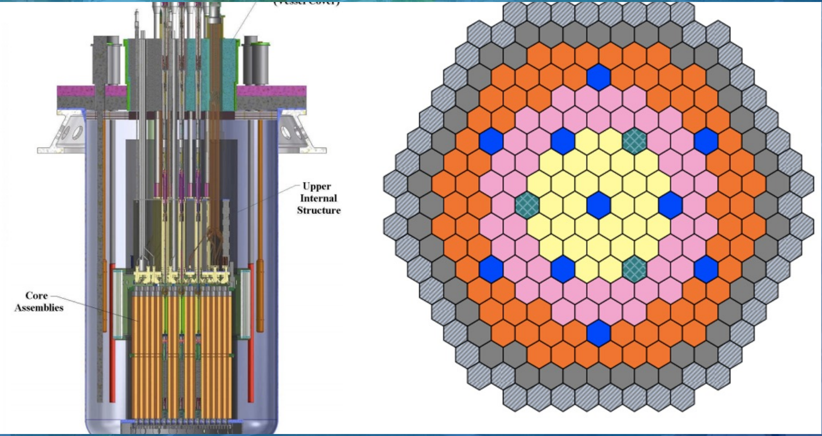
FAST REACTOR TECHNOLOGY



TANJU SOFU
Program Manager
Nuclear Science & Engineering Division
Argonne National Laboratory

OUTLINE

- Introduction to fast reactors
  - Basic characteristics, design variants, fuel cycle implications, experience
- Key design features
  - Reactor physics
  - Thermal-fluids
  - Fuel forms
- Major plant systems and components

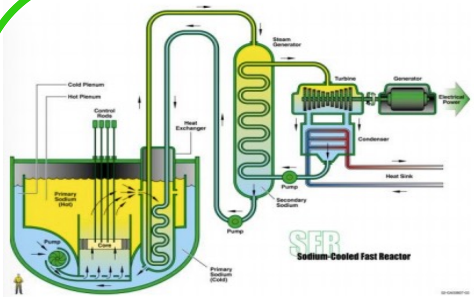
BASIC CHARACTERISTICS: NEUTRONICS

- Fast spectrum leads to ~10× longer neutron mean-free path in comparison to WCRs
  - Greater sensitivity to neutron leakage and minor geometric changes
  - Reactivity perturbations impact the whole core (negligible spatial self-shielding)
- High core power density (~5× in comparison to WCRs)
- Inherent safety with net negative reactivity feedback at elevated temperatures
  - Mainly due to Doppler feedback and increased neutron leakage as materials thermally expand
- Long core life is possible with "breed-and-burn" concepts
  - Breeding also leads to lower reactivity swing during each cycle
    - Reduced need for excess reactivity to control the reactor
    - Less reactivity is available for accidental insertion
- On the other hand, fast reactor cores are not in their most reactive configuration
  - Design must ensure re-criticality does not occur during severe accidents
- For large cores, sodium void worth is often positive

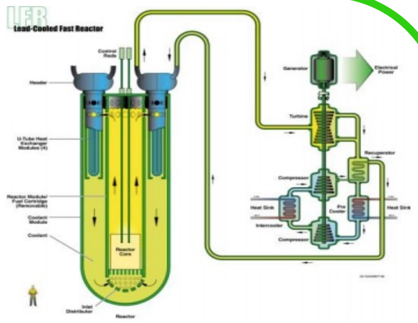
BASIC CHARACTERISTICS: SODIUM COOLANT

- ~100 times higher thermal conductivity than water
- Wide margin (>350°C) to boiling allowing high temperature operation and greater thermal efficiency for energy conversion (~40%)
- Large core ΔT (150°C in an SFR vs. ~30°C in an LWR) facilitates natural circulation for passive decay heat removal
- Low pressure primary and intermediate coolant systems
  - No LOCA concern, no need for high-pressure coolant injection system (ECCS)
    - Guard vessel (and guard pipes) to “maintain” coolant inventory
  - Low design pressure for containment
- Compatible with structural components and metallic fuels
- On the other hand, sodium chemically reacts with air and water, and it is opaque

FAST REACTORS: DESIGN VARIANTS

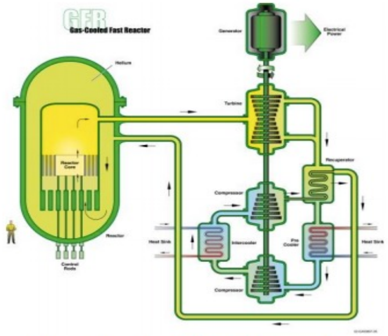


Sodium Fast Reactor

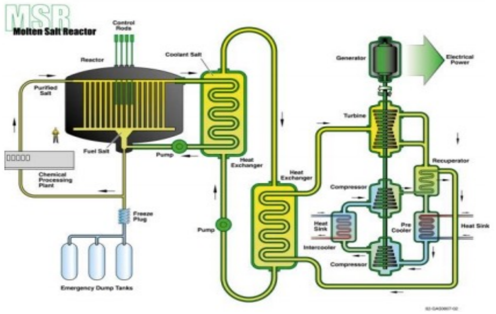


Lead Fast Reactor

LMRs



Gas Cooled Fast Reactor



Molten Salt Cooled Reactor

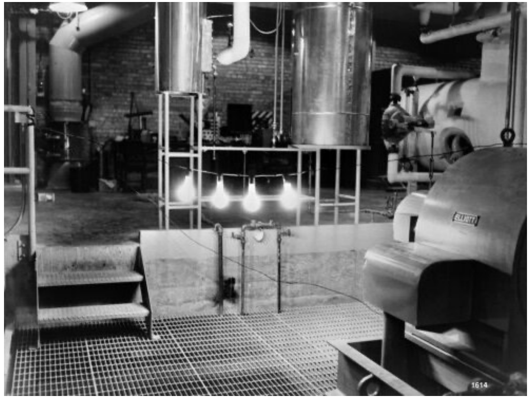
FUEL CYCLE IMPLICATIONS

Fast spectrum can breed and/or transmute transuranic isotopes

- Impact of energy spectrum on transmutation:
  - Fission/capture ratio is higher in fast spectrum
  - Also, fast fission of fertile isotopes is possible (threshold fission)
  - Net result is more excess neutrons and less actinide generation in a fast reactor
- Consequently, fast reactors are typically intended for closed fuel cycle with uranium conversion and resource extension
  - Can enhance U-238 conversion for traditional breeding or limit U-238 conversion for burning
  - Facilitates mass/volume reduction for geologic disposal
  - Increases the percentage of the natural fuel resource that is used in the fuel cycle (from few % up to theoretically 100% with continuous recycling)

PAST AND ONGOING EXPERIENCE

- SFRs have >400 reactor-years of experience acquired through the design, construction, operation and decommissioning of experimental, prototype, demonstration and commercial units
  - China: CEFR
  - France: Rhapsody, Phenix, Superphenix
  - India: FBTR, PFBR
  - Japan: Joyo, MONJU
  - Kazakhstan: BN-350
  - Russian Federation: BR-5/10, BOR-60, BN-600
  - U.K.: PFR, Dounray Fast Reactor
  - U.S.: EBR-I, EBR-II, FFTF, FERMI-1, SEFOR



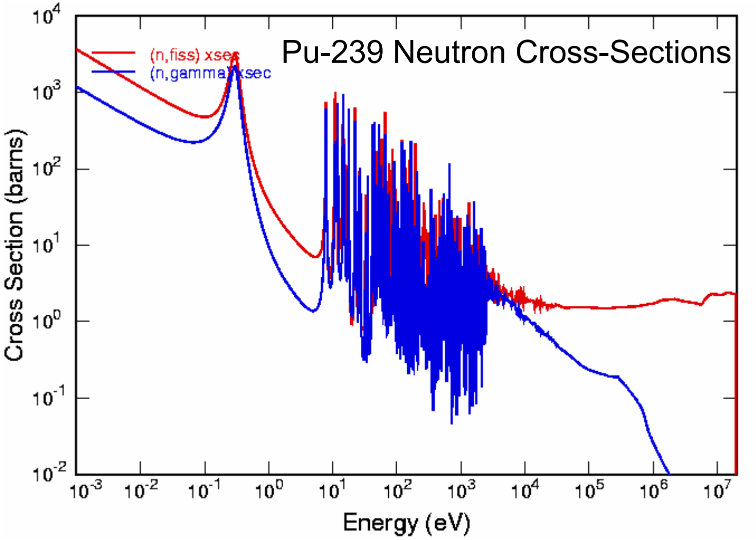
First production of nuclear electricity in EBR-I on December 20, 1951

- Several new construction projects are underway in China, India, Russian Federation and U.S.

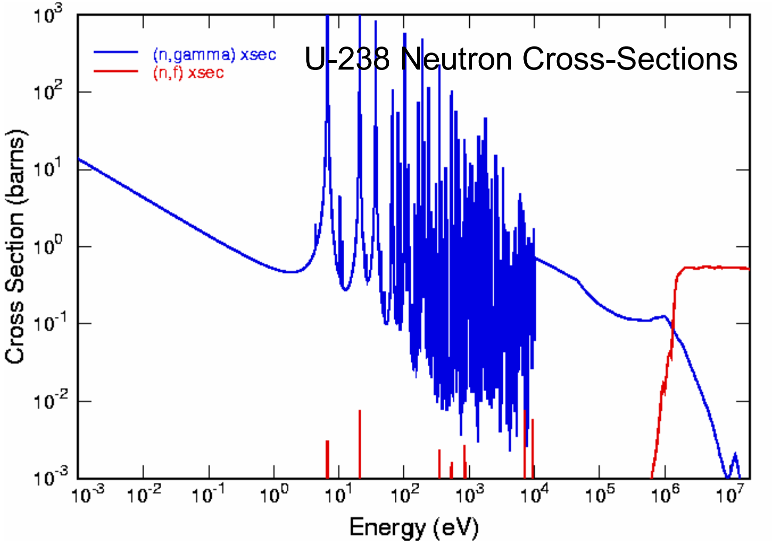
KEY CHARACTERISTICS

No moderators: Hard neutron energy spectrum

- Dominant fissile isotope is Pu-239 and key fertile isotope is U-238



- Large decrease in capture XS at high energies
- Fission XS levels off at high energies



- Large capture XS for enhanced internal conversion
- Fast fission fraction can be up to 15%

KEY CHARACTERISTICS

Reactor physics

- Need for a finer multi-group cross-section structure to resolve reactions at fast spectrum
  - Neutrons are either absorbed or they leak before they get “thermalized”
  - Mid-energy resonances contribute to significant Doppler feedback
- Impact of energy spectrum on transmutation:
  - Fission/capture ratio is higher in fast spectrum
  - Significant fission of fertile isotopes (threshold fission)
  - Number of neutrons released from each fission reaction is also greater in fast spectrum
  - Net result is more excess neutrons and less actinide generation
  - Improved neutron economy also allows greater flexibility for material selection (SS cladding)

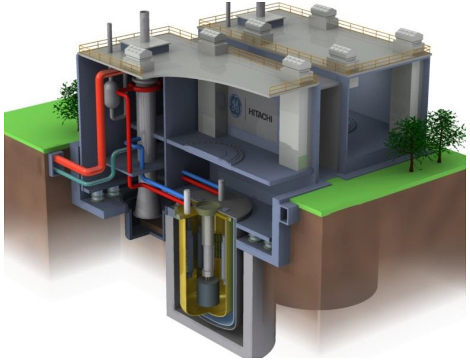
KEY CHARACTERISTICS

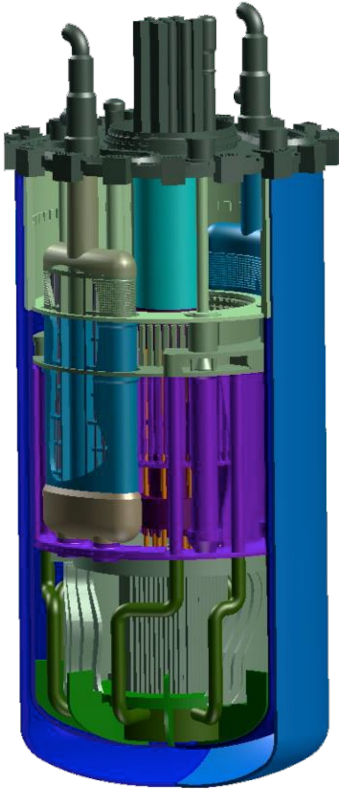
Reactor physics (cont.)

- Breeding or transmutation of transuranic waste products
  - Typically intended for closed fuel cycle with uranium conversion for improved resource utilization and waste minimization
  - Long core life with breed-and-burn concepts
- Higher enrichment is needed to achieve initial criticality (HALEU fuel)
- Inherent safety owing to “net” negative reactivity feedback during accidents with elevated core/coolant temperatures
  - For large cores, however, sodium void worth is often positive
- Also some shielding challenges due to fast fluence

MAJOR PLANT SYSTEMS AND COMPONENTS

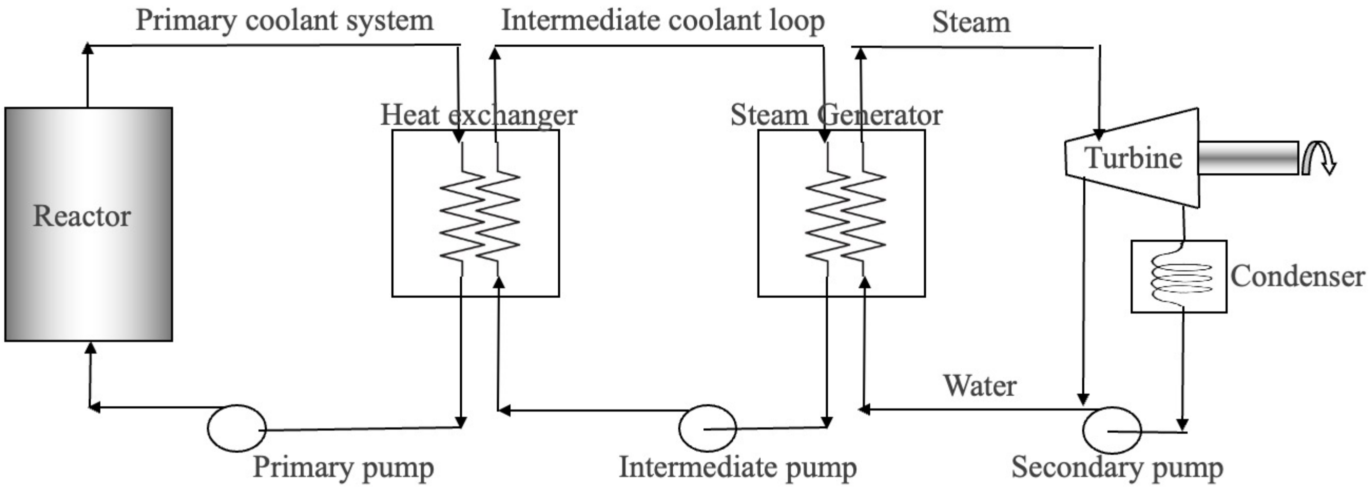
- Plant configurations
- Fuel design
- Reactor core
- Reactivity control and shutdown system
- Reactor and guard vessels
- Heat transport systems (primary and intermediate)
- Energy conversion system (balance of plant)
- Decay heat removal systems
- Containment
- I&C, coolant and cover-gas cleanup systems, spent fuel storage, ISI&M





PLANT CONFIGURATIONS

- Energy from nuclear fission is simply the heat that needs to be removed by a coolant in a thermodynamic energy conversion cycle

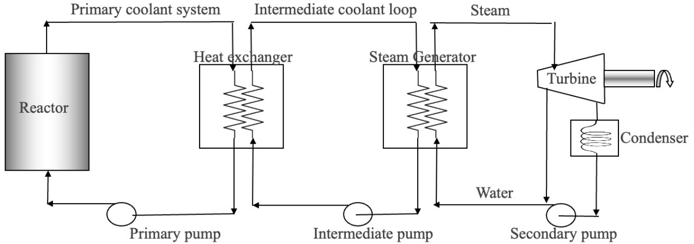


- Although the process is the same, power density is ~10,000 times higher than a fossil fueled plant and it poses significant heat transfer challenges

PLANT CONFIGURATIONS

- Loop: The primary coolant leaves the reactor vessel but the intermediate heat exchanger (IHX) is located in the containment area (outside the vessel)
  - Has reliability advantages—easier to isolate the loop and do maintenance on the intermediate heat exchanger
  - Primary vessel surrounded by a guard vessel
  - Usually requires double-walled primary coolant piping in areas outside the vessel
  - Preferred in Japan and used in some older U.S. designs (FFTF and CRBR)
- Pool: Primary coolant is kept within the reactor vessel which also encompasses IHX
  - Larger reactor vessel, reduces the impact of a primary coolant pipe break/leak
  - Preferred in the U.S., France, Russia, S. Korea, China, and India
  - Primary vessel surrounded by guard vessel

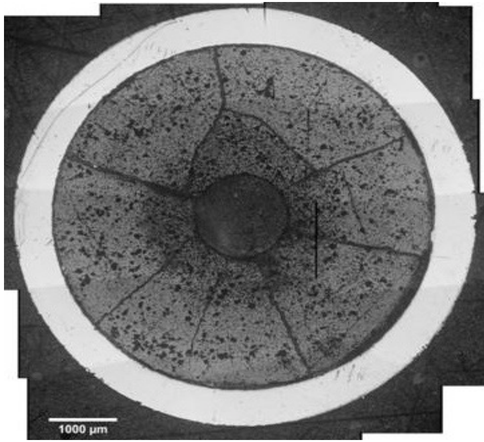
HEAT TRANSPORT SYSTEMS



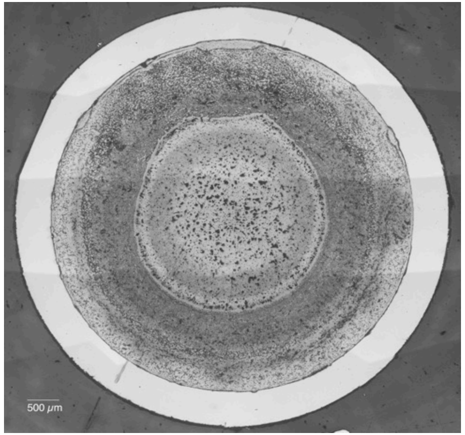
- SFRs have three heat transfer systems:
  - — Primary heat transfer system—cools the core
  - — Intermediate heat transfer system—transfers heat from the primary loop to the steam generator (also usually with sodium)
    - Needed to avoid the possibility of activated primary sodium coolant reacting with water from a steam generator tube rupture
  - — Energy conversion system (balance of plant)—to generate electricity with a turbine
- Both primary and intermediate systems are kept at low pressure (near ambient) since the boiling point of Na is significantly higher than normal operational temperatures
- Turbine/generator, condenser, feed-water systems are like a WCR except that they run at a higher temperature in an SFR
  - — Higher energy conversion efficiency

FUEL TYPES

- Ceramic oxide fuel
  - Sintered pellet (ceramic) Uranium- or Mixed-Oxide fuel similar in design to an LWR fuel
  - Helium-filled gap between fuel and cladding
  - Fission gas plenum
  - Irradiation experience in FFTF and international reactors in France/Russia/Japan
- Metal-alloy fuel
  - Binary (U-Zr) or ternary (U-Pu-Zr) metal-alloy long slugs in 316-SS, D9 or HT9 cladding
  - Sodium-filled gap between the fuel and cladding (bond sodium)
  - Large fission gas plenum to reach high burnup
  - Irradiation experience in EBR-II and FFTF
- Other fuel types (with less irradiation experience) include nitride (ceramic) and carbide fuels

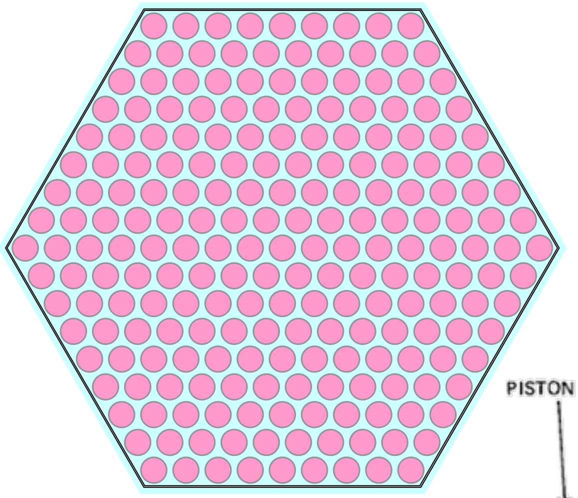


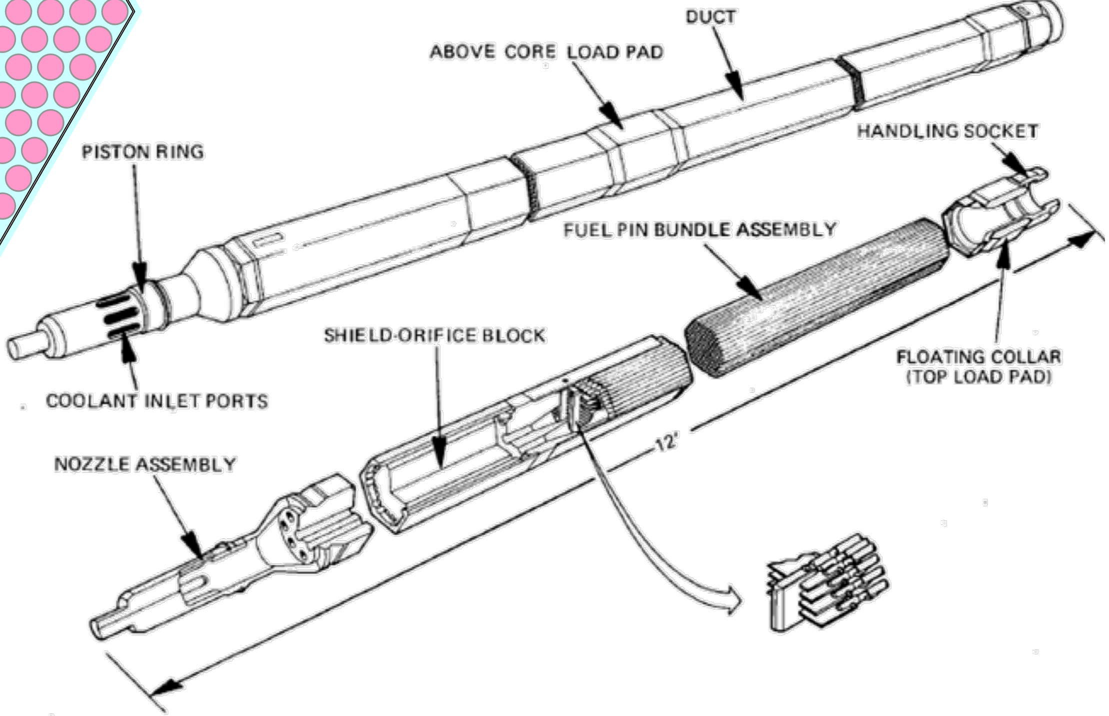
High Burnup MOX Fuel

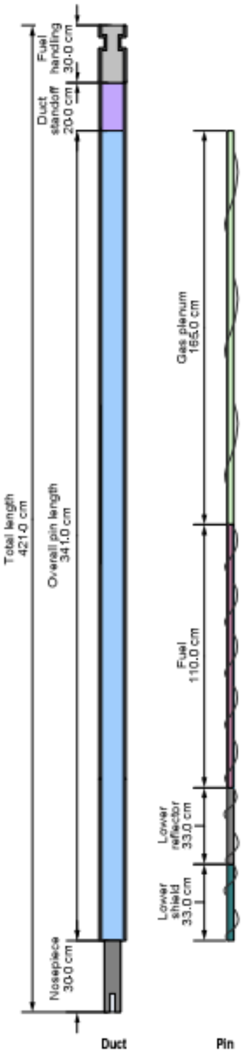


Metal Fuel with HT9 Clad

FUEL PIN AND ASSEMBLY DESIGN

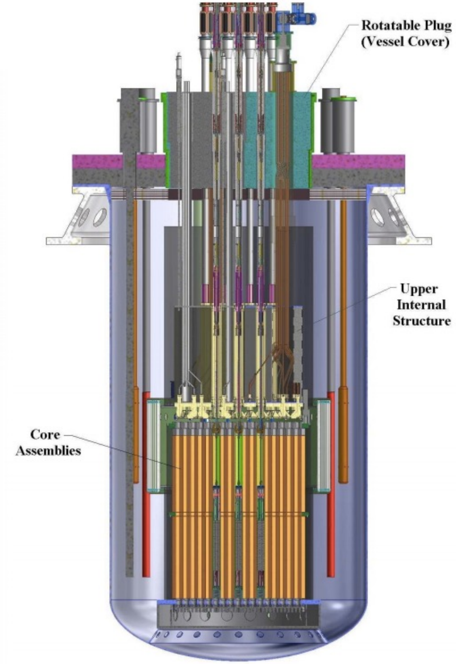


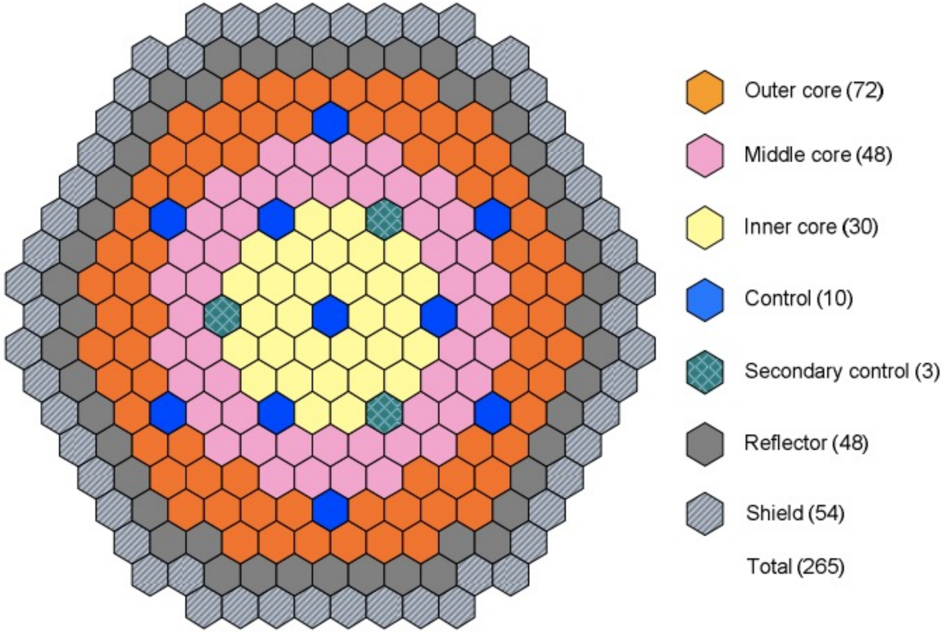




REACTOR CORE

- Multiple enrichment zones (with multiple orifice zones to control flow)
- Possible use of axial and radial blankets to increase plutonium breeding





REACTIVITY CONTROL

- Two independent, safety grade systems control the reactivity:
  - Primary control system: Capable to bring the reactor from any operating condition to “cold” subcritical state at refueling temperature (~200°C) with most reactive control assembly inoperative
    - Also serves to compensate for burnup reactivity swing and accommodates uncertainties in criticality and fissile loading
  - Secondary control system: Capable to bring the reactor from any operating condition to hot standby condition with most reactive control assembly inoperative
- Other alternative reactivity control systems
  - Self-actuated shutdown and ultimate shutdown systems to be detailed during the session on “Safety of SFRs”
  - Rod stop system: Prevents substantial power increase during unintended rod withdrawal event

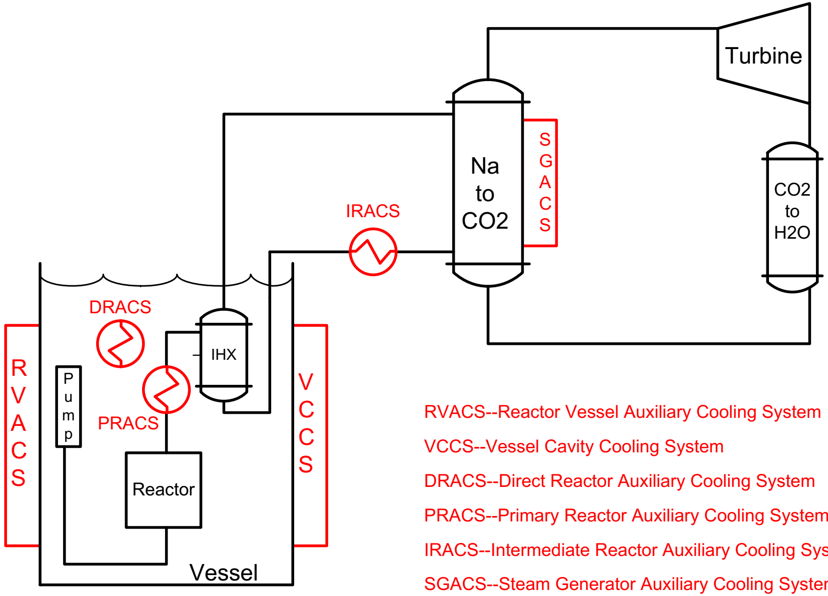
THERMAL DESIGN CONSIDERATIONS

- Sodium cooled fast reactors typically operate at near atmospheric pressure (~1.0 MPa at the core inlet)
- Reactor coolant outlet temperatures are typically around 500-550°C (with respective margins to boiling as 330-380°C)
- Each reactor fuel assembly typically produces about 5 MW of power
  - Average power densities in the reactor core are typically 350 to 500 kw/liter (1100 to 1500 kw/liter in the fuel)
- Typical coolant velocities in the fuel pin bundle are ~5 m/s

DECAY HEAT REMOVAL

Room for independent and diverse means for decay heat removal

- Normal shutdown heat removal is usually via balance-of plant
- When that path is not available, decay heat removal can be achieved via redundant and diverse emergency decay heat removal systems
- Usually based on passive heat removal mechanisms
  - Using natural convection
  - Often no valves or mechanical devices to control its operation



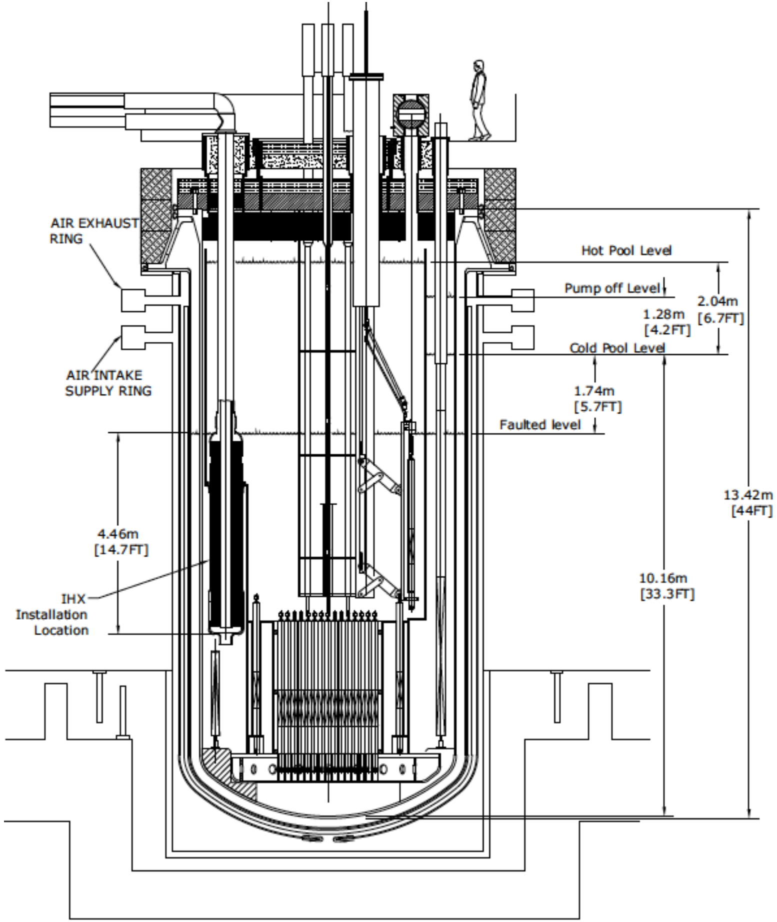
RVACS--Reactor Vessel Auxiliary Cooling System
VCCS--Vessel Cavity Cooling System
DRACS--Direct Reactor Auxiliary Cooling System
PRACS--Primary Reactor Auxiliary Cooling System
IRACS--Intermediate Reactor Auxiliary Cooling System
SGACS--Steam Generator Auxiliary Cooling System

REACTOR VESSEL

- Reactor vessel envelopes the core and most of primary heat transport system (PHTS) components
  - In pool type systems, entire PHTS is placed inside the reactor vessel (reactor primary coolant boundary)
  - Provides support for reactor core, inner barrel, thermal barriers, shielding…
  - Also acts as a barrier against the release of radioactive material
- Typically made of austenitic stainless steel and shaped as a cylindrical shell with a spherical bottom
  - Either hung from the top by a support ring, or supported at the bottom
- The fuel assemblies rest on a core support structure
  - Core support grid to guide the flow from the inlet plenum
  - Upper internals structure to guide the flow into the upper plenum
- An inert cover gas separates the sodium from the reactor head that provides access for control rods and rotating plugs as refueling ports
  - No penetrations of the reactor vessel in a pool type system

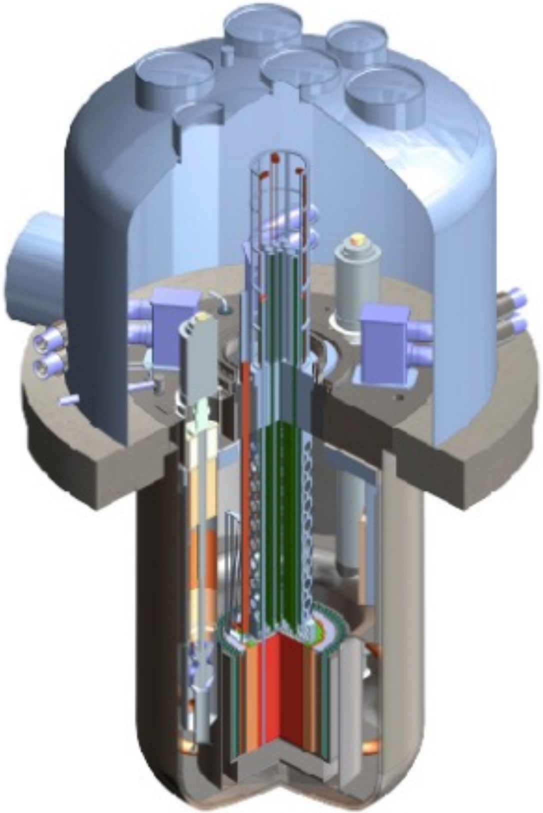
GUARD VESSEL

- In case of failure of the reactor vessel (from seismic events or thermal creep induced rupture), the guard vessel wraps the reactor vessel
  - Gap between the reactor and guard vessels does not contain Na under normal conditions
  - It is sufficiently wide to allow inspection but narrow enough to maintain high enough sodium level
    - to keep the core covered and decay heat removal systems functional
- Both cold and hot legs (i.e., sodium inlet and outlet pipes) enter above the guard vessel so that any pipe rupture does not result in coolant loss



CONTAINMENT

- Last barrier for prevention of uncontrolled release of radioactive substances in operational states and in accident conditions
- Early designs featured structures like a PWR containment because they were required to contain very high pressures and temperatures resulting from a core melt with large energy release
- Experiments and analyses indicate that such events are exceedingly rare, and the energy releases are far less than early analyses suggested
- In pool designs, combination of reactor vessel and guard vessel provide containment function
- In the loop designs, all primary piping is double walled to provide containment function



OTHER IMPORTANT SYSTEMS

- Instrumentation and control systems
- Sodium purification and cover-gas cleanup systems
- Na leak monitoring and fire protection
- Cell inerting systems and cell liners
- Refueling systems
- In-vessel and ex-vessel fuel handling and storage systems
- Trace heating
- Seismic isolation
- Steam generator isolation system
- Sodium washing systems (to eliminate the residual sodium for storage or transportation)