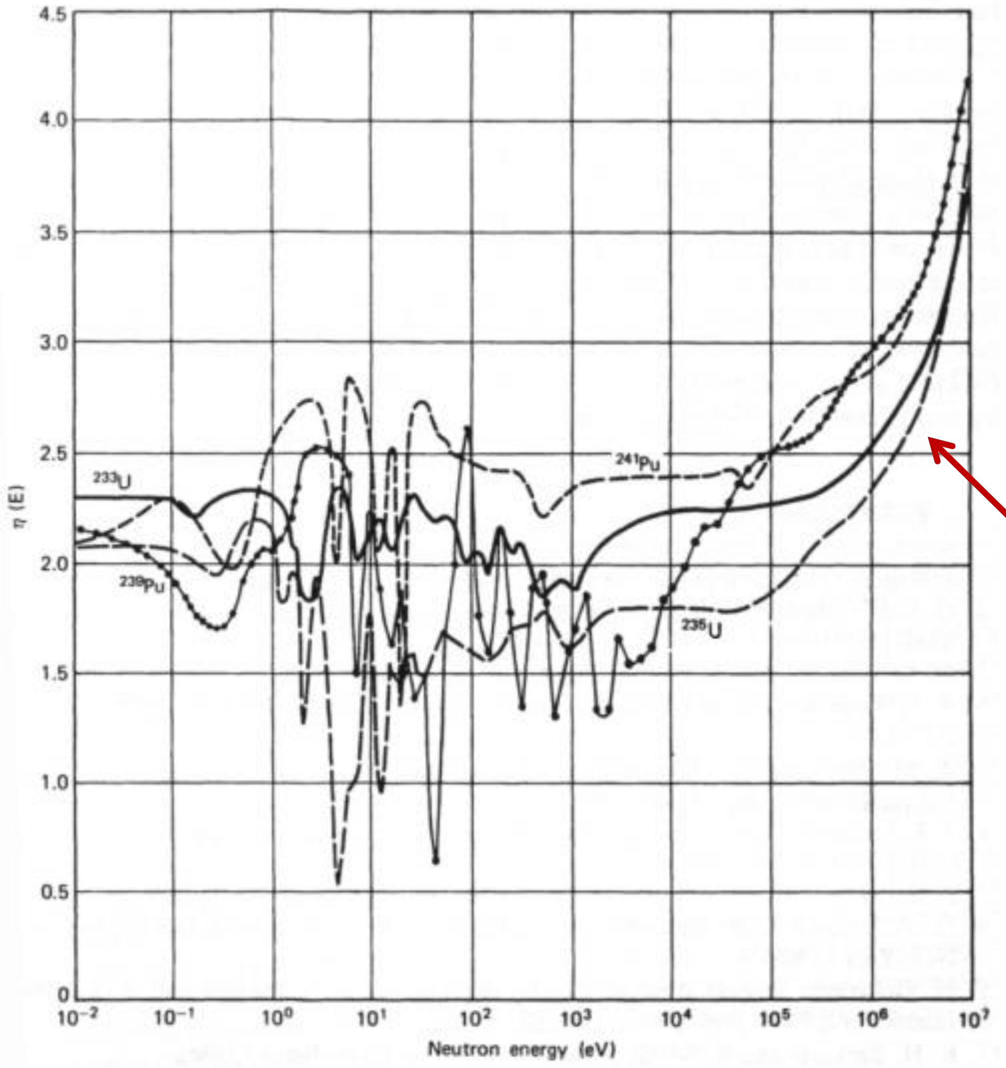
Why Fast Reactors?

Nuclear Conversion

- Define η as the number of new neutrons released per fissile nucleus consumed
- For a stable chain reaction, one neutron is needed to sustain the reaction: η must be larger than 1
- To convert a fertile atom to a fissile atom, one additional neutron is needed: η must be larger than 2
- Neutrons will leak from the reactor and be absorbed in other materials, so η must be appreciably larger than 2 to make a practical reactor with a conversion ratio > 1.

Why Fast Reactors?

η(E)



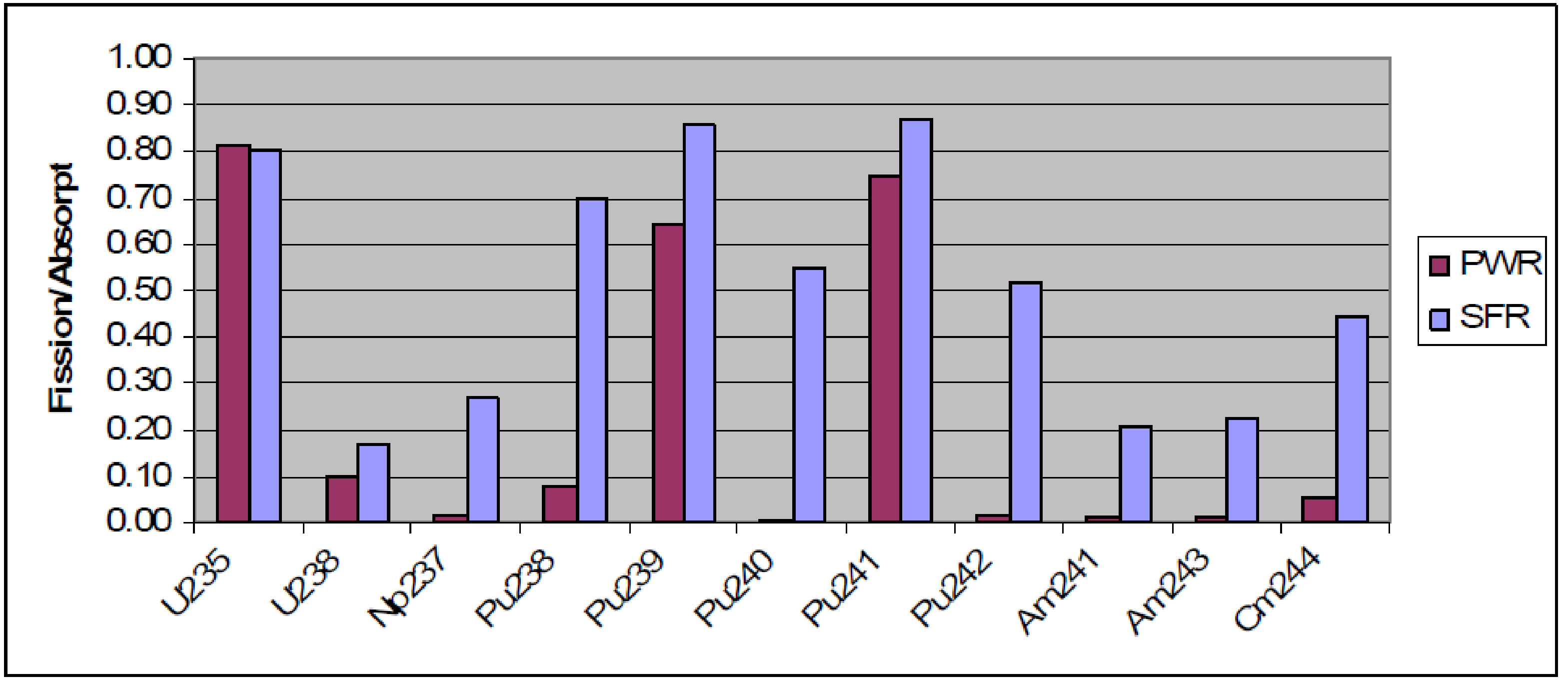
$$\eta(E) = \frac{\nu\Sigma_f^f(E)}{\Sigma_a^f(E)}$$

(defined for fuel only)

η is highest at high energies

Source: Internet

Actinide Burning



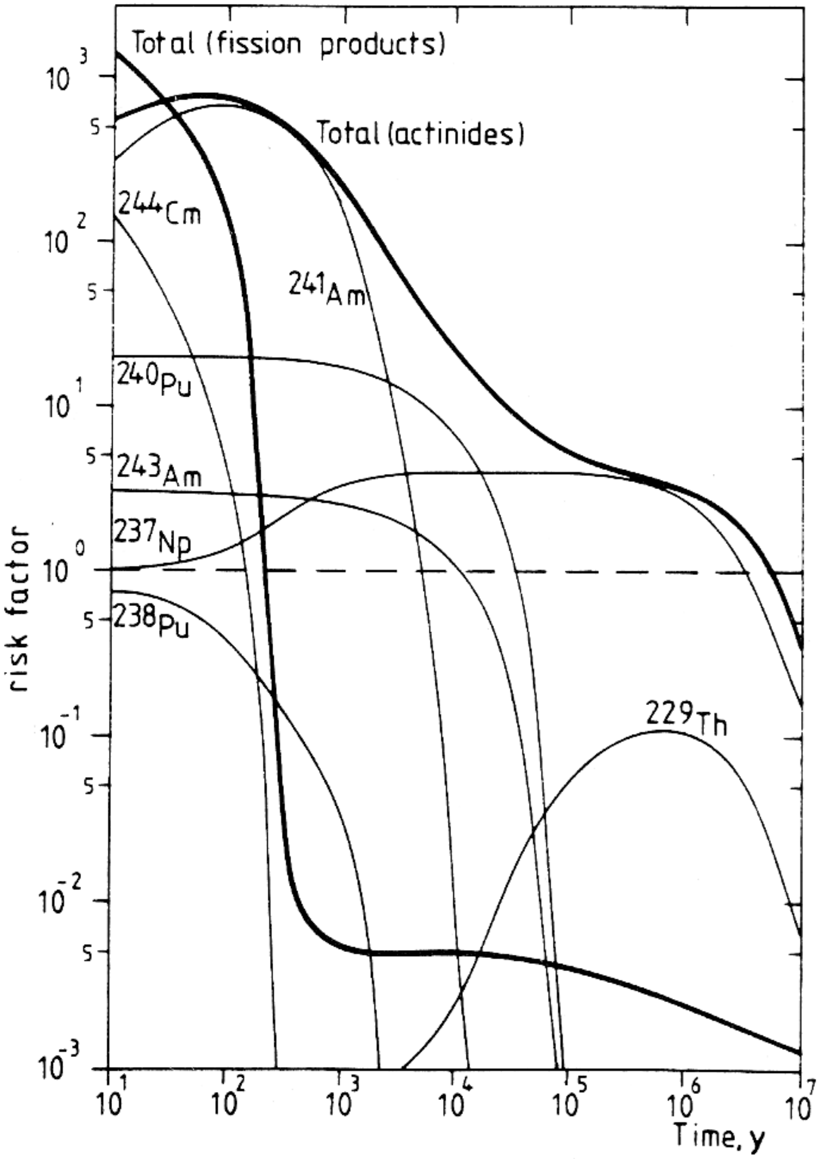
- Fast reactors are better at removing actinides from waste stream
- Actinide reduction is important for radioactive waste management
- Fissile isotopes are likely to fission in both thermal and fast spectrums
- Fertile isotopes are much more likely to fission in <u>fast</u> spectrum

Source: R. Hill, 2007 Student Seminar Series, Argonne

Actinides

- Why do we care about actinide burning?
- The short-term "risk" of spent fuel is dominated by fission products (short half-lives)
- The long term "risk" of is dominated by the actinides (longer half-lives).
- If you can reduce the actinides, you reduce the long-term risk

Radiotoxicity

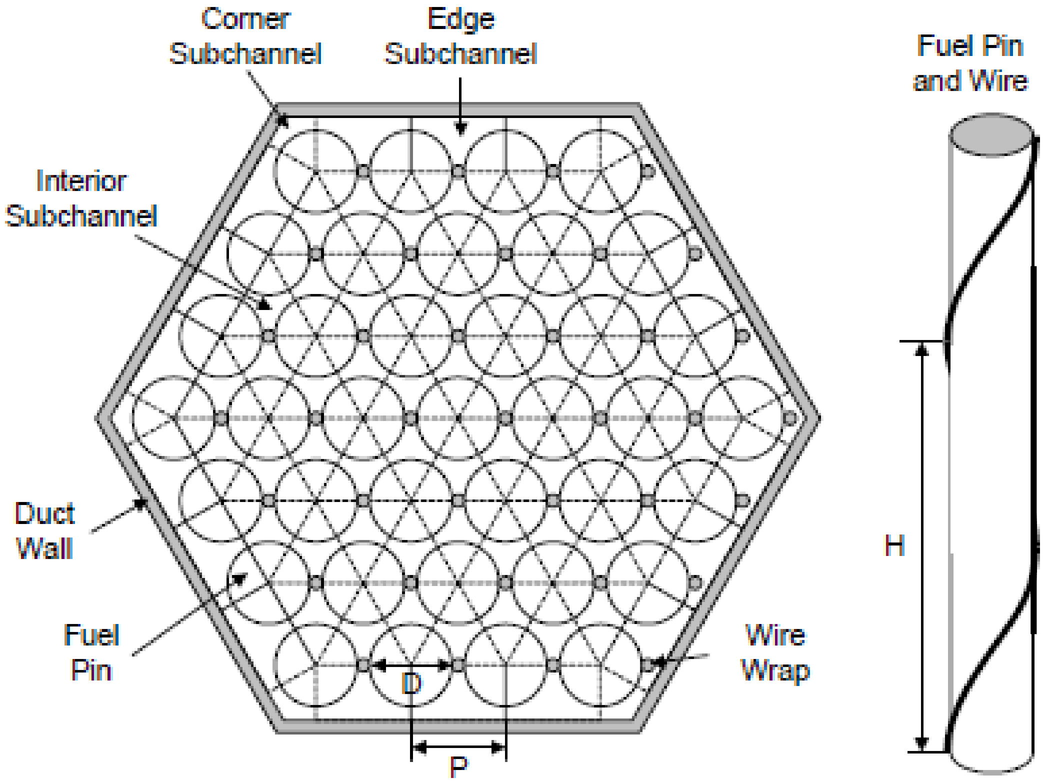


[Lewis Fig. 10.5 page 258]

Disadvantages of Conversion

- To utilize a "closed" fuel cycle where more fuel is produced than consumed, you must have fuel reprocessing to extract the fissile isotopes from the old fuel and create new fresh assemblies
- Reprocessing is not economical given the current prices of uranium
- Reprocessing may also introduce possibility of diverting fissile material into weapons production (proliferation)
- Japan was pursuing a closed fuel cycle with reprocessing, but it is doubtful this will be restarted after the Fukushima accident.

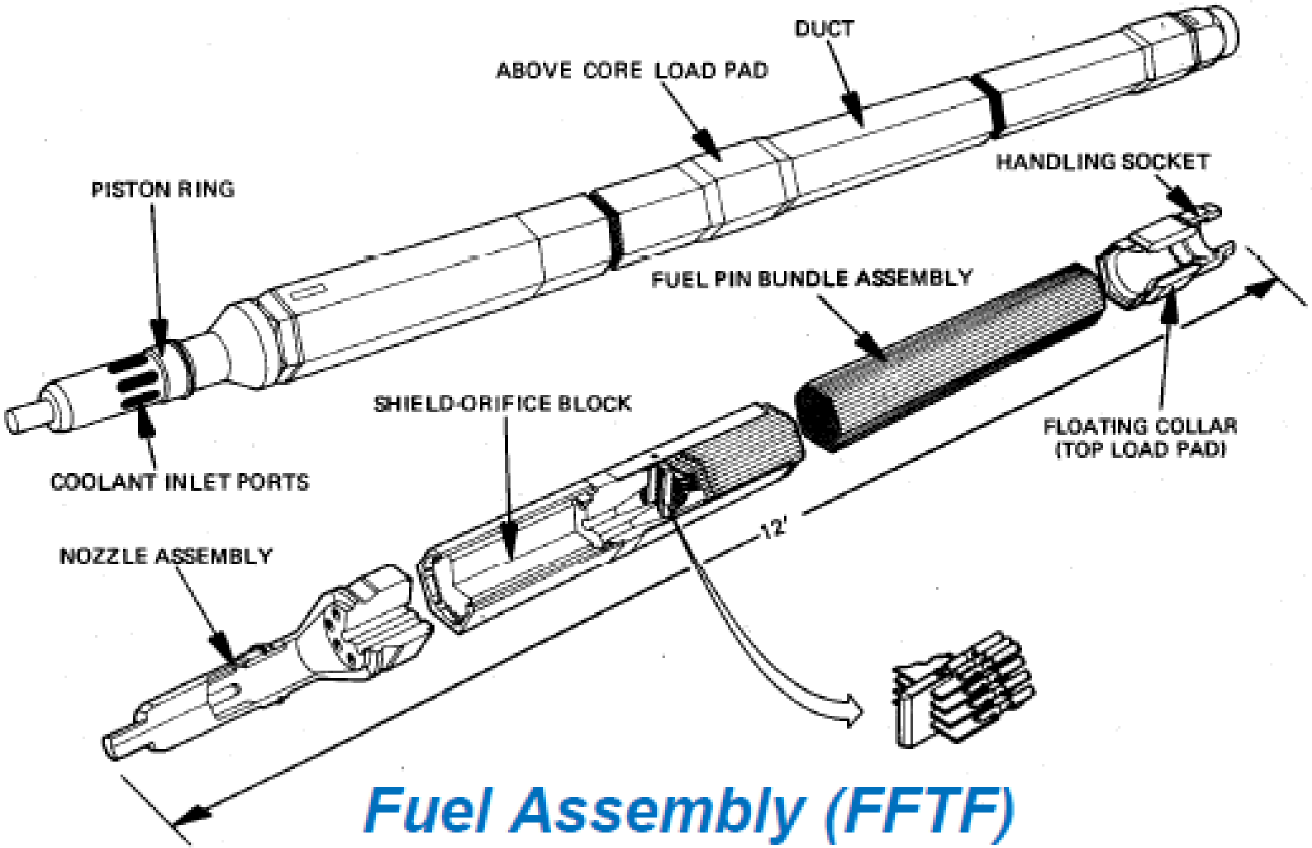
Fuel Assembly Geometry



- Hexagonal pitch to increase number density
- Wire wrapping to separate pins (no grid)
- Stainless steel cladding and box wall

Source: R. Hill, 2007 Student Seminar Series, Argonne

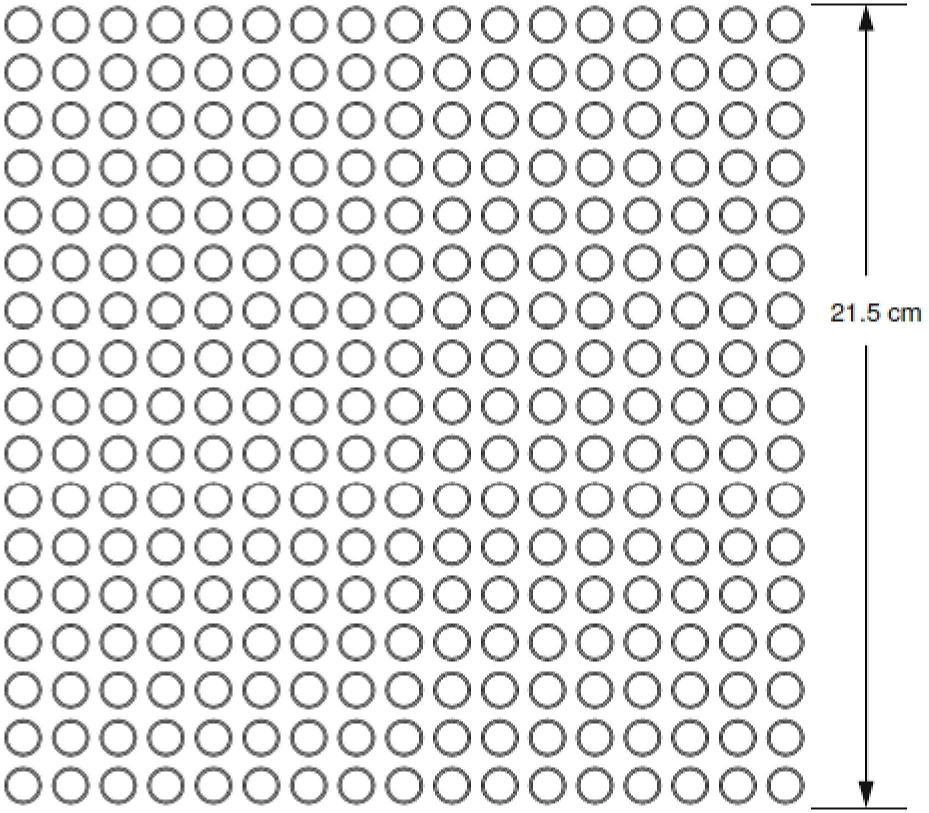
Fuel Assembly Geometry



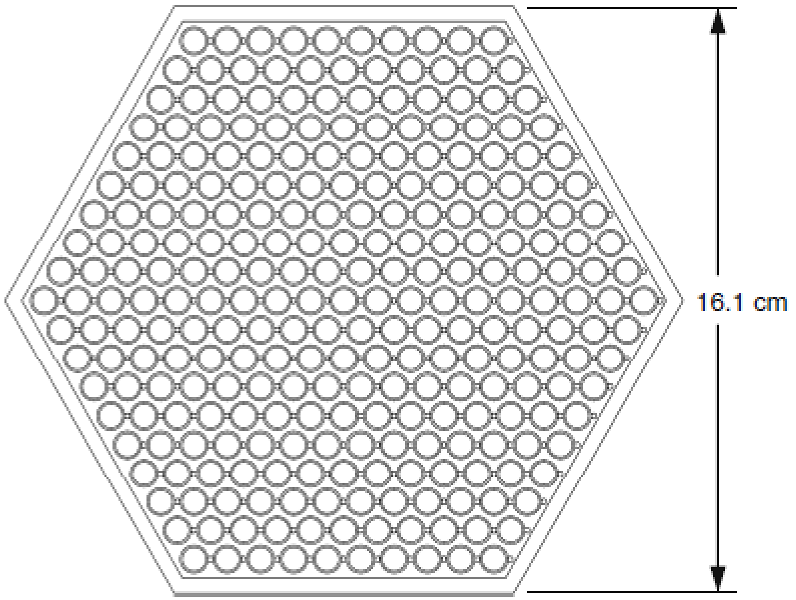
Fuel Assembly (FFTF)

Source: R. Hill, 2007 Student Seminar Series, Argonne

Fuel Assembly Geometry



Typical PWR Assembly (289 pin locations)
Pin Diameter = 9.4 mm
Pin Pitch = 12.5 mm



"Typical" SFR Assembly (271 pins)
Pin Diameter = 7.4 mm
Pin Pitch = 8.9 mm

Source: Fanning, 2007 Student Seminar Series, Argonne

Hexagonal Pitch

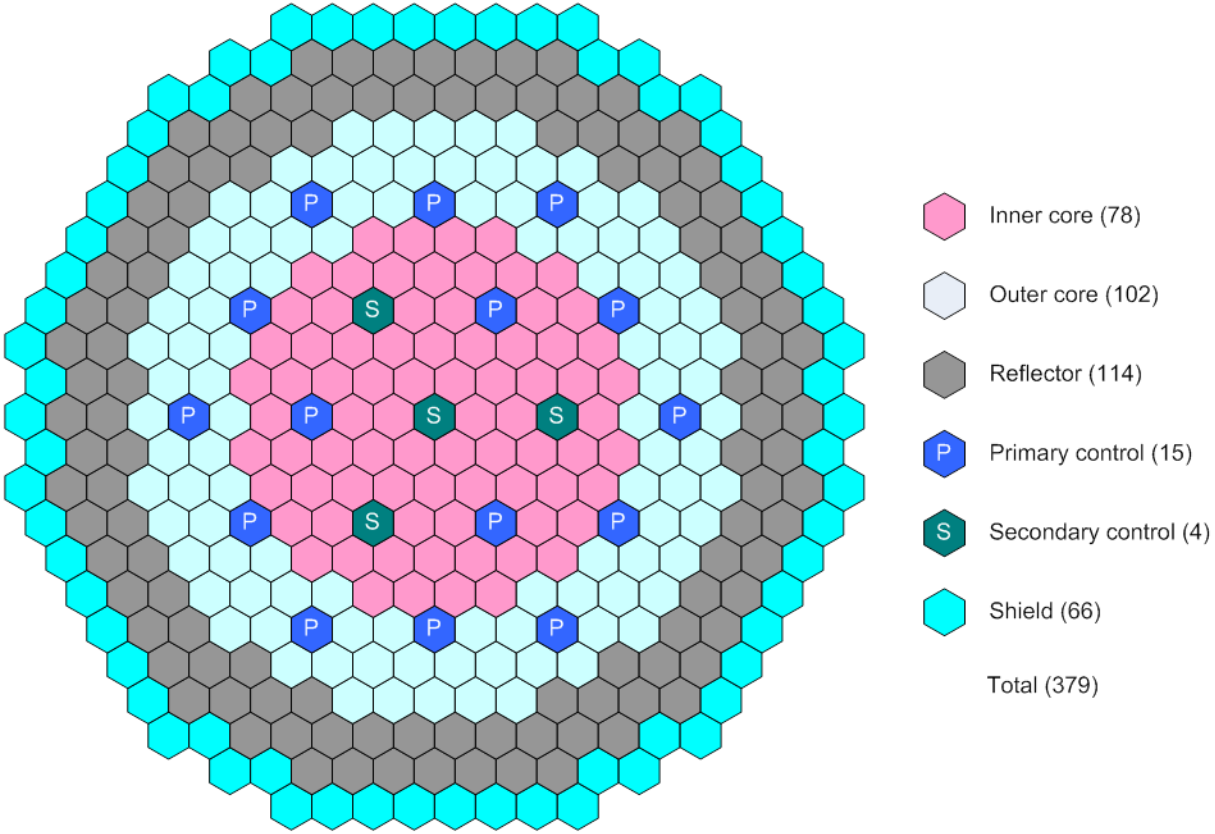
Homework:

What is the maximum 2D packing fraction for a square pitch and a hexagonal pitch?

$$PF = \frac{A_{rod}}{A_{total}}$$

Picture Source:
http://chemwiki.ucdavis.edu/Wikitexts/Simon_Fraser_Chem1%3A_Lower/States_of_Matter/Cubic_Lattices_and_Close_Packing

Fast Reactor Core Geometry (Typical)

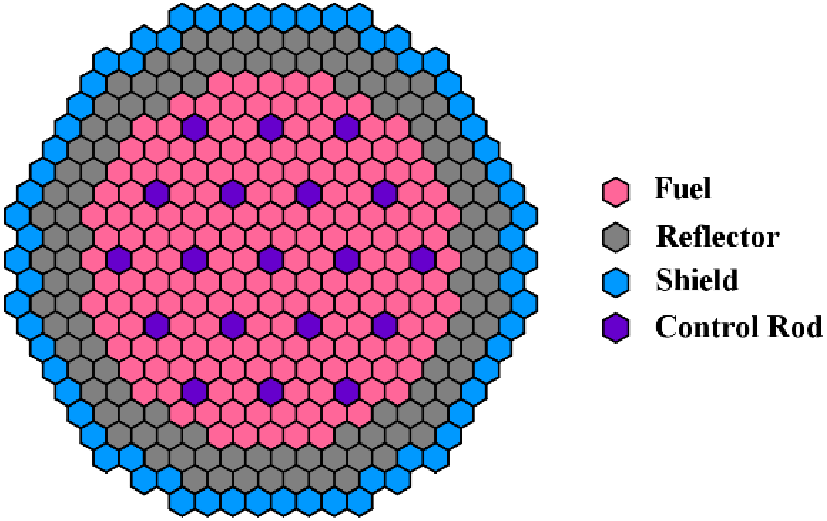


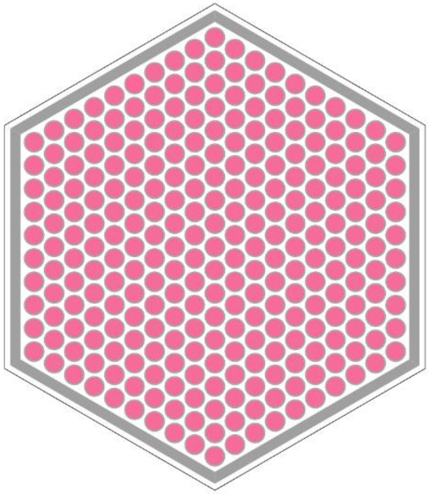
Fast Reactor Core Geometry (hexagonal assembly layout)

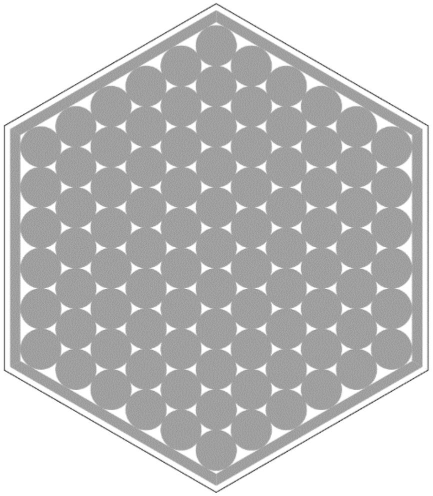
Source: R. Hill, 2007 Student Seminar Series, Argonne

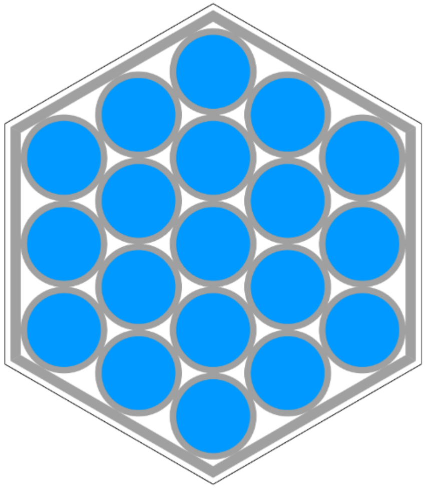
Bundle Designs

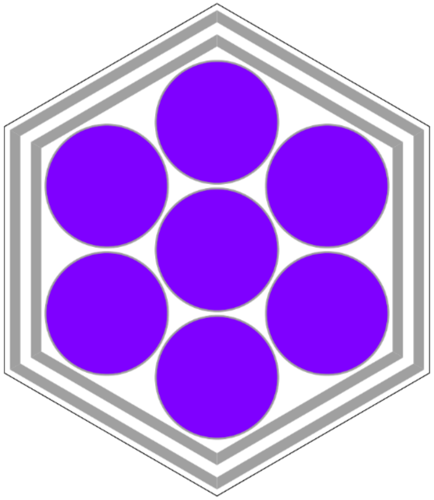
Advanced Burner Reactor (ABR)




Fuel Assembly


Reflector Assembly


Shield Assembly


Control Rod Assembly

T. K. Kim, W. S. Yang, C. Grandy, and R.N. Hill,
Core Design Studies for a 1000MWth Advanced Burner Reactor, Annals of Nuclear Energy, 36.3: 331-336, 2009

PRISM Reactor Design (GE)

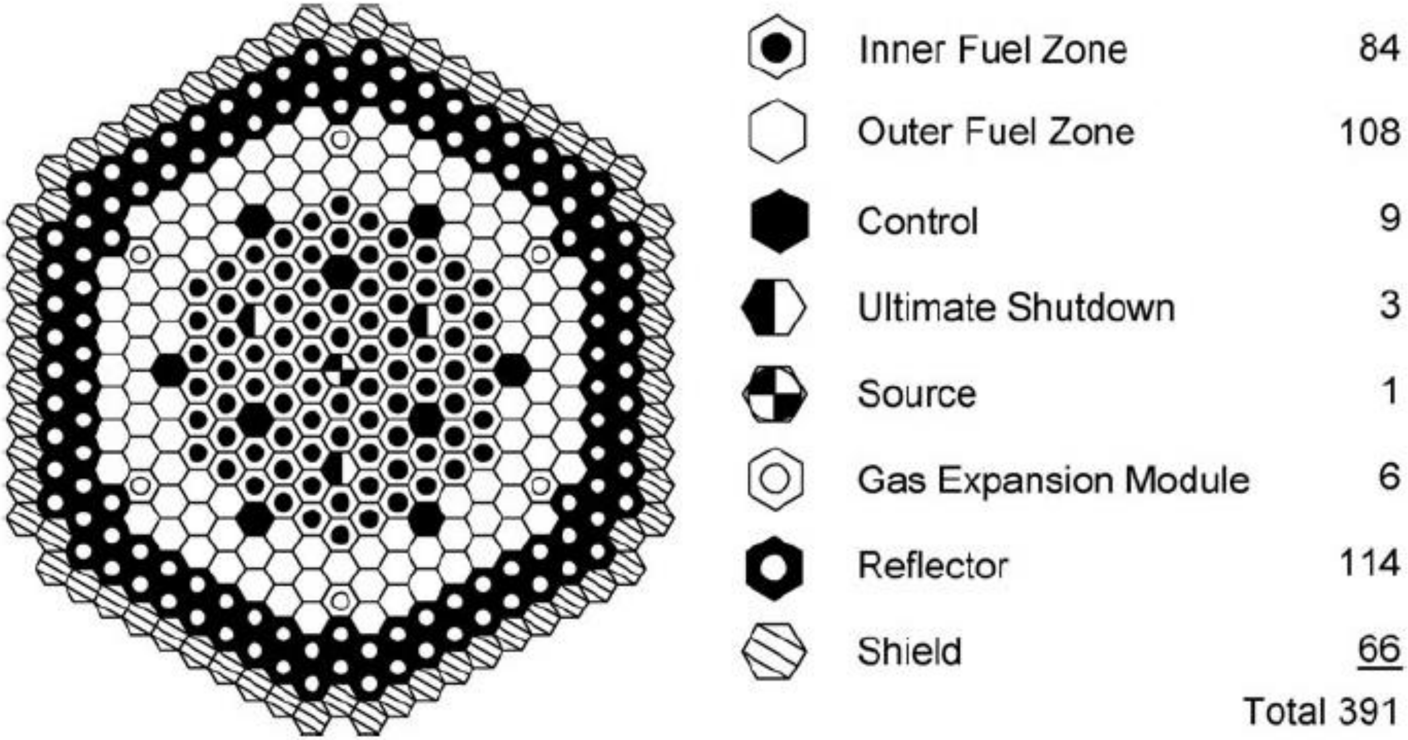
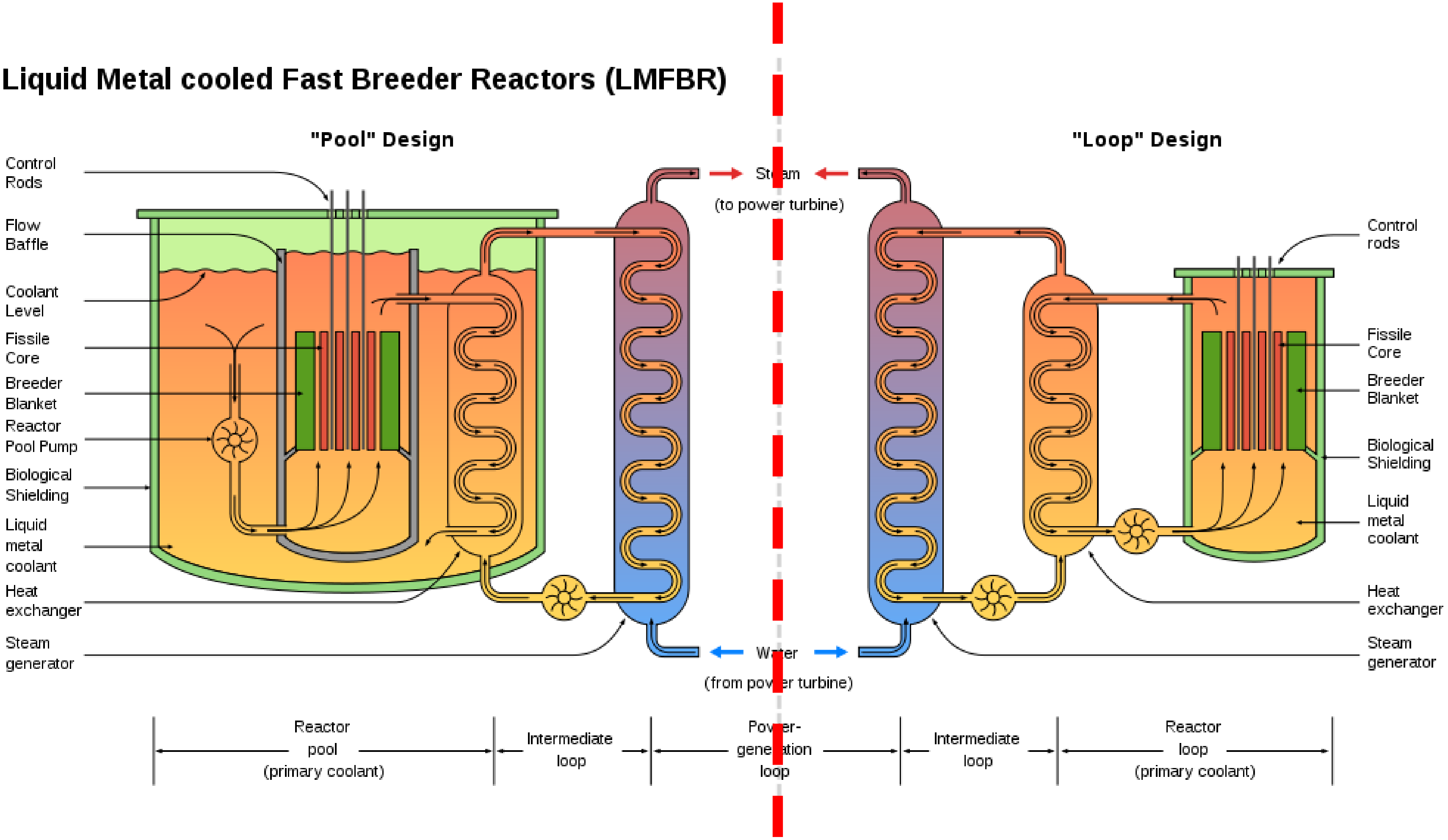


Fig. 8. Fuel assembly layout for UNF recycle core.

Two Types of LMFBR Vessels



"Pool" Designs and "Loop" Designs

Loop designs have intrinsic safety features, but are harder to scale up to large power reactors

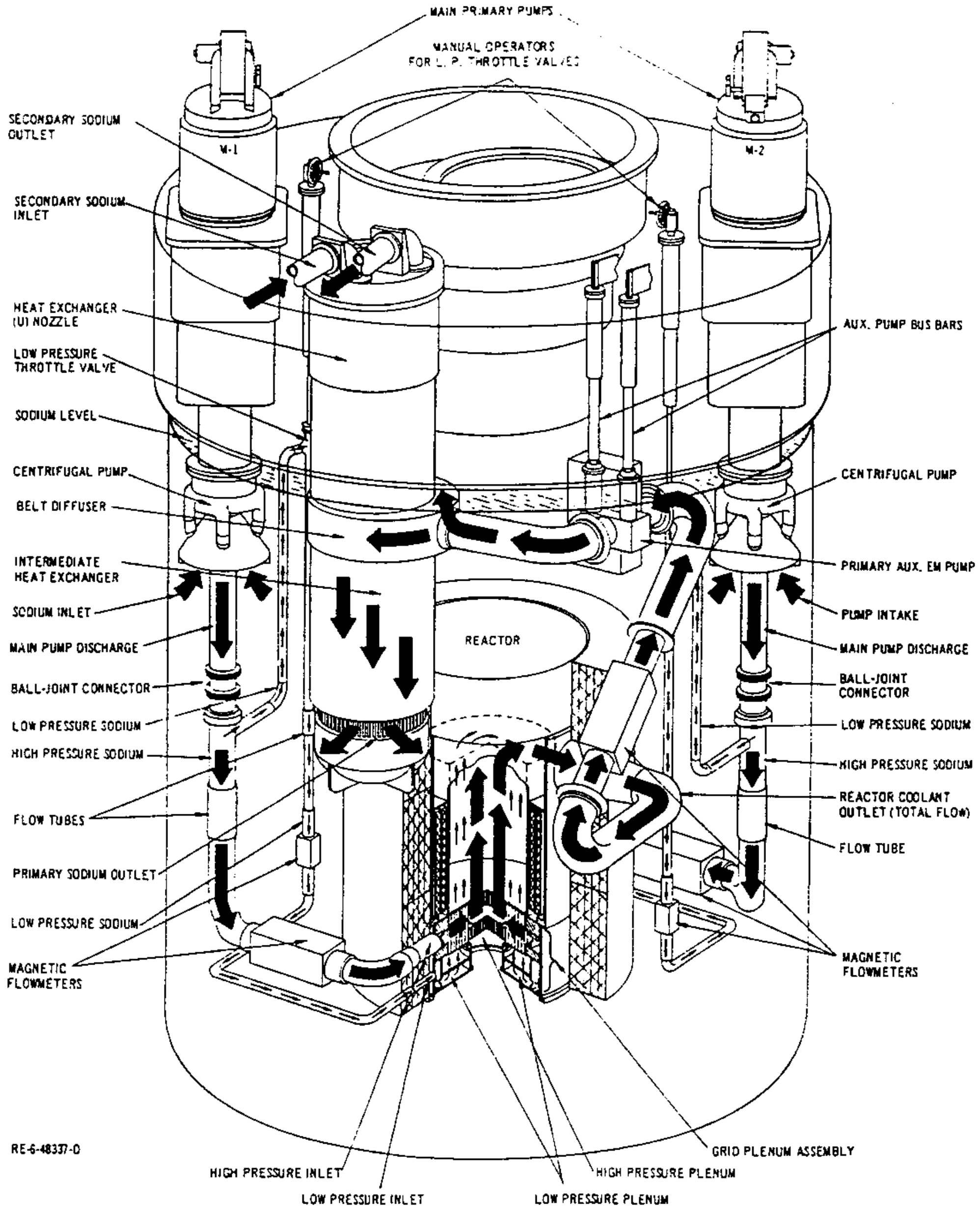
EBR-II Tank

Experimental
Breeder Reactor II

Pool Design
62.5 MWt
Sodium Coolant

Near Idaho Falls, ID

Everything is immersed in pool of sodium



Reactivity Control

- Fast Breeder Reactors typically only use control rods to control reactivity
- Since the reactor is producing fissionable isotopes as it depletes, the reactivity letdown curve is "flatter" than a LWR
  - Smaller excess reactivity needed at BOC
- Some small reactors actually remove fuel in the control rods rather than insert absorbers

Sodium Coolant

Advantages:

- Reactor vessel not kept under pressure
- Sodium provides very little neutron moderation thus neutrons remain at higher energies
  - Produces more neutrons/fission (η)
  - Allows the use of other fuel options such as actinides
- Enhanced heat transfer – high thermal conductivity
  - Sodium can remove more energy per volume
  - Increased power density

Disadvantages:

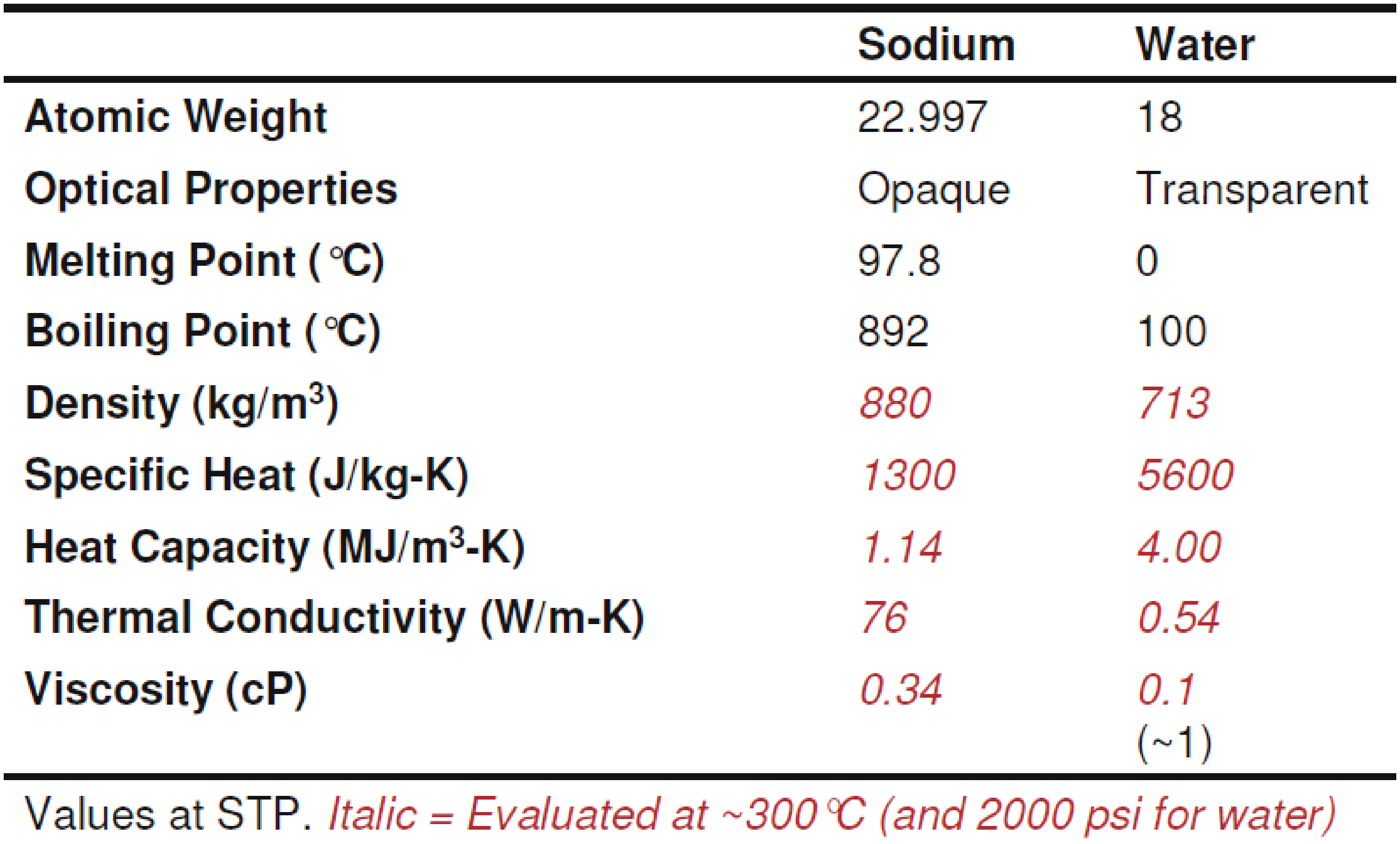
- Highly Reactive with water

Thermal Hydraulics

- Sodium is a liquid metal and does not increase density (pressure) as much as water when heated
- Sodium has a much higher thermal conductivity than water

Reactor	Reactor Pressure (psia)	Power Density (kW/L)
PWR	2250	100
BWR	1050	54
FBR (PRISM)	50	280

Selected Properties of Sodium and Water



	Sodium	**Water**
Atomic Weight	22.997	18
Optical Properties	Opaque	Transparent
Melting Point (°C)	97.8	0
Boiling Point (°C)	892	100
Density (kg/m³)	*880*	*713*
Specific Heat (J/kg-K)	*1300*	*5600*
Heat Capacity (MJ/m³-K)	*1.14*	*4.00*
Thermal Conductivity (W/m-K)	*76*	*0.54*
Viscosity (cP)	*0.34*	*0.1* (~1)

Values at STP. *Italic = Evaluated at ~300°C (and 2000 psi for water)*

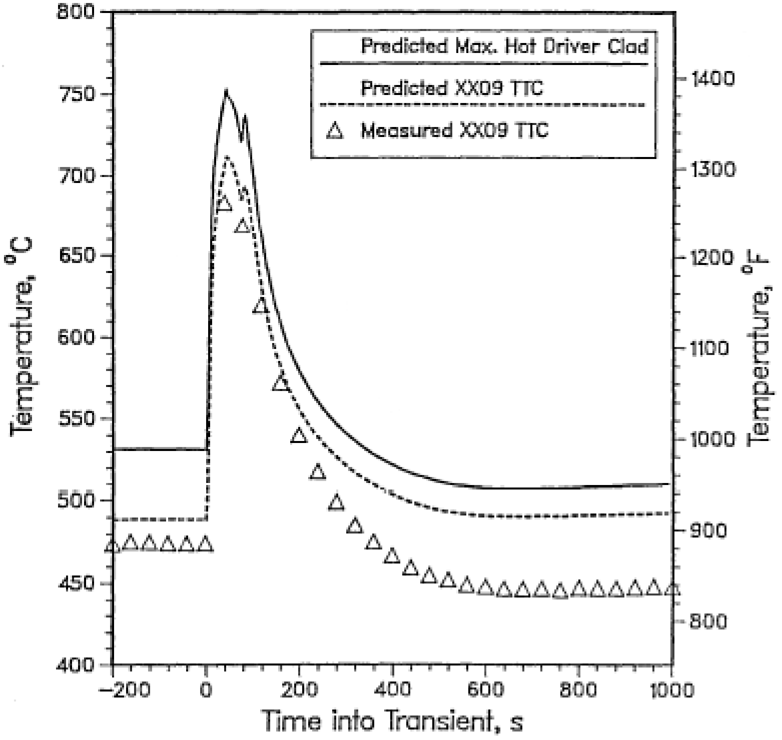
Source: Fanning 2007 Student Seminar Series, Argonne

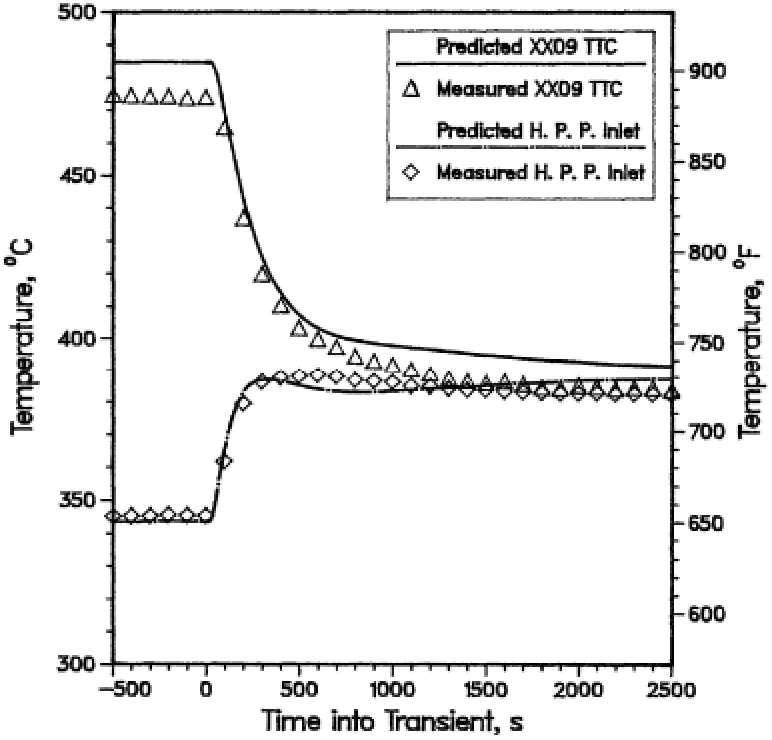
Safety

- Superior thermophysical properties of liquid metals allow:
    - Operation at high power density and high fuel volume fraction
    - Low pressure operation with significant margin to boiling
- The fast neutron spectrum leads to long neutron path lengths
    - Neutron leakage is enhanced, 25% at moderate sizes
    - Reactivity effect impacts the reactor as a whole, not locally
- High leakage fraction implies that the fast reactor reactivity is sensitive to minor geometric changes
    - As temperature increases and materials expand (thermal expansion), a net negative reactivity feedback is inherently introduced
- Favorable inherent feedback in sodium-cooled fast reactors (SFR) have been demonstrated
    - EBR-II and FFTF tests for double fault accidents

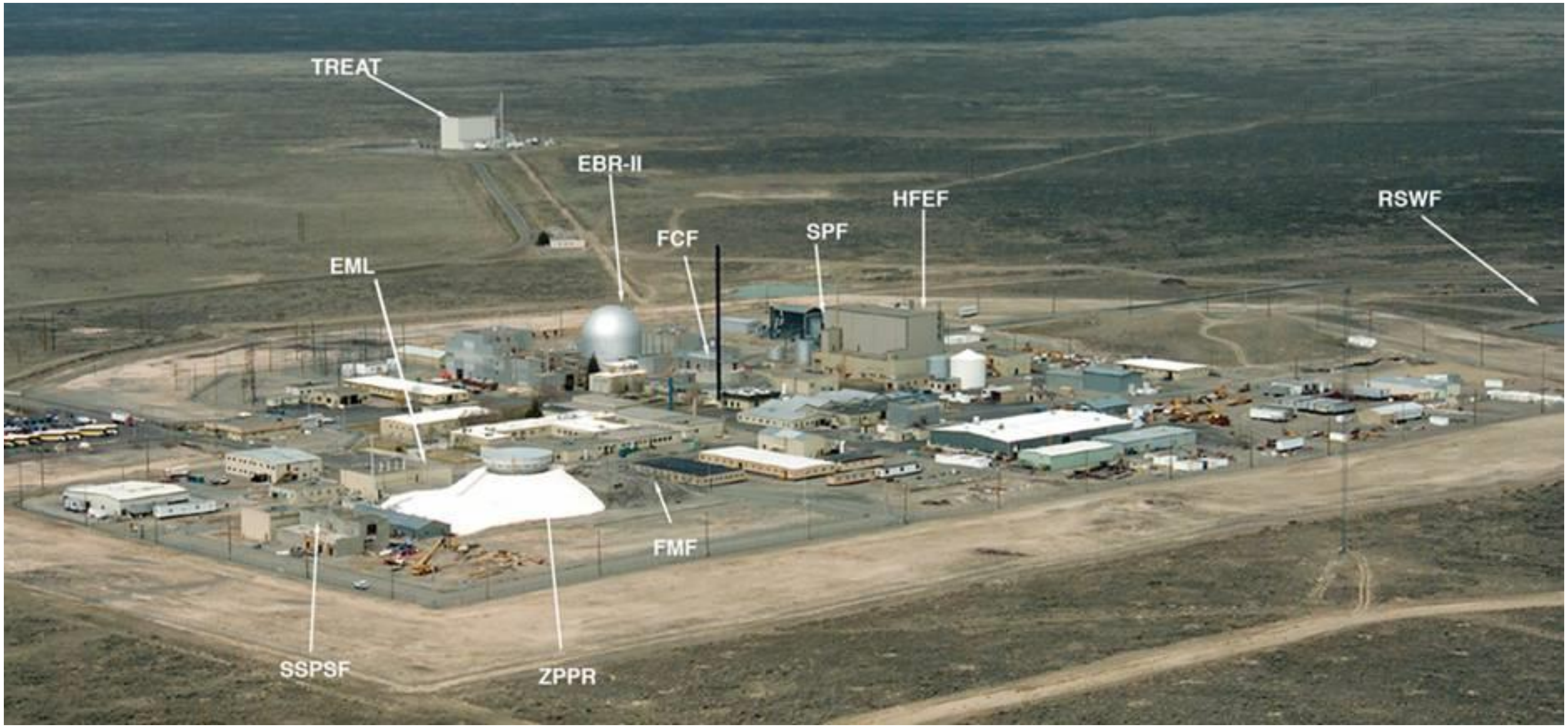
Passive Safety (Demonstrated in EBR-II in 1986)

- Unprotected (no scram) Loss of Flow (ULOF) results in brief temperature rise which is terminated by negative reactivity feedback effects
- Unprotected Loss of Heat Sink (ULOHS) causes increase in inlet temperature which introduces negative reactivity feedback effects.





EBR-II Site in Idaho



Visit if you can!

The EBR-1 site is located nearby and is a museum open to the public

The museum also contains prototypes of nuclear powered airplane engines

List of Fast Reactors Worldwide

		MW (thermal)	Operation
USA	EBR I	1.4	1951-63
USA	EBR II	62.5	1963-94
USA	Fermi 1	200	1963-72
USA	SEFOR	20	1969-72
USA	Fast Flux Test Facility	400	1980-93
UK	Dounreay FR	65	1959-77
UK	Protoype FR	650	1974-94
France	Rapsodie	40	1966-82
France	Phenix	563	1973-2009
France	Superphenix	3000	1985-98
Germany	KNK 2	58	1977-91
India	**FBTR**	**40**	**1985-**
India	PFBR	1250	2014?-
Japan	Joyo	140	1978-2011?
Japan	Monju	714	1994-96, 2010-2011?
Kazakhstan	BN-350	750	1972-99
Russia	BN 1/2	1/0.1	1950s
Russia	BR 5/10	5/8	1959-71, 1973-?
Russia	**BOR 60**	**55**	**1969-**
Russia	**BN-600**	**1470**	**1980-**
Russia	**BN-800**	**2100**	**2014-**
China	**CEFR**	**65**	**2011-**

(Highlighted reactors are currently in operation)

Fast Reactor Physics

[Lewis Section 4.3]

- Fuel enrichments are higher than typically found in thermal reactors, generally exceeding 10%
- To minimize moderations, designers eliminate materials with low atomic weights
- Cross Sections in a fast spectrum are substantially less than in a thermal spectrum
- The mean-free-path of high energy neutrons is higher than thermal neutrons
- Therefore, the spatial distribution of neutrons is quite flat

Fast Reactor Physics

[Lewis Section 4.3]

- Increasing the number densities of the coolant or structure will decrease the eigenvalue
- This is different than for a LWR where decreasing the coolant number density may increase or decrease the eigenvalue!
- In fact, from a neutronics point of view, it would be better not to have any coolant.
- However, from a T/H point of view, you need some way to remove heat from the core

Questions?

- Finished with Fast Reactors
- Next Topic will be CANDU Reactor Description

CANDU Reactors

Reactor Types

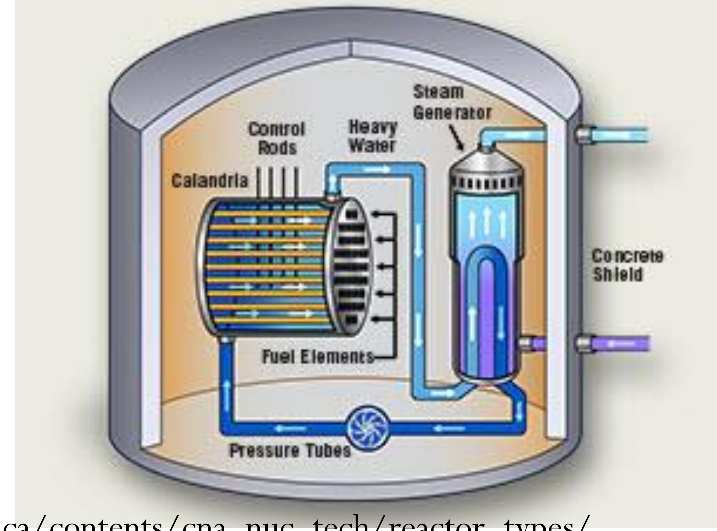
[Lewis Chapter 4]

Reactor Type	**Fuel**	**Moderator**	**Coolant**	**Number**
Pressurized Water Reactor (PWR)	Enriched UO_2	Water	Water	250
Boiling Water Reactor (BWR)	Enriched UO_2	Water	Water	58
Pressurized Heavy Water Reactor "CANDU" (PHWR)	Natural UO_2	Heavy water	Heavy water	48
Gas-cooled reactor (GCR)	Natural U (metal), enriched UO_2	Graphite	Carbon dioxide	16
Light Water Graphite Reactor (LWGR)	Enriched UO_2	Graphite	Water	15
Fast breeder reactor (FBR)	PuO_2 and UO_2	None	Liquid sodium	2

Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/ (Fall 2014)

Pressurized Heavy Water Reactors

Also known as CANDU reactors, pressurized heavy water reactors (PHWRs) represent about 12% of the reactors in the world and are used at all Canadian nuclear power generation stations. They use heavy water as both coolant and moderator, and use natural uranium as fuel. As in a PWR, the coolant is used to boil ordinary water in a separate loop. CANDU reactors can be refueled without shutting the reaction down.



Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

CANDU

- CANDU stands for “Canada Deuterium Uranium"
- Natural Uranium fuel and Heavy Water moderator
  - only reactor system in which no fuel enrichment required
  - highest neutron economy of all commercial reactor systems
  - proliferation resistant (in theory)
- Online, full power refueling
  - extremely high capability factors possible in theory because there are less outages

Deuterium Moderator

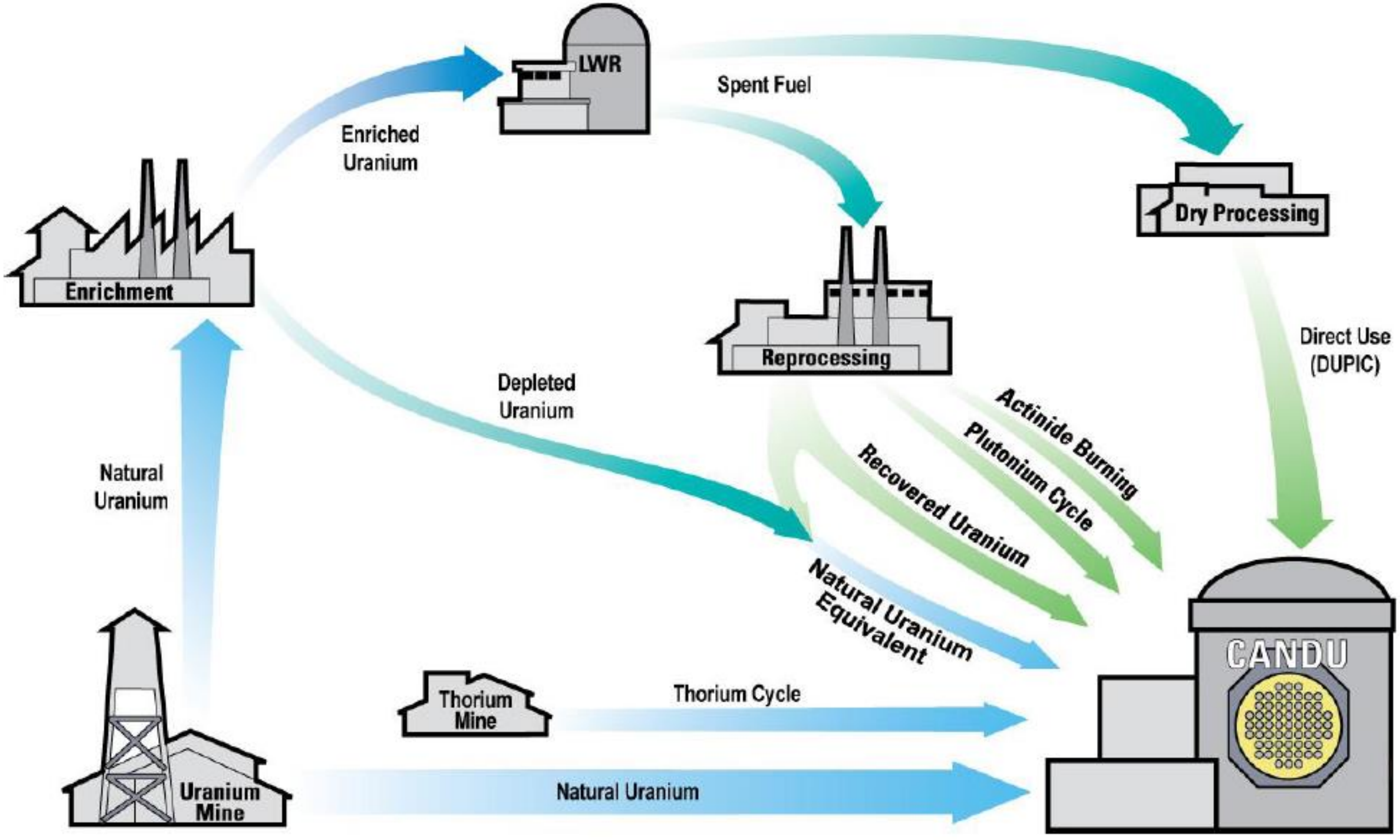
- Isotope of Hydrogen containing one proton and one neutron
- Replaces the H atom in H_2O to make D_2O or Heavy Water
- 10% heavier than ordinary water
- Occurs in natural water 1 part in 7000
- Has a moderating ratio 80 times higher than ordinary water
  - Deuterium absorption cross section very low
  - Allows the use of natural uranium as fuel!
- Separated by a gas-bubbled hydrogen sulfide exchange tower or by electrolytic hydrogen catalyst

Uranium Fuel

- CANDU uses natural uranium – 0.7% fissionable (useful) fuel
- No enrichment required!

- However CANDU's can run with slightly enriched fuel, Spent PWR fuel (DUPIC, Oreox process), recovered Uranium from LWR fuel, MOX, actinide matrix fuel, Th/U233 near breeder cycle
- New fuel designs actually use 2.5% enriched fuel

Possible CANDU Fuel Cycles



Source: Shalaby (2010)
http://www.jaif.or.jp/ja/wnu_si_intro/document/2010/shalaby_g3_candu.pdf

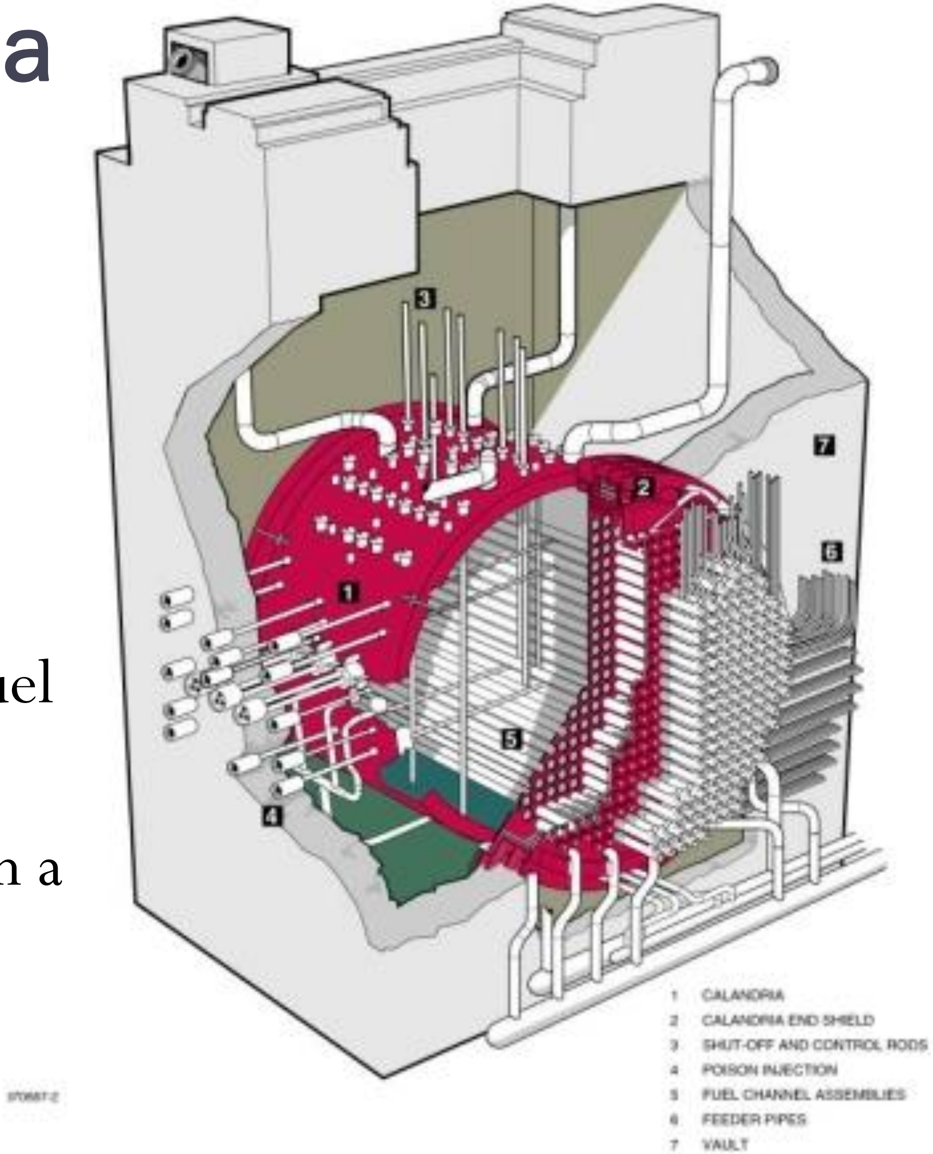
CANDU’s Worldwide

- Argentina (1 named Embalse - the first CANDU to use SEU)
- Canada (14 in use, 8 out of service?)
- China (2 operating)
- India (2 CANDU’s named RAPS operating, 9 ‘clone’ reactors also)
- Pakistan (1 reactor named Kanupp)
- Romania (2 operating reactors, 3 partially finished at Cernavoda)
- South Korea (4 reactors operating at Wolsong)

Source: A. McLean, “the CANDU System: A Canadian Achievement” (2000)
https://canteach.candu.org/Info/Documents/The%20CANDU%20System%20-%20A%20Canadian%20Achievement.pdf
(broken link)

CANDU Calandria

- Low pressure D_2O “Calandria” tank provides moderation
- Horizontal pressure tubes run through the calandria that contain coolant and fuel at high pressure
- The calandria is larger than a BWR or PWR core

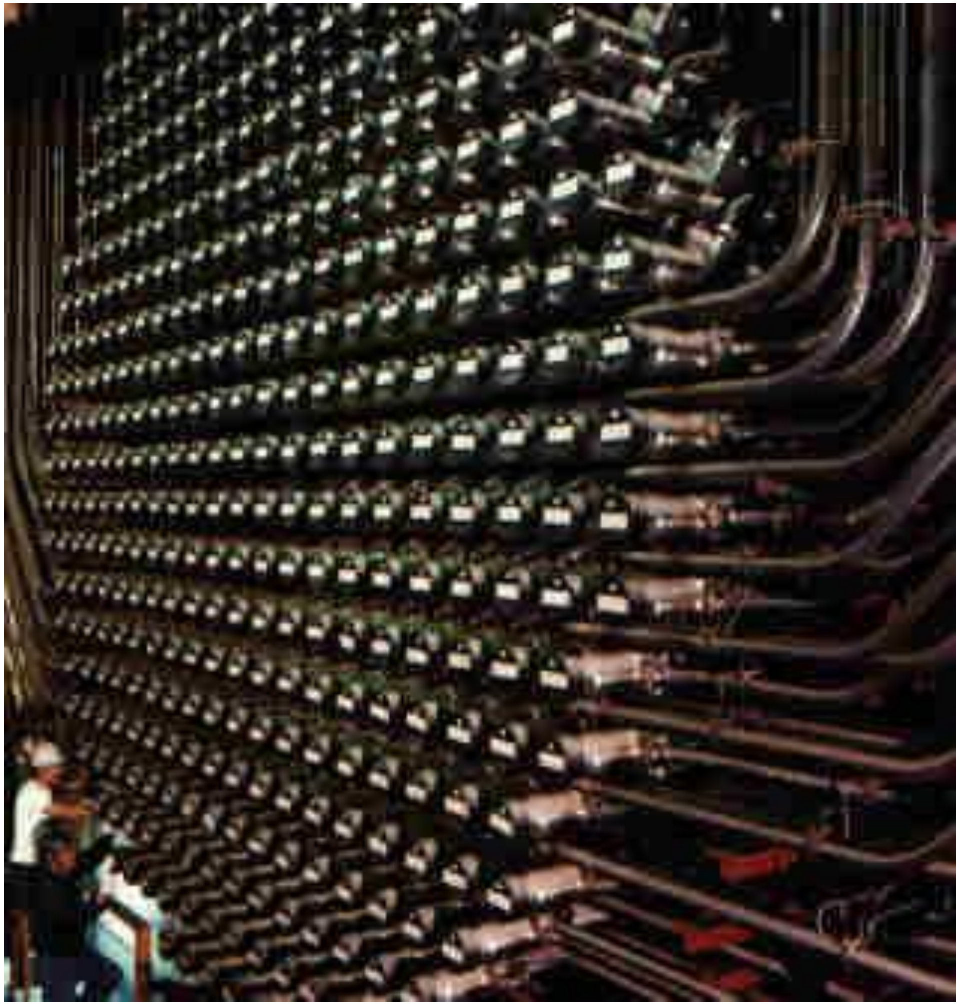


CANDU 6 Reactor Assembly

Source: http://www.nuclearfaq.ca/calandria.jpg

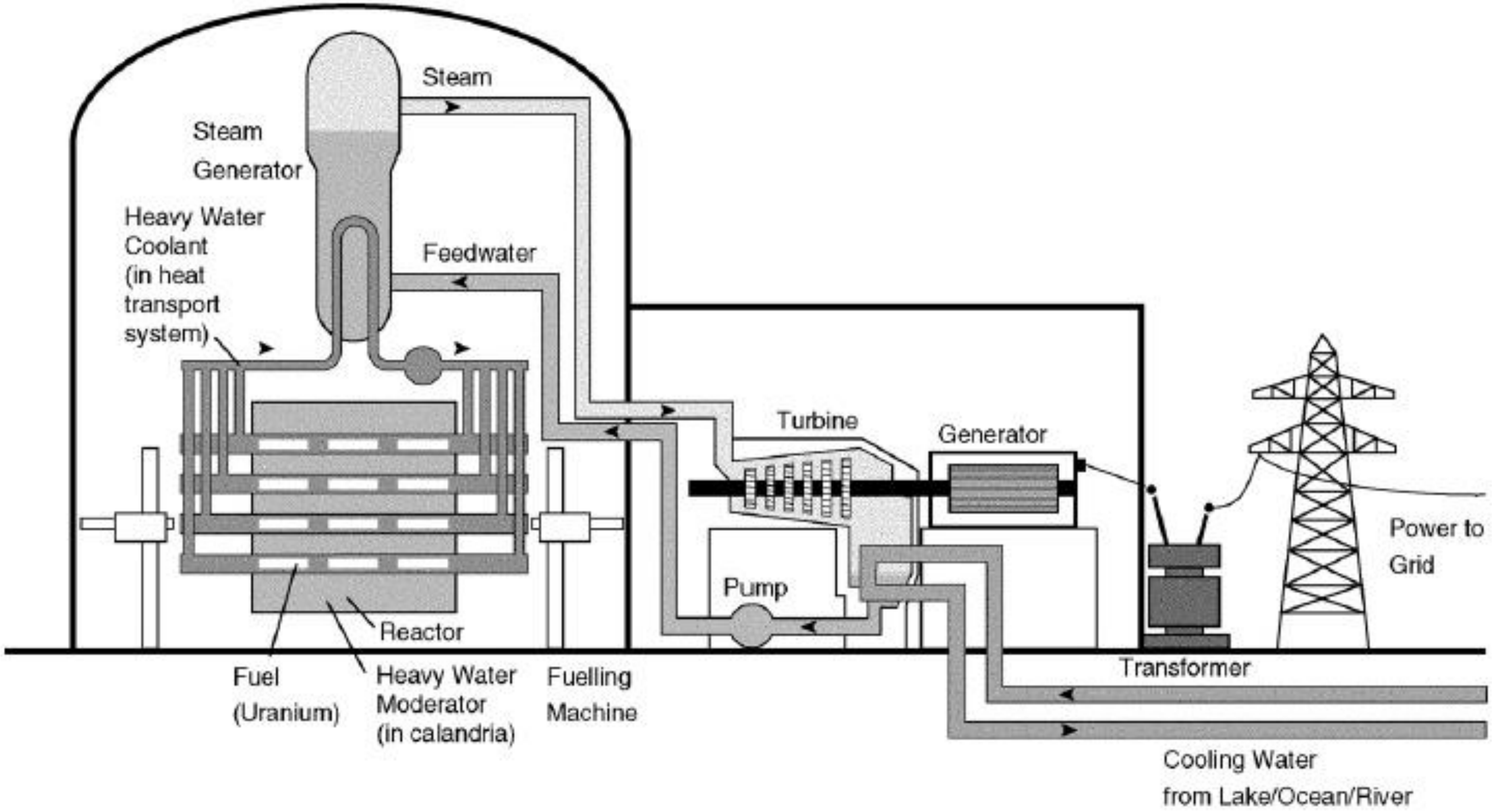
Calandria Pressure Tubes

- Picture of a CANDU reactor face, showing end-fittings
- Pressure tubes can be isolated on each end and fuel can be shuffled while at full power with a refueling machine
- Pressure tubes are cylindrical, but arranged on a square grid



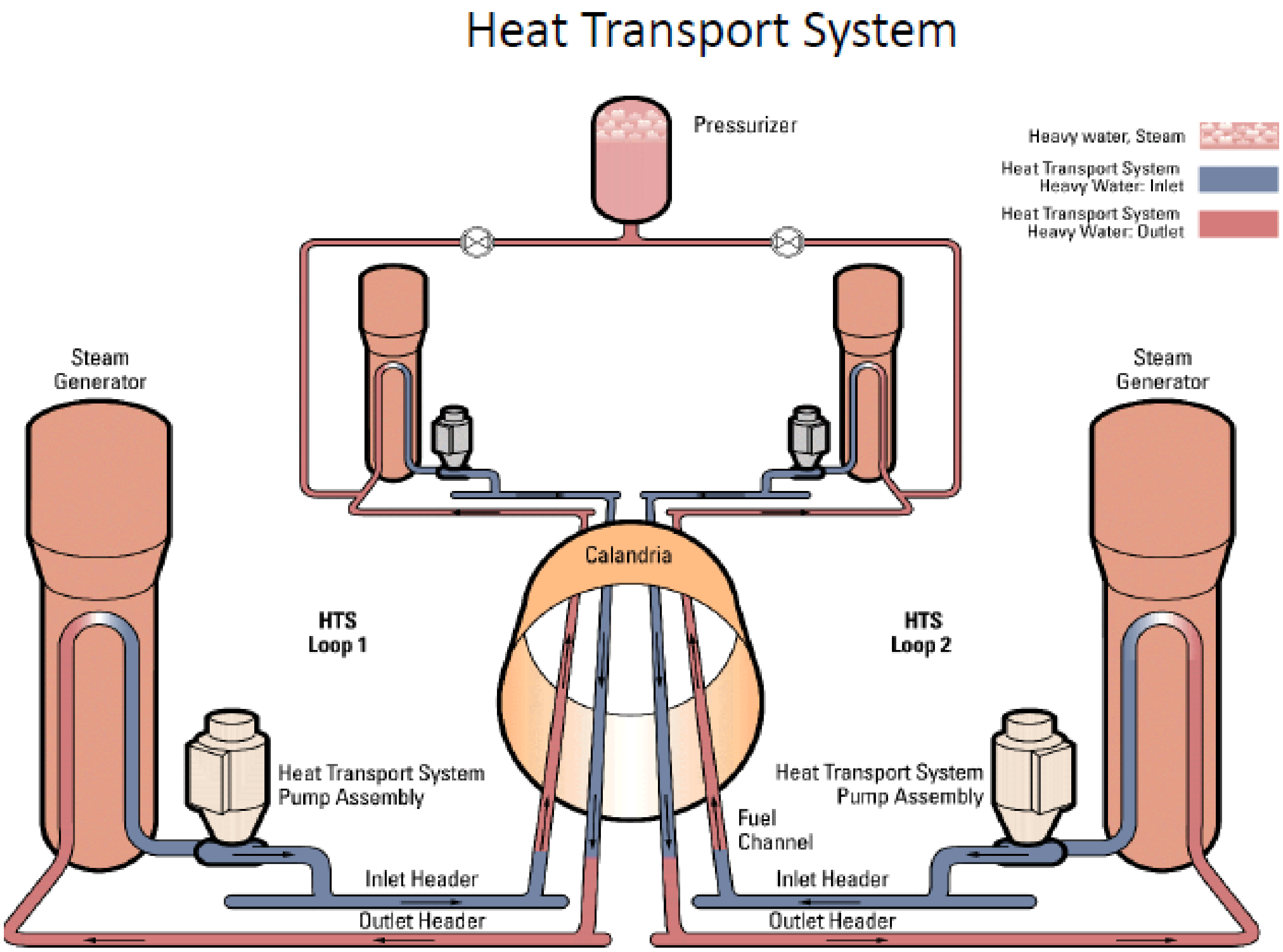
Source: http://www.nuclearfaq.ca/clnd2_sm.jpg

CANDU Power Station



Source: W. J. Garland, "How and Why is CANDU designed the way it is"
https://canteach.candu.org/Info/Documents/How%20and%20Why%20is%20CANDU%20designed%20the%20way%20it%20is.pdf

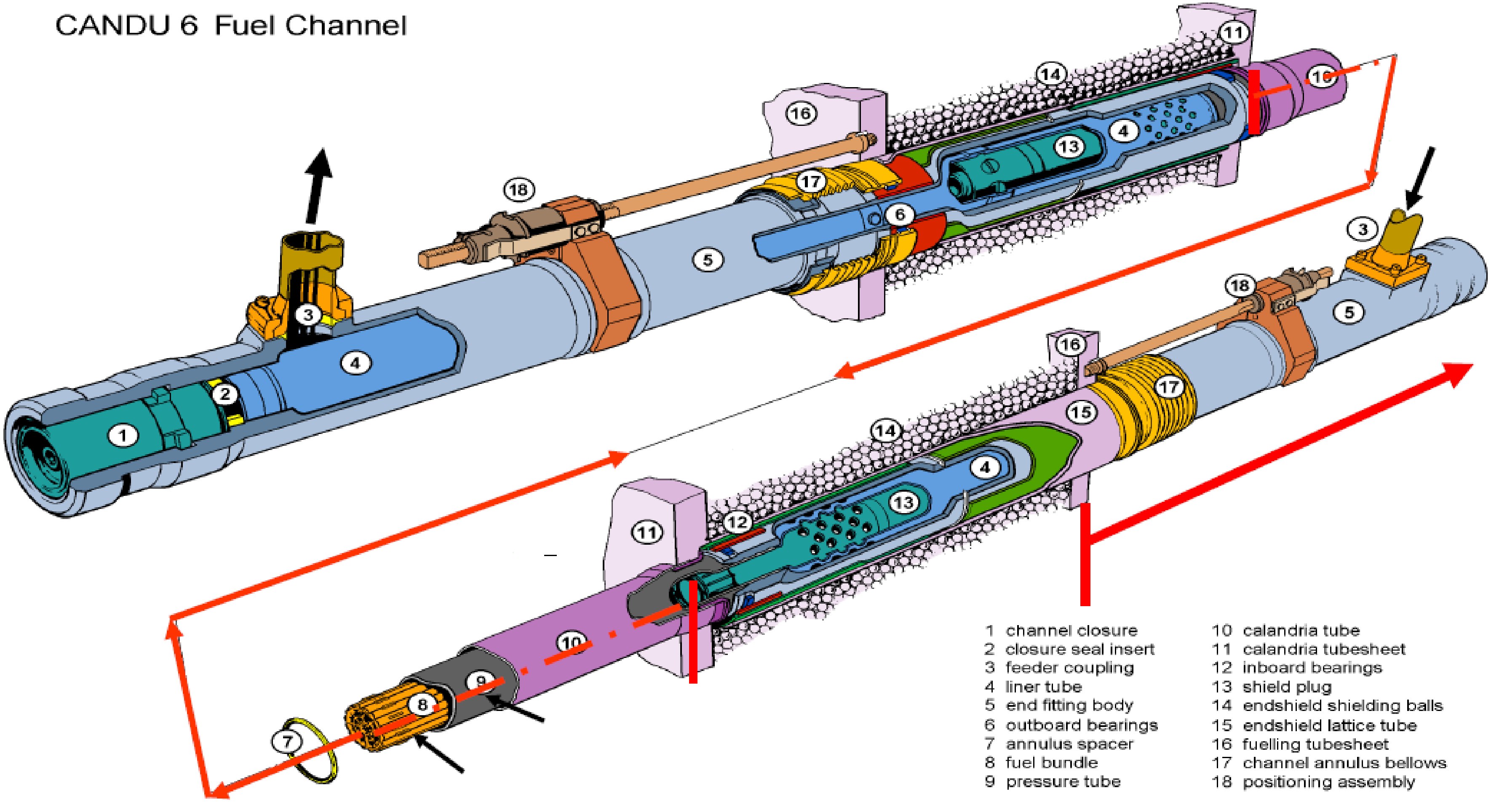
Coolant Flow



Source: Shalaby (2010)
http://www.jaif.or.jp/ja/wnu_si_intro/document/2010/shalaby_g3_candu.pdf

Fuel Channel Assembly

CANDU 6 Fuel Channel

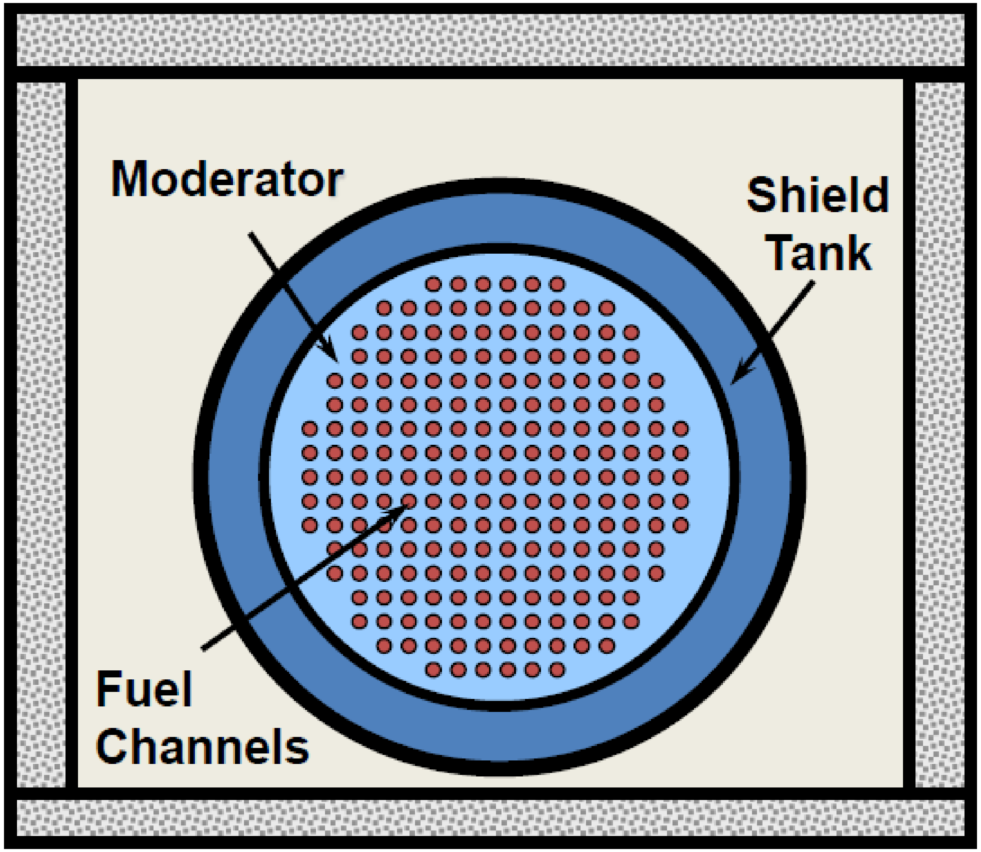


1 channel closure
2 closure seal insert
3 feeder coupling
4 liner tube
5 end fitting body
6 outboard bearings
7 annulus spacer
8 fuel bundle
9 pressure tube
10 calandria tube
11 calandria tubesheet
12 inboard bearings
13 shield plug
14 endshield shielding balls
15 endshield lattice tube
16 fuelling tubesheet
17 channel annulus bellows
18 positioning assembly

Source: Shalaby (2010)
http://www.jaif.or.jp/ja/wnu_si_intro/document/2010/shalaby_g3_candu.pdf

Passive Heat Sinks: Inherent in Design

- Two large tanks of water surrounding the core with independent cooling systems
- Moderator water prevents fuel melting, even if emergency core cooling fails
- Shield tank contains debris in severe accident if moderator heat removal fails



Source: Shalaby (2010)
http://www.jaif.or.jp/ja/wnu_si_intro/document/2010/shalaby_g3_candu.pdf

CANDU Fuel Elements

- 28, 37, and 43 rod designs
- Zircaloy clad and structure
- Each bundle about 1 m long

Source: http://www.nuclearfaq.ca/ + other internet

Reactivity Control

- Long-term reactivity control is achieved through fuel management (i.e., on-line refueling limits the amount of excess reactivity needed).
- New fuel design uses 2.5 wt% enriched fuel with $Dy_2O_3+Gd_2O_3$ to produce slight negative coolant void reactivity
- Short-term reactivity control is provided by controllable light-water compartments (power shaping), as well as absorber rods in the calandria.
- Shutdown system uses cadmium rods that drop into the Caldaria and a liquid gadolinia injection

CANDU Drawbacks

- Positive void coefficient
  - Calandria still provides moderation in a loss of coolant accident
  - can be mitigated with other systems and switch to slightly enriched fuel + burnable absorber
- Pressure tube degradation (sagging)
  - Need to retube (i.e. life extension)

Comparing Moderators

- Mean lethargy gain per collision
  - It is a measure of how much energy is lost per collision.
  - It is a function of the atomic mass
  - The better the moderator, the higher the number ξ

$$\xi$$

- Moderating Power
  - The scattering cross section should also be high

$$\xi\Sigma_s$$

- Moderating Ratio
  - Moderator must also be a weak absorber of neutrons

$$\frac{\xi\Sigma_s}{\Sigma_a}$$

Moderator Properties

Moderator	**A**	**α**	**ξ**	**ρ (g/cm^3)**	**Number of collisions***	**$\xi\Sigma_s$**	**$\xi\Sigma_s/\Sigma_a$**
H	1	0	1	gas	15	--	--
D	2	0.111	0.725	gas	20	--	--
H_2O	--	--	0.920	1.0	16	1.35	71
D_2O	--	--	0.509	1.1	29	0.176	**5670**
He	4	0.360	0.425	gas	34	1.60E-05	83
Be	9	0.640	0.207	1.85	70	0.158	143
C	12	0.716	0.158	1.60	92	0.06	192
Na-23	23	0.840	0.084	0.93	172	0.006	0.725
U-238	238	0.983	0.008	19.1	1731	0.003	0.0092

* From 2 MeV to 1 eV

D_2O is a tremendous moderator!

Source: Duderstadt and Hamilton (1976) p. 324, with some slight modifications

Reactor Review

- What do the fuel assemblies look like for each reactor type?
- Which reactor type
  - has the largest assembly (radially)?
  - has the longest assembly?
  - have “cans” around the assemblies?
  - Have the largest core sizes?
- What reactor types have the most excessive reactivity?
  - Explain why

Next:

- Finished with CANDU Descriptions
- Large database of CANDU information can be found at http://canteach.candu.org

- Next: Molten Salt Reactors

Molten Salt Reactors

Brief overview since there are no operating MSRs

Molten Salt Reactors (MSRs)

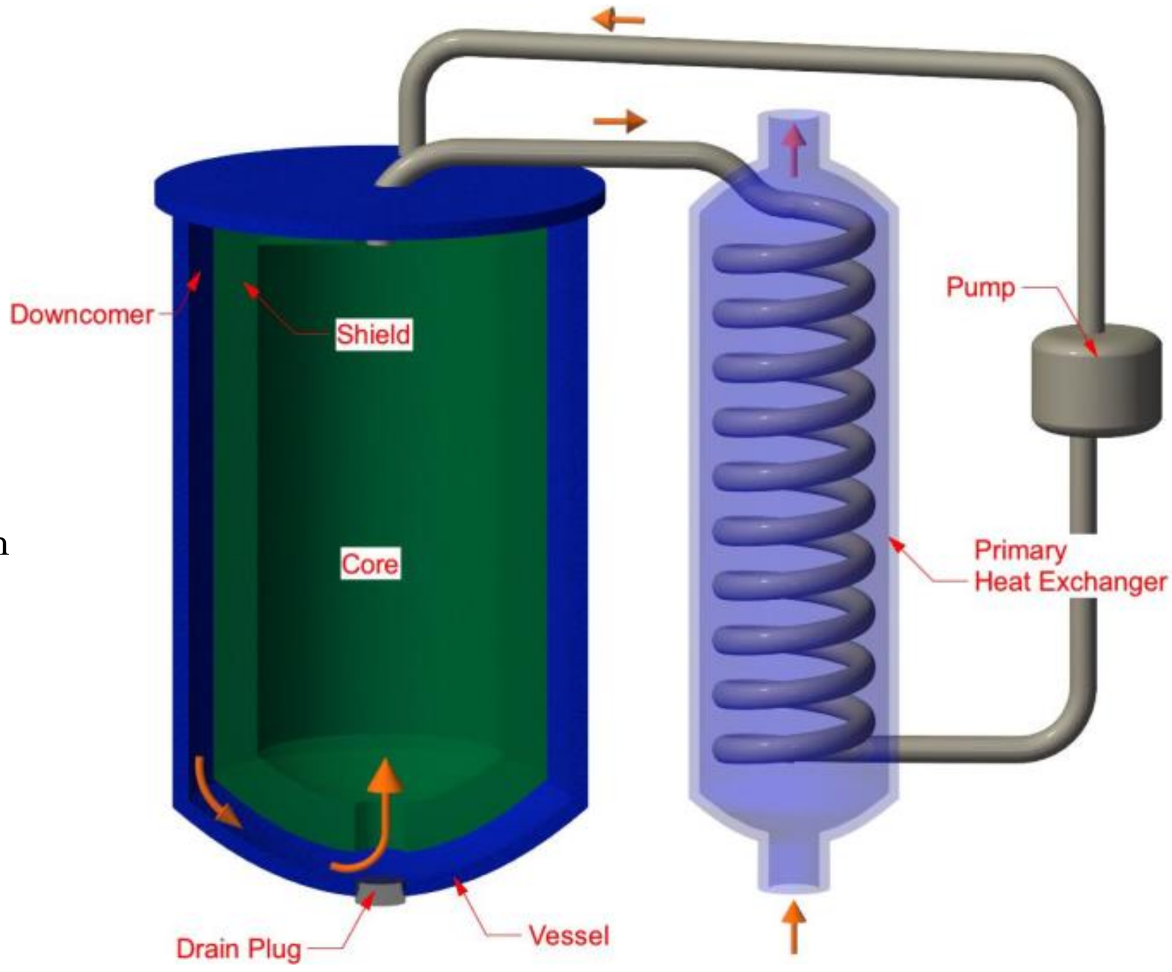
- Completely different reactor design that what we have discussed so far
- The nuclear fuel is a liquid salt compound. There is no solid fuel.
- The original idea of a MSR is to turn a “materials problem” into a “chemistry problem”
- Thorium, uranium, and plutonium all form suitable fluoride and chloride salts
- The salt remains liquid at very high temperature (1400°C) at very low pressures.

Simple Design

No fuel melt

Very high radiation in pumps and heat exchanger (fuel)

Delayed neutrons are mobile



History

- Developed at Oak Ridge National Laboratory
  - Aircraft Reactor Experiment – 2.5 MWt (1954)
  - Molten Salt Reactor Experiment (MSRE) -8 MWt (1965-1969)
  - See link to YouTube video on Moodle site
- US stopped MSR development around 1970 to focus on sodium cooled fast reactors
- MSR designs receiving renewed interest as a Generation IV reactor concepts ("inherently safe")
- Several commercial designs are proposed
  - Terrestrial Energy
  - Transatomic Power
- Many different designs out there! (paper reactors)

Advantages

- On-line refueling
- Gas fission products (e.g. xenon) are removed on-line
- No fuel melt issues
- Low Pressure
- Salt is very stable and does not react with air or water
- Fast or thermal flux spectrum
- Can work with thorium fuel cycle (nonproliferation)

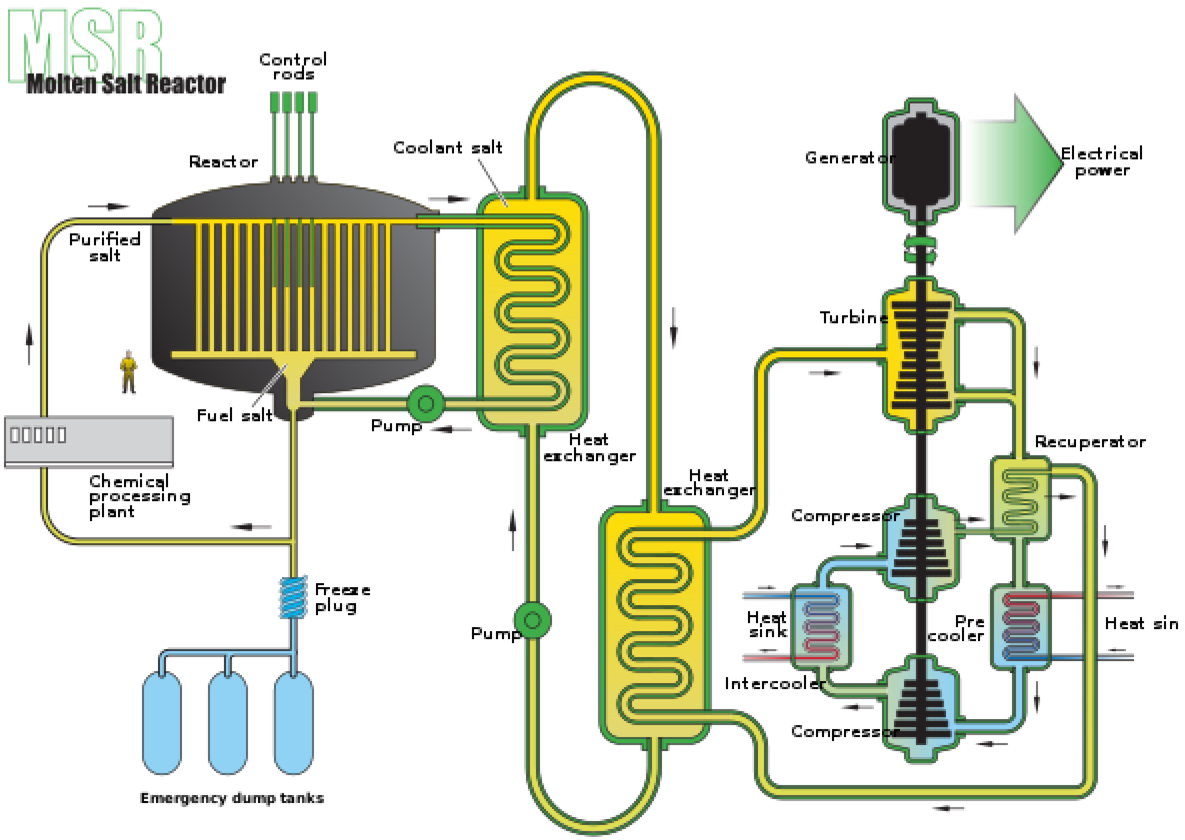
Disadvantages

- Salt is corrosive to metals (pressure vessel and heat exchanger)
- Salts are solid at room temperature (300-600 C)
- Unproven fuel reprocessing issues
- Tritium production
- Very high radiations in steam generators and pumps
- Very high radiation in the center of the core

Safety

- Large negative temperature and void reactivity coefficients
    - Nuclear reaction shuts down automatically
- Freeze plugs melt if temperature gets too high and coolant drains into storage tanks
- Low fission product inventory (low decay heat)
- Salts are very stable at high temperatures

Molten Salt Reactor Diagram



US Department of Energy Nuclear Energy Research Advisory Committee - http://www.ne.doe.gov/genIV/documents/gen_iv_roadmap.pdf

Interesting Physics

- High knowledge of chemistry is needed to know what elements are soluble in salt and what is not
  - solubility is temperature dependent
- Delayed neutrons are mobile and you need to track spatial distribution
- Several thermal and fast reactor designs available
  - Thermal designs usually have graphite blocks

Next:

- Finished with reactor descriptions