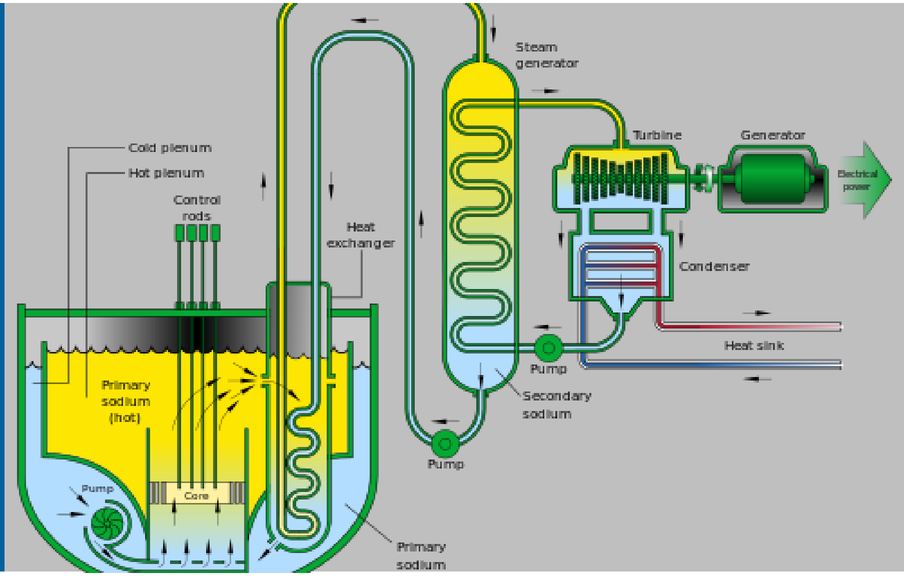
Argonne NATIONAL LABORATORY

SFR TECHNOLOGY OVERVIEW



TANJU SOFU

ARGONNE NATIONAL LABORATORY

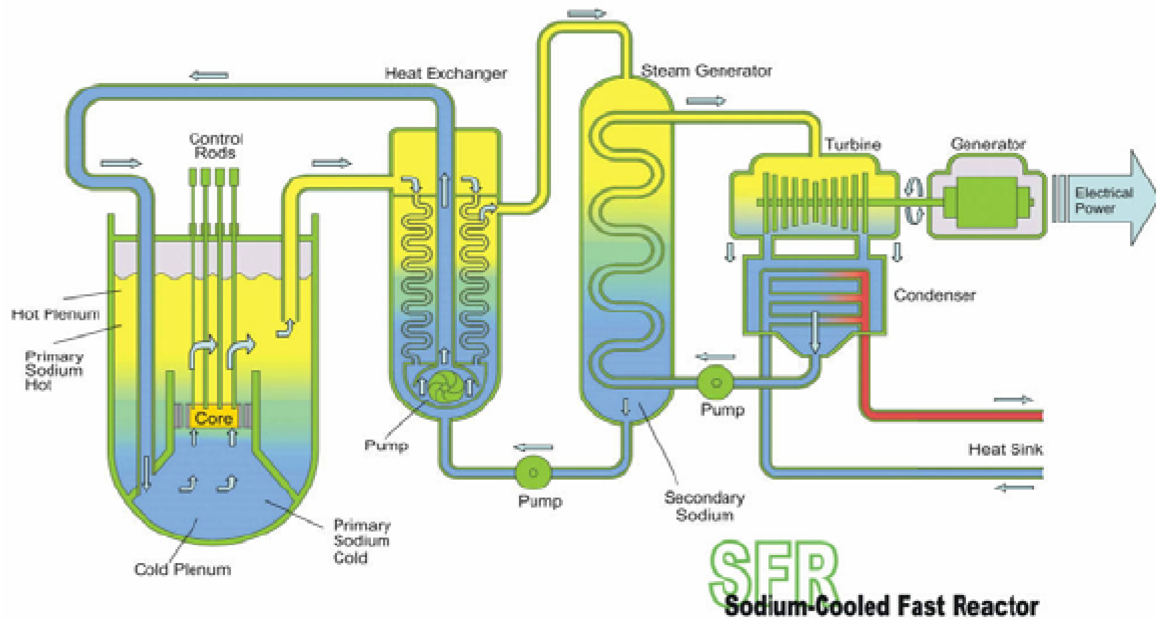
March 26, 2019
Fast Reactor Technology Training
U.S. Nuclear Regulatory Commission

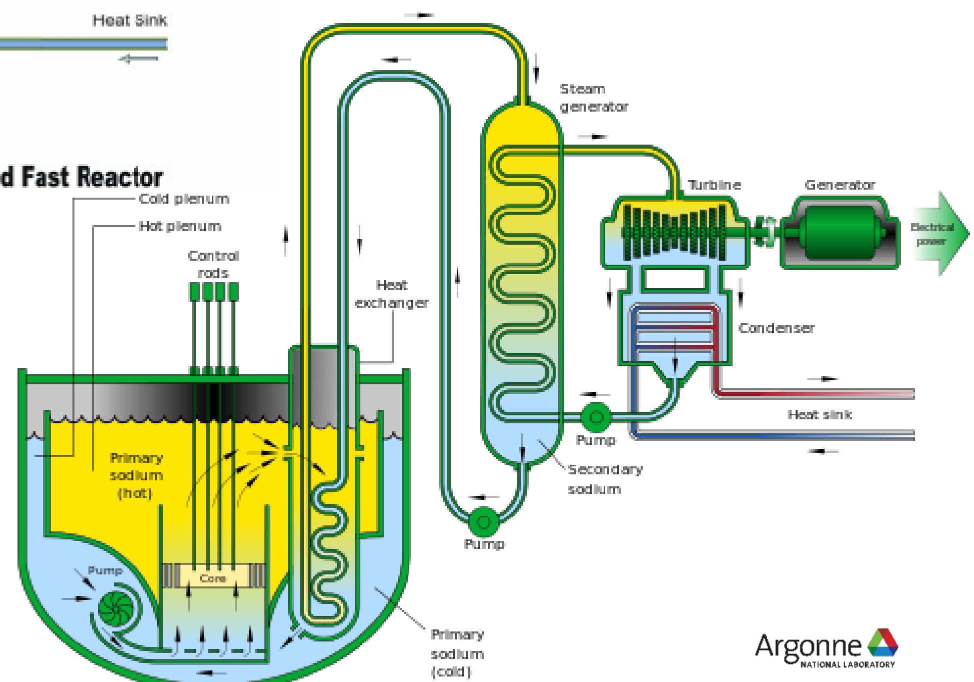
OUTLINE

- Plant configurations
  - Loop type
  - Pool type
- Major systems and components
  - Reactor core
  - Reactivity control and shutdown systems
  - Reactor and guard vessels
  - Heat transport systems
    - Pumps, IHX, steam generator
  - Decay heat removal system
  - Containment
  - Refueling system
  - Instrumentation
  - Auxiliary systems

PLANT CONFIGURATIONS

Two major types of SFR configurations: Loop and pool types





LOOP CONFIGURATION

Pumps, primary sodium to secondary sodium intermediate heat exchanger (IHX), piping, etc., are separated from the reactor vessel

- The primary coolant leaves the reactor vessel
  - Susceptible to pipe breaks
  - Primary loop with activated sodium may require guard pipes to contain leaks
- Intermediate heat exchanger (IHX) is located in the containment area
  - May require larger containment
  - But allows more flexible relative elevation of components to enhance natural circulation
- Has reliability improvements
  - Major components are separate for easier maintenance and replacement
  - Simpler vessel head design
- Less sodium in the primary system with shorter grace period
- Less neutron shielding needed to reduce intermediate loop sodium activation
- Usually requires double-walled piping for primary sodium in areas outside the vessel
- Preferred in Japan, FFTF was a loop-type reactor

POOL CONFIGURATION

Core, primary piping, IHX, and primary pumps are in a pool of sodium

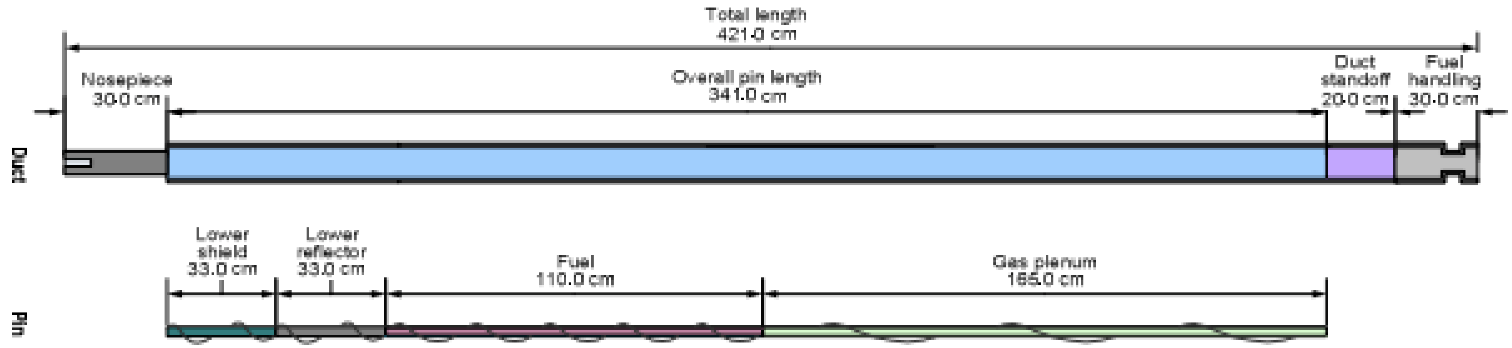
- Primary coolant is kept within the reactor vessel (much reduced risk for leaks)
- Including IHX inside the pool requires a larger reactor vessel
  - Sufficient elevation difference between IHX and core is needed to ensure natural convection
- Large mass of primary sodium provides greater heat capacity (larger thermal inertia) and longer grace period during accidents
- Simpler cover gas system with only one free surface
- More complex vessel head that support more systems (IHTS pipes, pumps) and fuel handling equipment
- Restricted access to components—harder to perform maintenance on components
- Requires more neutron shielding to minimize activation of secondary sodium
- Choice for current U.S. fast reactor R&D program and commercial vendors (also 4S), preferred in the United States, France, Russia, S. Korea, China, and India

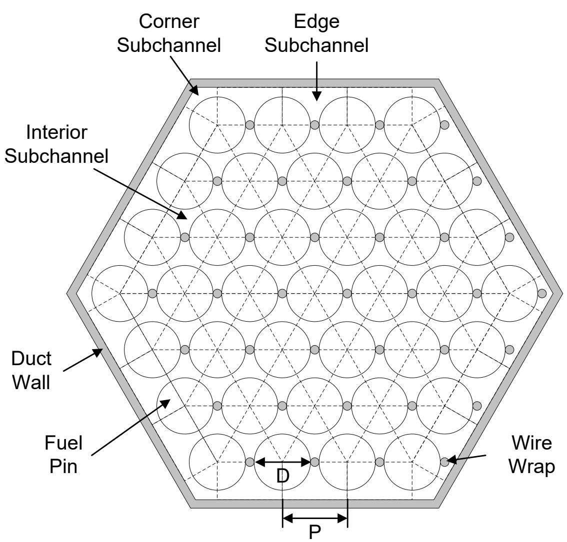
MAJOR SYSTEMS AND COMPONENTS

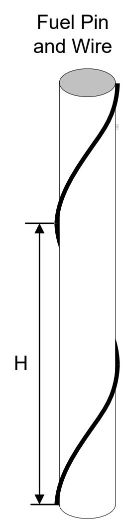
- Reactor core
- Reactivity control and shutdown systems
- Reactor and guard vessels
- Fuel handling and storage
- Heat transport systems (primary and intermediate coolant systems, BOP)
- Sodium pumps
- Intermediate heat exchanger
- Energy conversion system (balance of plant)
- Decay heat removal systems
- Containment
- I&C, coolant and cover-gas cleanup systems, spent fuel storage

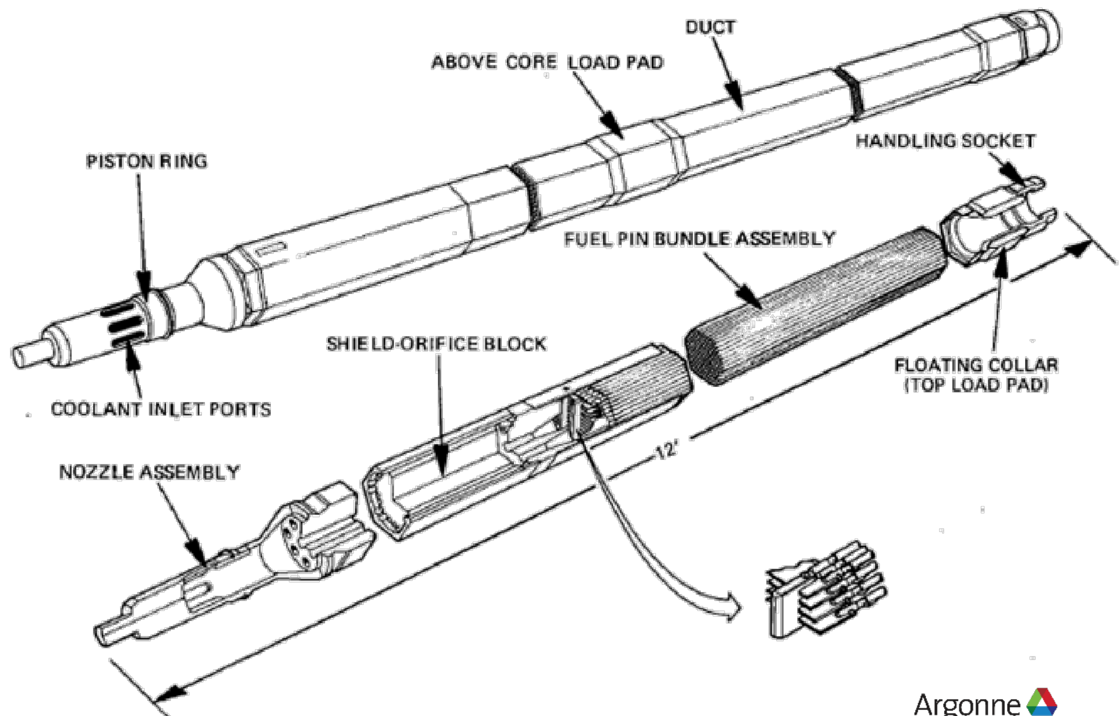
REACTOR CORE

Fuel pin and fuel assembly (ANL’s AFR-100 design)



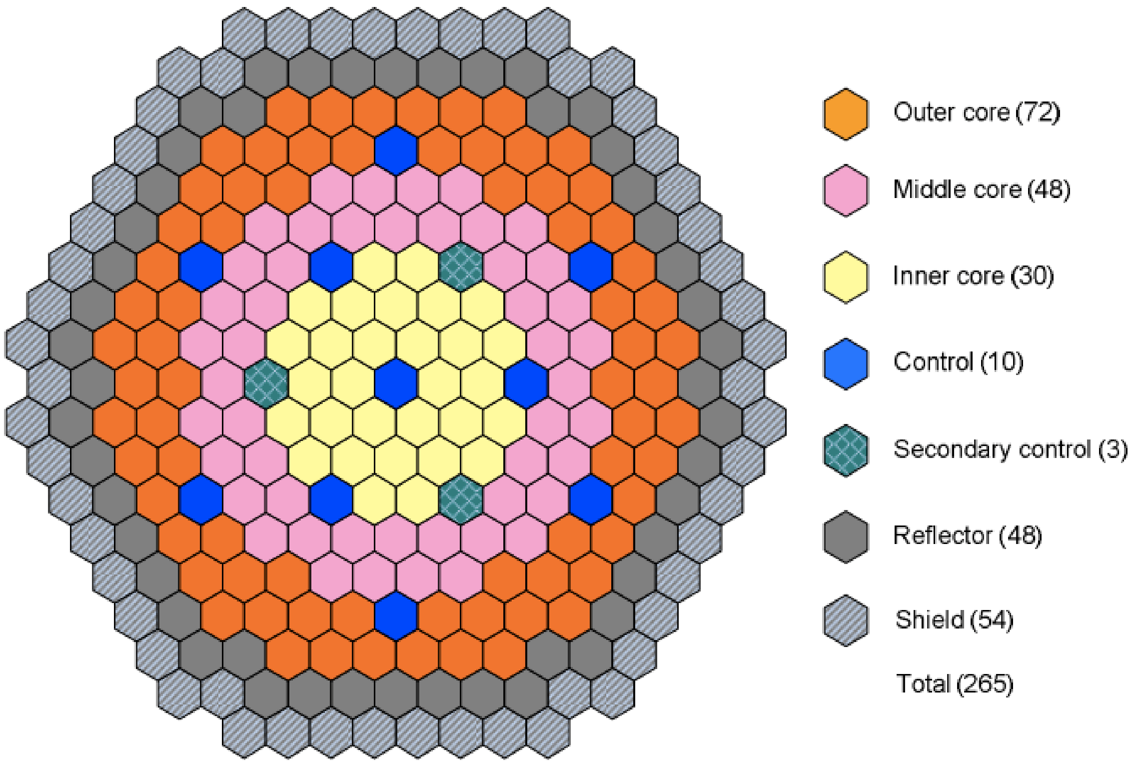


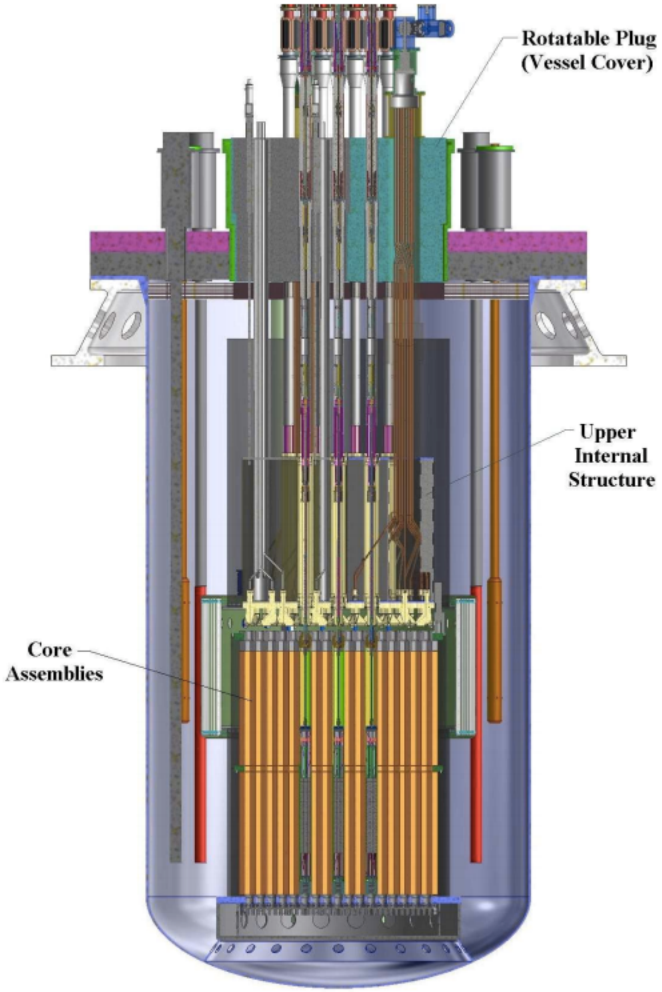




REACTOR CORE

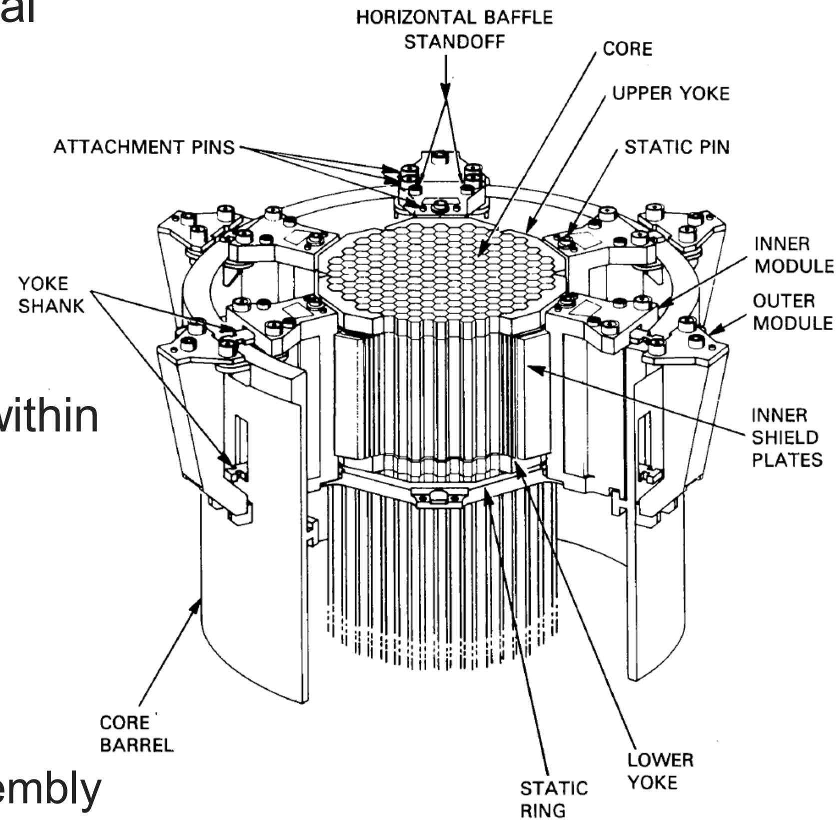
Typical SFR core configuration (ANL's AFR-100 design)





CORE BARREL AND RESTRAINT SYSTEM

- Provides lateral rigidity and controls horizontal movements of core assemblies from thermal expansion, irradiation-induced swelling, irradiation-enhanced creep
  - Reactivity effects should be acceptable
  - Control-rod driveline alignments should be maintained within specified tolerances
- Accommodates horizontal seismic motions within alignment and stress specifications
- Maintains sufficient clearances to facilitate refueling
- Design parameters include
  - Length and stiffness of lower adaptors
  - Number, location, and configuration of assembly load pads
  - Rigidity of peripheral boundary



FFTF core barrel and restraint system

REACTIVITY CONTROL AND SHUTDOWN SYSTEMS

Two independent active systems

- Reactivity control system: Capable to bring the reactor from any operating condition to hot standby condition with most reactive control assembly inoperative
  - Also serves to compensate for burnup reactivity swing and accommodates uncertainties in criticality and fissile loading
- Shutdown system: Capable to bring the reactor from any operating condition to subcritical state at refueling temperature (~200°C) with most reactive control assembly inoperative

Other optional supplementary reactivity control systems

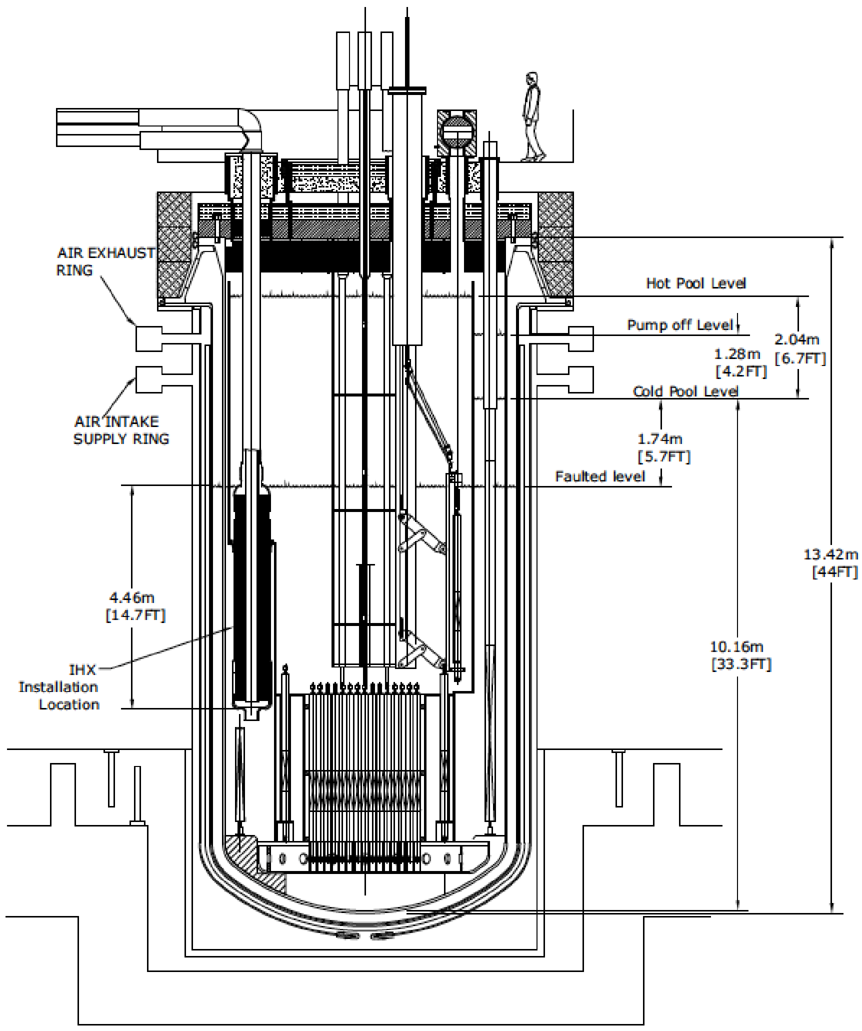
- Rod stop system: Prevents substantial power increase during unintended rod withdrawal event
- Passive devices that require no electric power or actuation signal
  - Curie point magnetic alloy that facilitates automatic detachment of control rods when the coolant temperature rises
  - Hydraulically suspended rods
  - Gas expansion modules
- Ultimate shutdown system: Manually shuts down reactor in the event that all methods of active or passive scram options fail

REACTOR VESSEL

- Reactor vessel envelopes the core and most of primary system components
  - Provides support for reactor core, inner barrel, thermal barriers, shielding…
  - Also acts as a barrier against the release of radioactivity
- Typically made of austenitic stainless steel and shaped as a cylindrical shell with a dome or torospherical bottom
  - Typically less than less than 2” thick (0.75” for EBR-II, 2.36” for SuperPhenix)
  - 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 guides the flow from the inlet plenum
  - Upper internal structures 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



HEAT TRANSPORT SYSTEMS (1/2)

- SFRs generally have three heat transfer systems:
  - **Primary coolant system (PCS)**—cools the core
  - **Intermediate coolant system (ICS)**—transfers heat from the primary system to steam generator (usually with sodium)
    - To avoid the possibility of activated primary sodium burning with steam and pressurization of PCS as a result of a steam generator tube rupture
  - **Energy conversion system** (balance of plant)—to generate electricity with a turbine
- Both PCS and ICS are kept at low pressure (near ambient) since the boiling point of Na is significantly higher than normal operational temperatures
  - Peak pressures are set by core pressure drop and gravity head characteristics (up to about 1 MPa at reactor inlet)
- Balance of plant design is based on choice of energy conversion system
  - Conventional steam cycle
    - Turbine/generator, condenser, feedwater systems are similar to a PWR but they run at a higher temperature for higher energy conversion efficiency
  - Supercritical CO2 Brayton cycle
- Intermediate loop is generally equipped with a pressure relief system to prevent over-pressurization in case of a SG tube rupture event

HEAT TRANSPORT SYSTEMS (2/2)

Primary heat transfer system:

- Core outlet temperatures are typically around 500^{o}C to 550^{o}C, depending on cladding material (margin to boiling 330^{o}C to 380^{o}C)
- Average power densities in the reactor core are typically 350 to 500 kW/liter
- Average fuel pin linear power ratings are typically 23 to 28 kW/m for fuel pins with cladding diameters of 6 to 8 mm
- Each reactor fuel assembly typically produces about 5 MW of power
- Typical coolant velocities inside the fuel assembly are 5 to 7 m/s

SODIUM PUMPS

- Mechanical pumps in the primary and intermediate loops are generally vertical-shaft, single-stage, double-suction impeller, free-surface centrifugal pumps
  - Always in the cold leg in pool configurations
    - Easier on seals, bearings, etc., because of lower temperatures
  - Can be in the hot leg or the cold leg in loop configurations
    - Hot-leg pump location for loop designs is usually preferred because of easier control of free surface in pump (short piping connection between the core and the pump) and net positive suction head (NPSH) requirements
  - Mechanical pumps are normally in the cold leg of the intermediate loop
- Electromagnetic pumps can also be used in SFRs since sodium has a very high-electrical conductivity
  - Used on intermediate loop in EBR-II and SEFOR, the primary loop of the Dounreay, in some backup decay heat removal systems of SNR-300 and SuperPhenix
  - Supplementary flow coastdown feature (e.g., an inertia-driven electrical generator) is needed to assure adequate inertia during loss of flow accidents to avoid abrupt stop

INTERMEDIATE HEAT EXCHANGER (IHX)

- All SFRs have intermediate heat exchangers and intermediate loop to transfer heat from the primary coolant to the balance of plant
- IHX isolates primary system from leaks in steam generators, and steam generators from radioactive primary sodium
- Steam generator pressures are much higher than IHX pressure, which is slightly higher than primary system pressures
  - Leaks propagate from intermediate loop to primary system
- Generally shell-and-tube heat exchangers in counter flow configuration are used
  - Design considerations include straight vs. bent tubes, shell vs. tube-side primary flow, counter-current vs. parallel vs. cross flow
  - Primary sodium on shell side (slightly higher pressure in tubes)
- Smaller differential thermal expansion between tubes and shell than in steam generators because of smaller temperature differences

STEAM GENERATOR

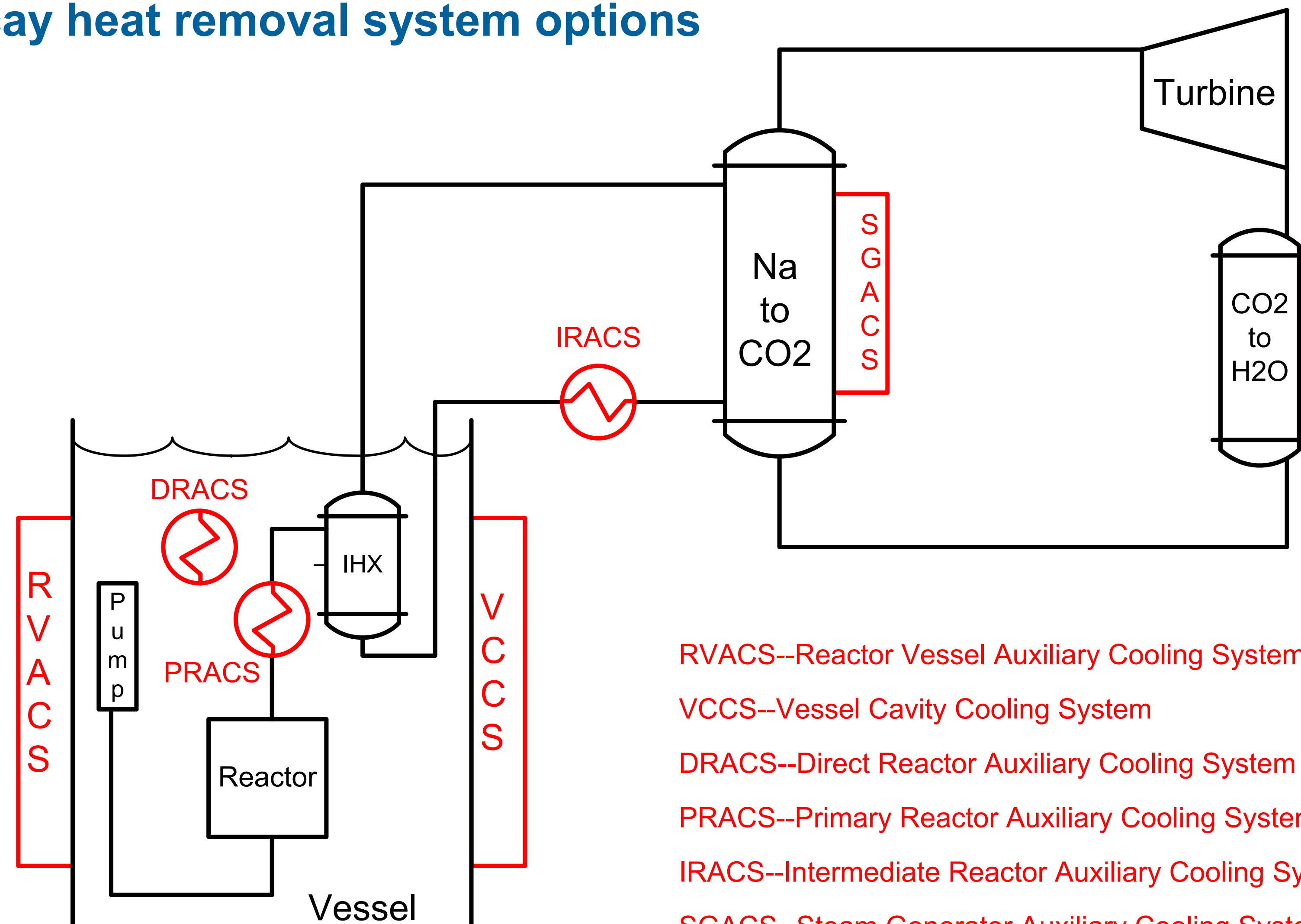
- Steam generators transfer the heat from the intermediate sodium to the water/steam in the power conversion system
  - Can be separate boilers and superheaters or once-through boiler/superheater systems
- Isolates high-pressure steam at ~7 MPa from the low-pressure sodium systems
- Often made with 2-1/4 Cr–1 Mo % ferritic steel
  - Super-Phenix used Incoloy 800, PFR used austenitic SS
- Require accommodations of thermal expansion to a greater extent than IHXs
- Steam generators with single tube wall separating steam from intermediate sodium are susceptible to sodium water reactions and are difficult to identify/isolate the leaking tubes
- Double wall steam generator tubes have two walls separated by a mesh that allows leaked material to transport to a sensing device
  - Water leaks (from the outside) and sodium leaks (from the inside) can be detected
- Double wall steam generators are costlier and less efficient because of the greater heat transfer resistance in double walls

DECAY HEAT REMOVAL SYSTEMS

- SFRs rely on independent and diverse means for removal of decay heat
- Normal shutdown heat removal is usually via balance-of plant (BOP)
  - Based on diverting steam (or supercritical CO2 in Brayton cycle) from the turbine to heat sink via a bypass line
  - Usually not a safety-grade system
- In the event BOP path is not available, shutdown heat removal is achieved via redundant safety-grade decay heat removal systems
  - To maintain continuous effective core cooling and keep the primary system component temperatures below allowed limits during postulated accidents
  - Can be based on passive heat removal mechanisms (using natural convection with no valves or mechanical devices to control its operation)

DECAY HEAT REMOVAL SYSTEMS

Decay heat removal system options



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

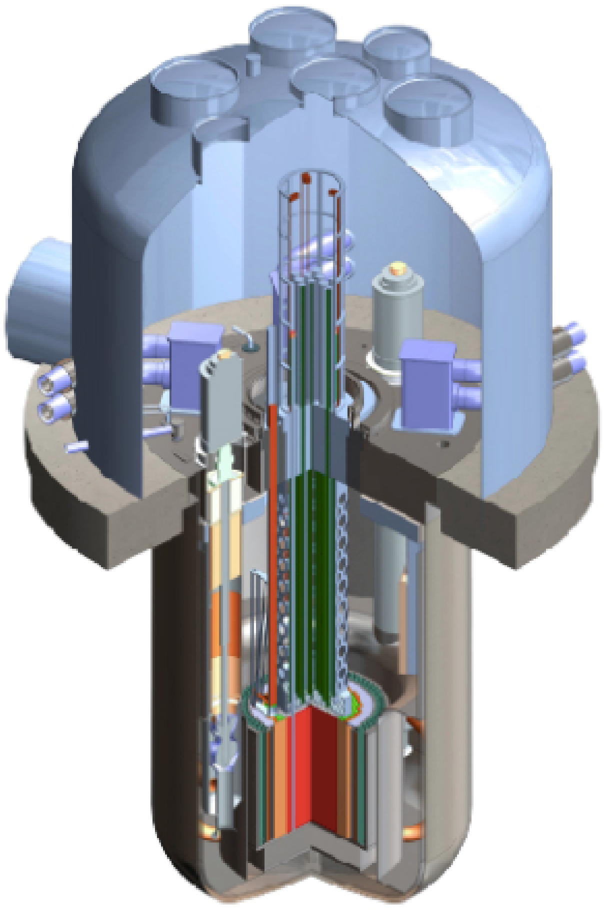
SGACS--Steam Generator Auxiliary Cooling System

CONTAINMENT

Last barrier for prevention of uncontrolled release of radioactivity in accident conditions

SFR containment systems have evolved:

- Early systems were over-designed against energetic events from a Hypothetical Core Disruptive Accident
- Experiments and analyses indicated that such events are exceedingly rare, and the energy releases are far less than early analyses indicated
- In most modern designs, containment design basis is a large sodium fire
  - Sodium aerosol analyses and experiments indicate agglomeration along with plate-out in the systems inside containment
- 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.
- Recent designs propose an underground reactor with a dome over the reactor vessel



REFUELING SYSTEM

- Refueling is done with the vessel head in place, unlike LWRs where the head is removed
- Sodium is opaque, so visual guidance is not available (some concepts of ultrasonic imaging is being considered)
- Refueling can be done through rotating plugs in a rotating head, providing access to all areas of the core
- Some concepts use refueling mechanism independent of top head plugs
- Some concepts store spent fuel in the primary vessel—some store externally
- Fuel must be in inert gas throughout the process
- Typically, refueling starts 2 days after shutdown (a fuel assembly will have ~30–40 kW at that time) and takes 2 weeks
  - Typically replaces one-third of the core every year

INSTRUMENTATION

Liquid metal coolants pose unique instrumentation challenges

Critical core parameters:

- **Flux**: In-core, ex-core (in-vessel), and ex-vessel neutron detectors
- **Temperature**: Resistance Temperature Detectors (RTDs) and thermocouples throughout the primary and intermediate loops to determine thermal power, operating conditions, and monitoring for anomalies
- **Flow**: Venturi flowmeters (accurate but with slow response time) and magnetic flowmeters (less accurate but faster response time) to complete the thermal power calculations, determine loop operating conditions and monitor flow anomalies
- **Pressure**: Via NaK filled capillary tube
- **Failed fuel detection and location**
- **Sodium leak detection**

Covered in greater detail in "Operational Considerations" presentation

INSTRUMENTATION

Flux

- Flux monitoring is typically done by a group of neutron detectors located in the reactor cavity external to the reactor vessel
  - Feasible due to longer mean-free-path of fast neutrons
  - Needed to protect the instruments from irradiation damage (in-core or in-vessel detectors may be used during initial startup)
- Signals from these detectors are used for both the reactor control system and the plant protection system

Temperature

- Sodium temperature is measured throughout the primary and secondary loops
  - Calculate thermal power
  - Determine loop operating conditions
  - Monitor for potential abnormal activities
- Two types of sensors are commonly used
  - Resistance temperature detectors (RTDs)
    - Provide a highly accurate and reliable measurement
    - Do not require a cold junction (as do thermocouples)
  - Thermocouples

INSTRUMENTATION

Flow

- Flow measurements complete the thermal power calculations and determine operating conditions
  - Venturi type flowmeters are highly accurate but has slow response time
  - Magnetic flowmeters are less accurate but with rapid response time
  - Venturi flowmeter is used to provide in-place calibration of the rapid-response magnetic flowmeter
  - Another calibration method is sodium activation with a pulsed neutron device and using the time-of-flight technique

Pressure

- Liquid pressure measurements are normally made by routing a small column of high-pressure liquid onto one side of a sensing diaphragm
- This causes complication with sodium because sodium solidifies well above room temperature
- Alternate method is to interface the sodium with NaK via a bellow system. (NaK is liquid at room temperatures and requires no trace heating)

INSTRUMENTATION

Failed fuel detection and location

- Failed fuel can be detected by sensing fission products in the cover gas
  - Xenon isotopes have sufficiently high gamma energy to allow detection
- A technique that has been used successfully in EBR-II and FFTF is gas tagging
  - Mixtures of xenon and krypton isotopes can provide over 100 unique gas tags (each subassembly set can have its unique tag identification mixture)

Sodium leak detection

- Important because:
  - Primary sodium is radioactive
  - Liquid sodium will burn in air
  - Loss of sodium could impair heat transport systems
- Leaks can be detected by conductivity probes (usually in low spots below sodium-containing tanks) or by sensing of sodium aerosols
- Sodium level monitoring—particularly important where sodium inventory is crucial
  - Level monitoring can be done with electrical induction probes
  - Needed for sodium inventory tracking

AUXILIARY SYSTEMS

Inert cover gas

- Nitrogen used as inert gas in cells with sodium-containing systems
  - Not suitable at temperatures >400°C because of nitriding problems with steel
- Argon used as cover gas within vessels and components because it does not react with structural materials and is inexpensive for an inert gas
- Argon subsystems provide pressure control and atmosphere for all sodium-gas interfaces
- Because of possible radioactive contamination, radioactive argon processing system (RAPS) is needed to remove xenon and krypton isotopes

Trace heating

- Sodium solidifies at 98°C, so it must be heated at reactor low power to keep it in liquid state
- Trace heaters provide a heat flux of about 10 to 20 kW/m2
- Trace heating systems can require 10 MW during startup (cold core) conditions—less for when pumps can be used for heating

OTHER SYSTEMS

- Sodium purification system
- Cover-gas cleanup system

} Covered in greater detail in "Operational Considerations" presentation

- Na fire protection
- Cell inerting systems
- Cell liners
- Under the head refueling systems
- Ex-vessel fuel handling and storage
- Seismic Isolation
- Unique ISI systems for opaque coolant

QUESTIONS?

TYPICAL DESIGN SPECIFICATIONS: PWR VS. SFR

			PWR	SFR
General	Specific power (kWt/kgHM)		786 (U-235)	556 (Pu fissile)
	Power density (MWt/m³)		102	300
Fuel	Rod outer diameter (mm)		9.5	7.9
	Clad thickness (mm)		0.57	0.36
	Rod pitch-to-diameter ratio		1.33	1.15
	Enrichment (%)		~4.0	~20 Pu/(Pu+U)
	Average burnup (MWd/kg)		40	100
Thermal Hydraulic	Coolant	pressure (MPa)	15.5	0.1
		inlet temp. (℃)	293	332
		outlet temp. (℃)	329	499
		reactor Δp (MPa)	0.345	0.827
	Rod surface heat flux	average (MW/m²)	0.584	1.1
		maximum MW/m²)	1.46	1.8
	Average linear heat rate (kW/m)		17.5	27.1
	Steam	pressure (MPa)	7.58	15.2
		temperature (℃)	296	455

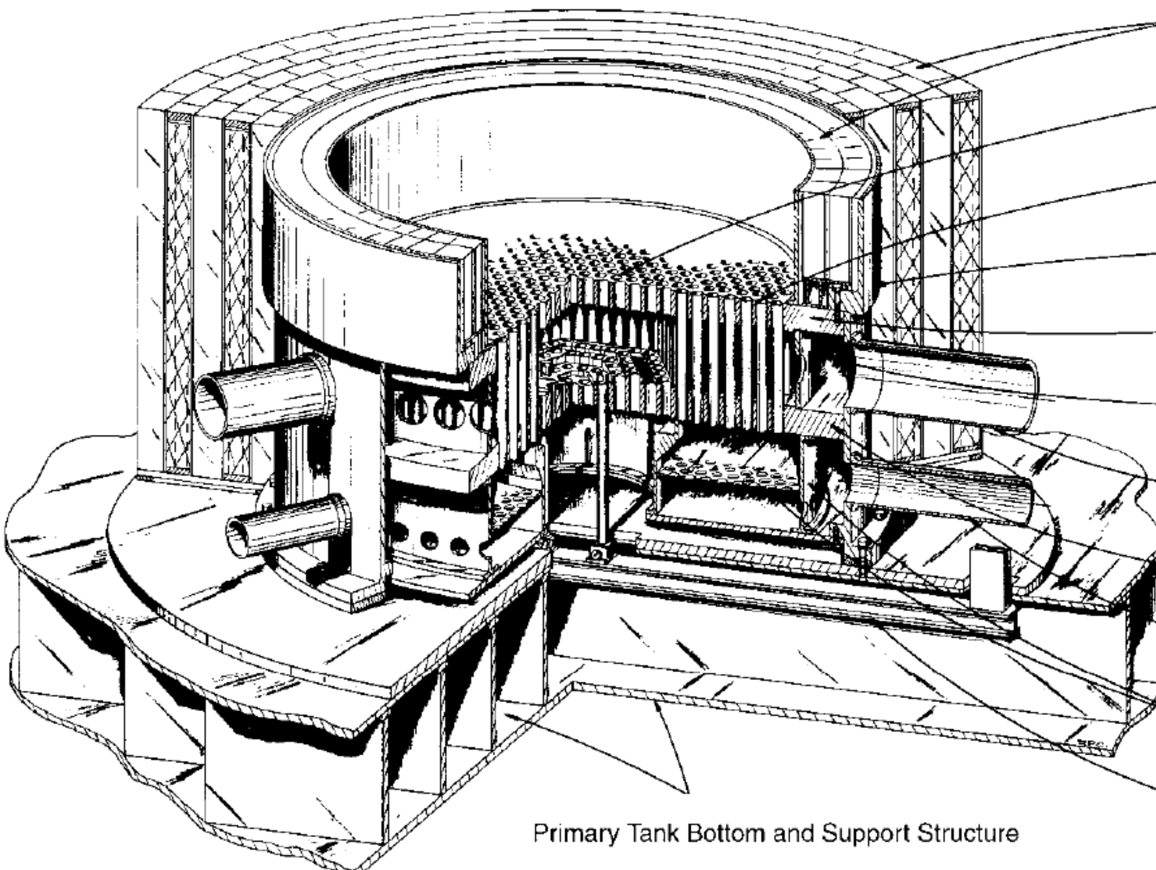
REACTOR VESSEL

Design considerations

SFR	LWR
Compatibility with sodium (low-carbon stainless steel)	Compatibility with water using SS cladding on vessel material (boric acid could cause corrosion problems)
No thermal shock concern	Thermal shock is an issue under certain ECCS conditions
Head contains rotating plug (usually); control rod drives and refueling system done with head in place	Head contains control rod drives—refueling done with head removed (bottom head for CRD in BWRs)
Concern with fast neutron fluence	Concern with radiation embrittlement under high pressure
Needs argon cover gas	No cover gas needed (steam in pressurizer)
Needs guard vessel to contain sodium leaks and maintain sodium inventory	High-pressure injection system to control coolant inventory

GRID PLATE, INLET PLENUM, AND CORE SUPPORT STRUCTURE (EBR-II)

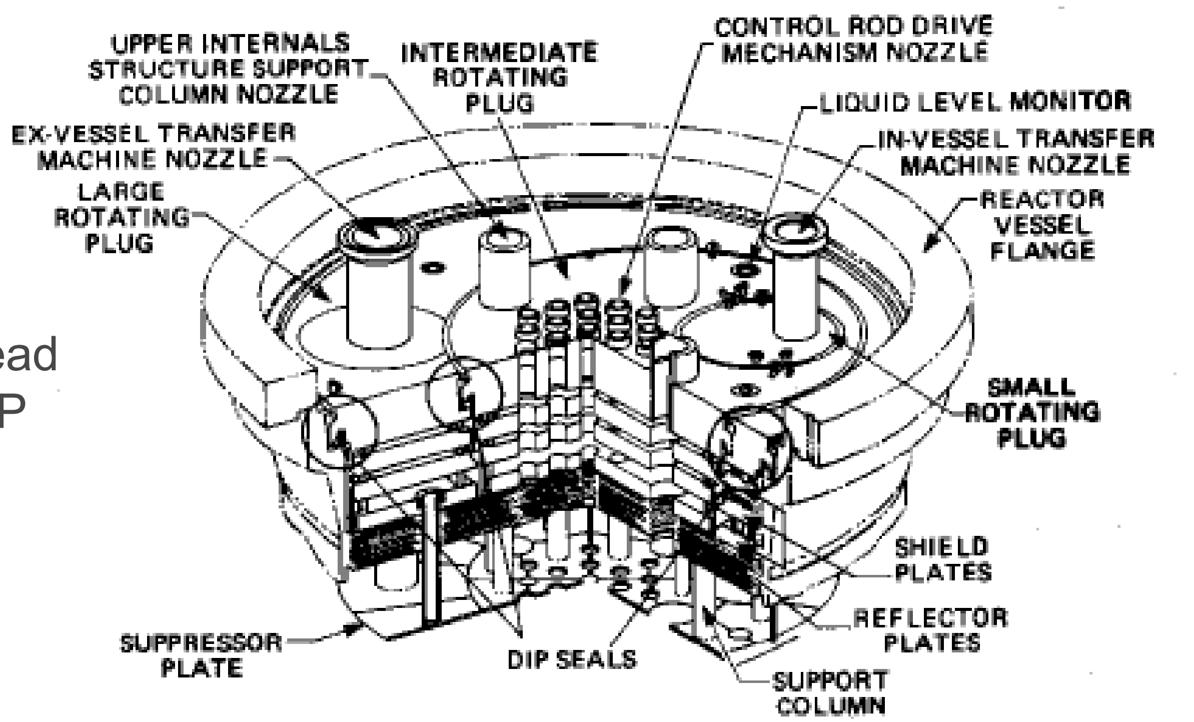
- Core Assemblies are inserted into the Grid Plate structure
- Cold sodium is pumped into the inlet plenum
  - High pressure plenum feeds fueled assemblies
  - Low pressure plenum feeds blankets, reflectors, and shield (as appropriate)
- Core Support structure is underneath grid plate and plenum structure



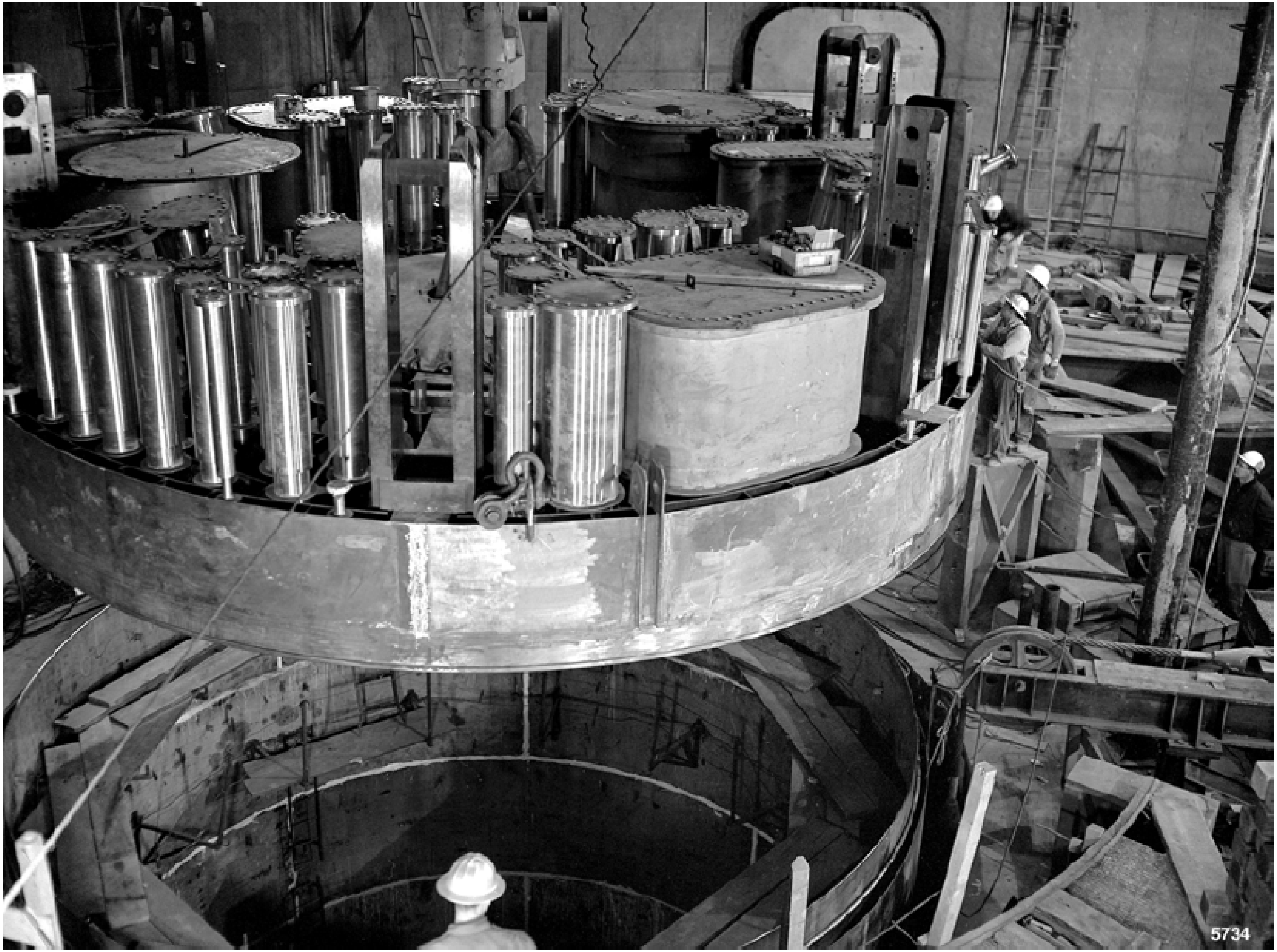
REACTOR VESSEL HEAD

- Seals the primary sodium and must contain an inert cover gas (typically argon)
  - Must be thermally insulated from the hot surface sodium
- Pool-type head is more complex because it must support the core, pumps, IHX, and allow fuel handling access

Reactor Vessel Head for CRBRP



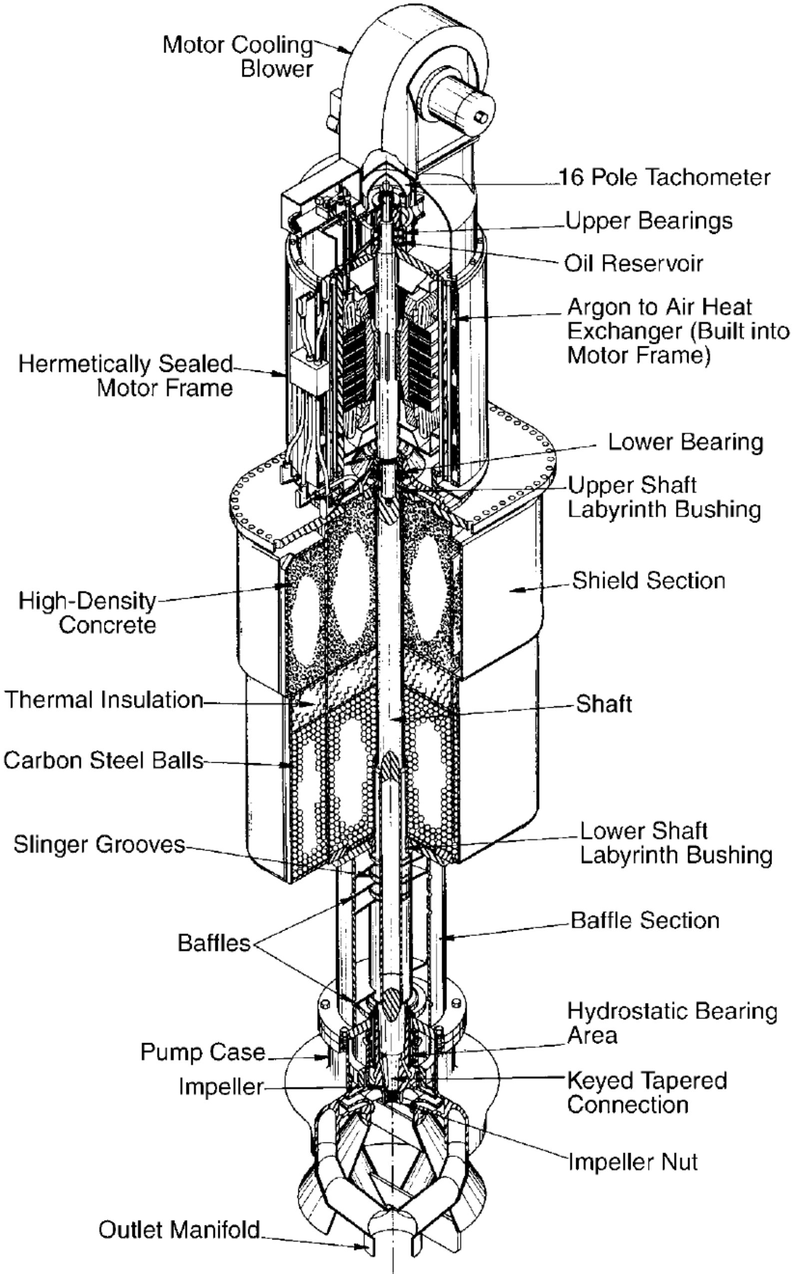
EBR-II REACTOR VESSEL COVER

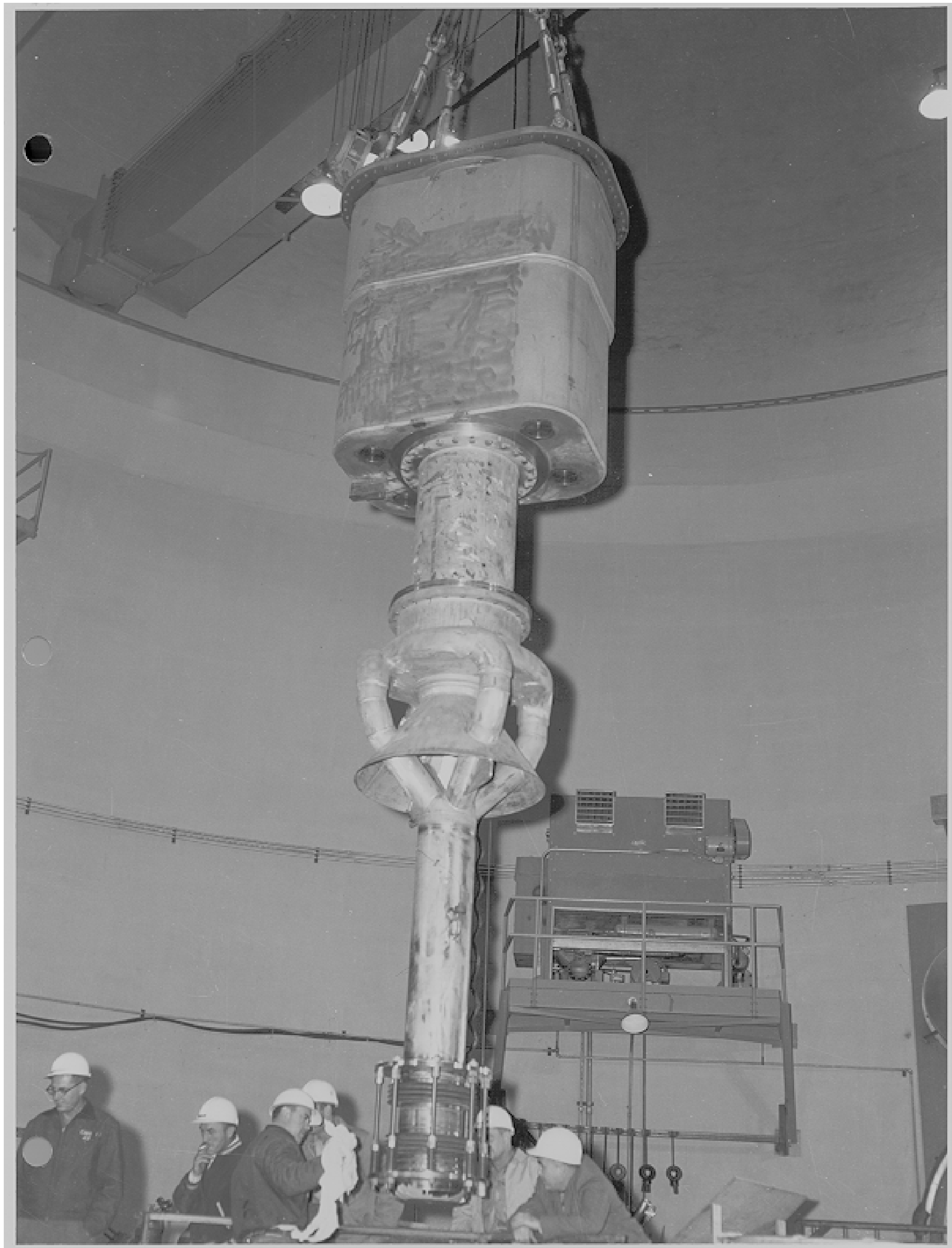


HEAT TRANSPORT SYSTEMS

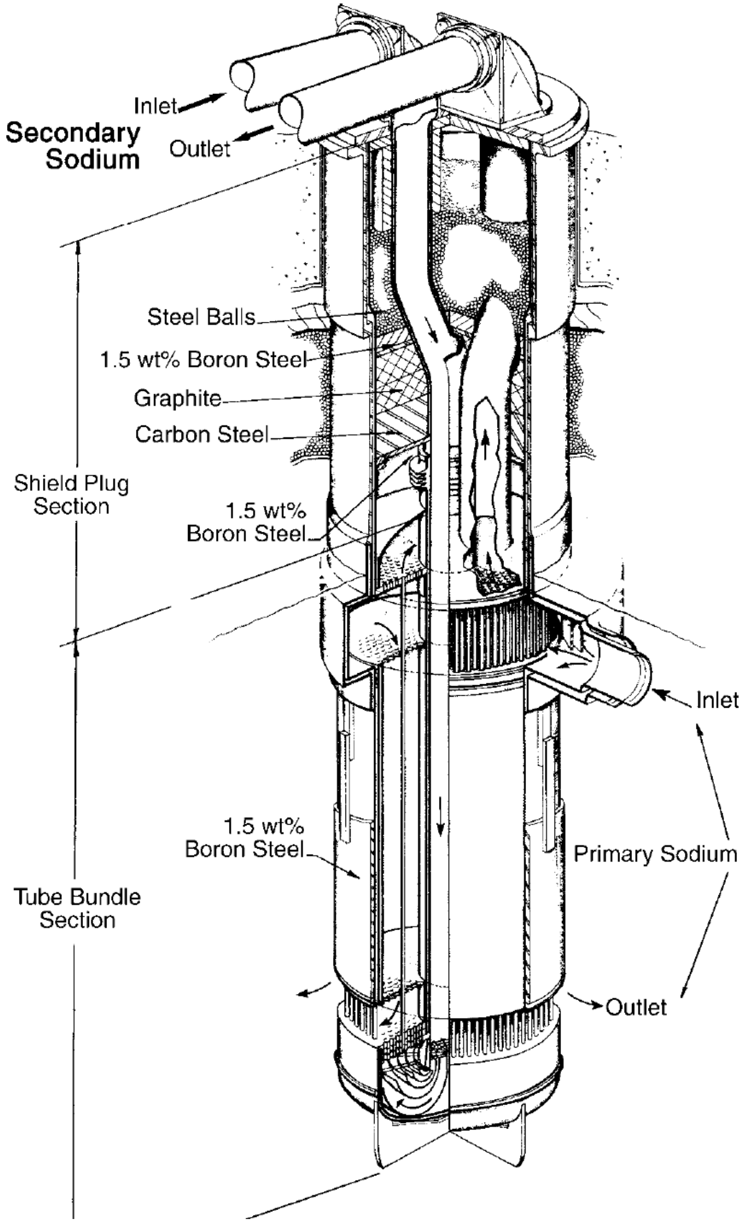
- PCS and ICS operate at near atmospheric pressure
  - Peak pressure is set by core/IHX pressure drop and gravity head characteristics (up to about 1.0 MPa at reactor inlet)
- Each reactor fuel assembly typically produces about 5 MW of power
- Average core power density is typically 350 to 500 kW/liter (1100 to 1500 kW/liter in the fuel)
  - Average fuel pin linear power ratings are typically 23 to 28 kw/m for pins with cladding diameters of usually < 1 cm
- Typical coolant velocities in the fuel pin bundle are 5 to 7 m/s
- Primary coolant outlet temperatures are ~500-550°C, depending on cladding material (boiling margin ~350°C)
- SFRs allow more efficient steam conditions than a conventional steam cycle
  - Water reactors are limited to ~325°C outlet temperatures and 15.5 MPa—limited to saturated steam cycles—with efficiencies ~35%
  - SFR can attain temperatures high enough for superheated steam and “modern” steam conditions with sodium outlet temperature ~550°C
    - Allows ~453°C 10.5 MPa steam and higher thermodynamic efficiency ~40+%
    - Conventional designs uses saturated steam cycle

EBR-II Primary Pump Installation

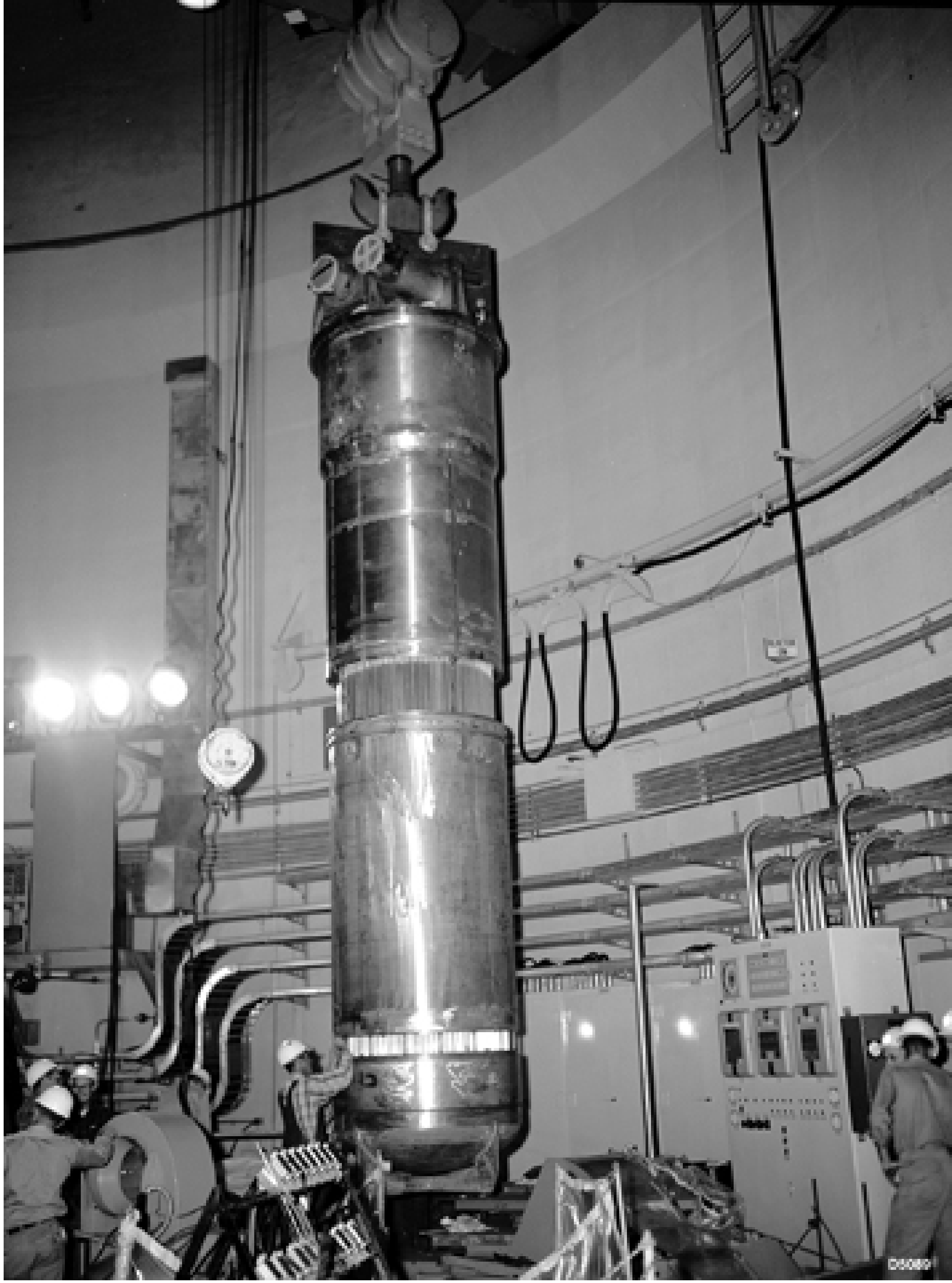




EBR-II IHX



Inlet
Secondary Sodium
Outlet
Steel Balls
1.5 wt% Boron Steel
Graphite
Carbon Steel
Shield Plug Section
1.5 wt% Boron Steel
Inlet
1.5 wt% Boron Steel
Primary Sodium
Tube Bundle Section
Outlet



"LEAK" BEFORE "BREAK" CONCEPT

- Reactor vessel is normally operated at ~2-8 psig for pool plants and a little higher for loop plants
- All radioactive sodium systems are guarded with outer vessels or outer piping to accommodate potential leaks at welds while maintaining the reactor core sufficiently covered with primary coolant
  - Guard vessels
  - Guard piping
  - Sensors to detect leaking sodium
- Systems operate at low pressure – therefore, piping and vessels "leak" before "break" giving operators time to address leaking component
- Leaks from reactor vessel will slowly fill up guard vessel – designed so that reactor core will remain covered