GENERATION IV NUCLEAR ENERGY SYSTEMS

HOW THEY GOT HERE AND WHERE THEY ARE GOING

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OUTLINE OF PRESENTATION

- Introduction to the Gen IV (long-term) Nuclear Energy Systems

- The Roadmap - how we got to the Gen IV concepts

- The Not-Gen IV Nuclear Energy Systems
  aka the international near-term deployment concepts

- What do the Gen IV concepts look like; what are some of their R&D needs

GENERATION IV NUCLEAR ENERGY SYSTEMS

	Neutron Spectrum	*Fuel Cycle*	*Size*	*Applications*	*R&D*
Gas-Cooled Fast Reactor (GFR)					
Lead-alloy Fast Reactor (LFR)					
Sodium Fast Reactor (SFR)					
Very High Temp. Gas Reactor (VHTR)					
Supercritical Water Reactor (SCWR)					
Molten Salt Reactor (MSR)					

GENERATION IV NUCLEAR ENERGY SYSTEMS

	Neutron Spectrum	Fuel Cycle	Size	Applications	R&D
Gas-Cooled Fast Reactor (GFR)	Fast	Closed			
Lead-alloy Fast Reactor (LFR)	Fast	Closed			
Sodium Fast Reactor (SFR)	Fast	Closed			
Very High Temp. Gas Reactor (VHTR)	Thermal	Open			
Supercritical Water Reactor (SCWR)	Thermal, Fast	Open, Closed			
Molten Salt Reactor (MSR)	Thermal	Closed			

GENERATION IV NUCLEAR ENERGY SYSTEMS

	Neutron Spectrum	*Fuel Cycle*	*Size*	*Applications*	*R&D*
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	Med	Electricity, Actinide Mgmt., Hydrogen	Fuels, Materials, Safety
Lead-alloy Fast Reactor (LFR)	Fast	Closed	Small to Large	Electricity, Actinide Mgmt., Hydrogen	Fuels, Materials compatibility
Sodium Fast Reactor (SFR)	Fast	Closed	Med to Large	Electricity, Actinide Mgmt.	Advanced Recycle
Very High Temp. Gas Reactor (VHTR)	Thermal	Open	Med	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Supercritical Water Reactor (SCWR)	Thermal, Fast	Open, Closed	Large	Electricity	Materials, Safety
Molten Salt Reactor (MSR)	Thermal	Closed	Large	Electricity, Actinide Mgmt., Hydrogen	Fuel, Fuel treatment, Materials, Safety and Reliability

THE TECHNICAL ROADMAP

- Discusses the benefits, goals and challenges, and the importance of the fuel cycle
- Describes evaluation and selection process
- Introduces the six Generation IV systems chosen by the Generation IV International Forum
- Surveys system-specific R&D needs for all six systems
- Collects crosscutting R&D needs
- GIF countries will choose the systems they will work on
- Programs and projects will be founded on the R&D surveyed in the roadmap
- Information available at gif.inel.gov/roadmap/

TECHNOLOGY GOALS

- Sustainability
  1. Provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production
  2. Minimize and manage their nuclear waste and notably reduce the long term stewardship burden, thereby improving protection for the public health and the environment
- Safety and reliability
  3. Operations will excel in safety and reliability
  4. Will have a very low likelihood and degree of reactor core damage
  5. Will eliminate the need for offsite emergency response

TECHNOLOGY GOALS

- Economics
  6. Will have a clear life-cycle cost advantage over other energy sources
  7. Will have a level of financial risk comparable to other energy projects

- Proliferation resistance and physical protection
  8. Will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

INTERNATIONAL NEAR-TERM DEPLOYMENT (1/2)

- Deployment by 2015
- Industry involvement
- Improvement over current advanced LWR performance
- Advanced Boiling Water Reactors
  - ABWR-II
  - ESBWR
  - SWR-1000
  - HC-BWR
- Modular High-Temperature Gas-Cooled Reactors
  - GT-MHR
  - PBMR

INTERNATIONAL NEAR-TERM DEPLOYMENT (2/2)

- **Advanced Pressure Tube Reactor**
  - **ACR-700**

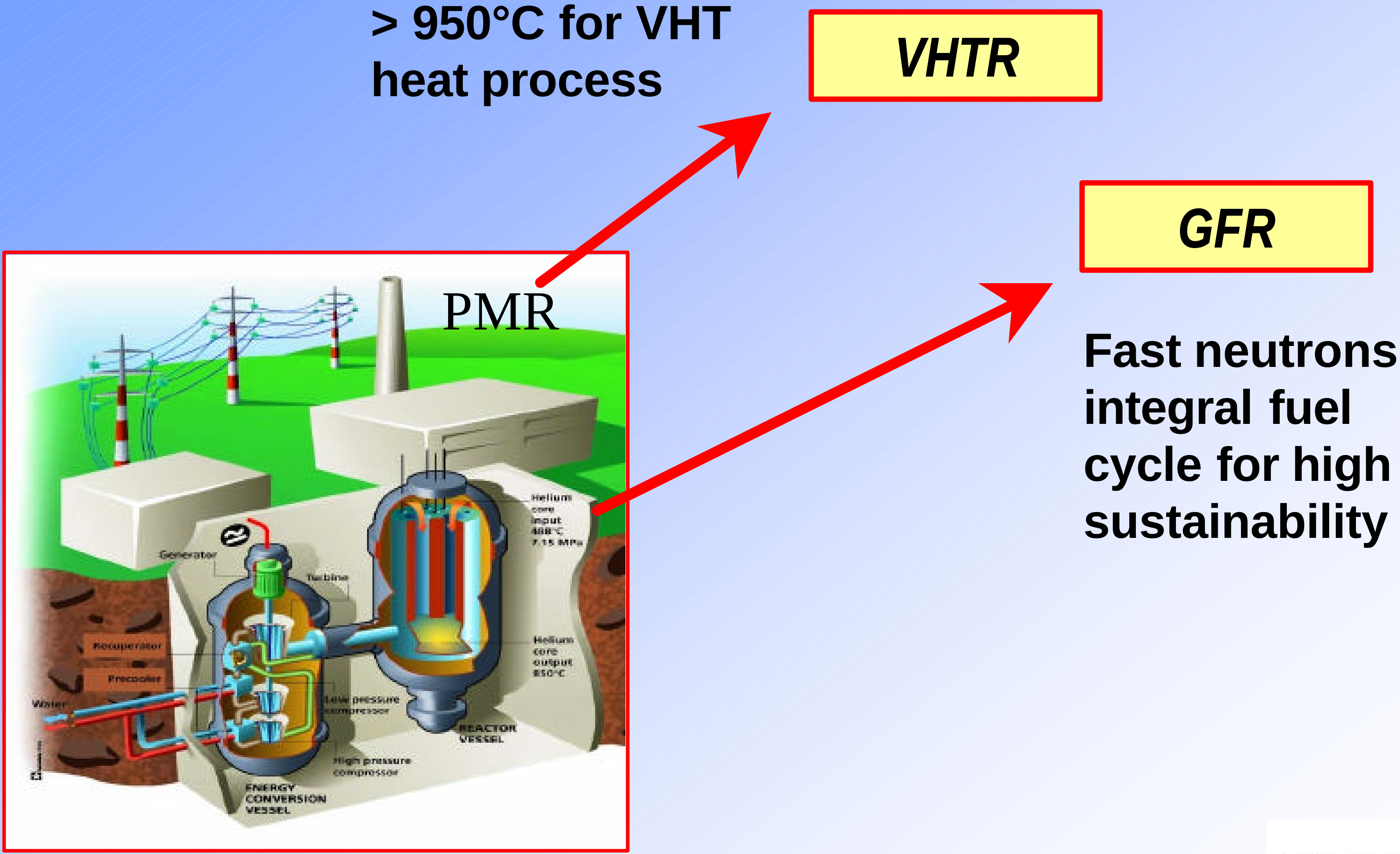
- **Advanced Pressurized Water Reactors**
  - **AP-600**
  - **AP-1000**
  - **APR-1400**
  - **APWR+**
  - **EPR**

- **Integral Primary System Reactors**
  - **CAREM**
  - **IMR**
  - **IRIS**
  - **SMART**

GEN IV NUCLEAR ENERGY SYSTEMS

- Very High Temp. Gas Reactor (VHTR)
- Gas-Cooled Fast Reactor (GFR)
- Supercritical Water Reactor (SCWR)
- Sodium Fast Reactor (SFR)
- Lead-alloy Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

SEQUENCED DEVELOPMENT OF HIGH TEMPERATURE GAS COOLED NUCLEAR ENERGY SYSTEMS



> 950°C for VHT heat process

VHTR

GFR

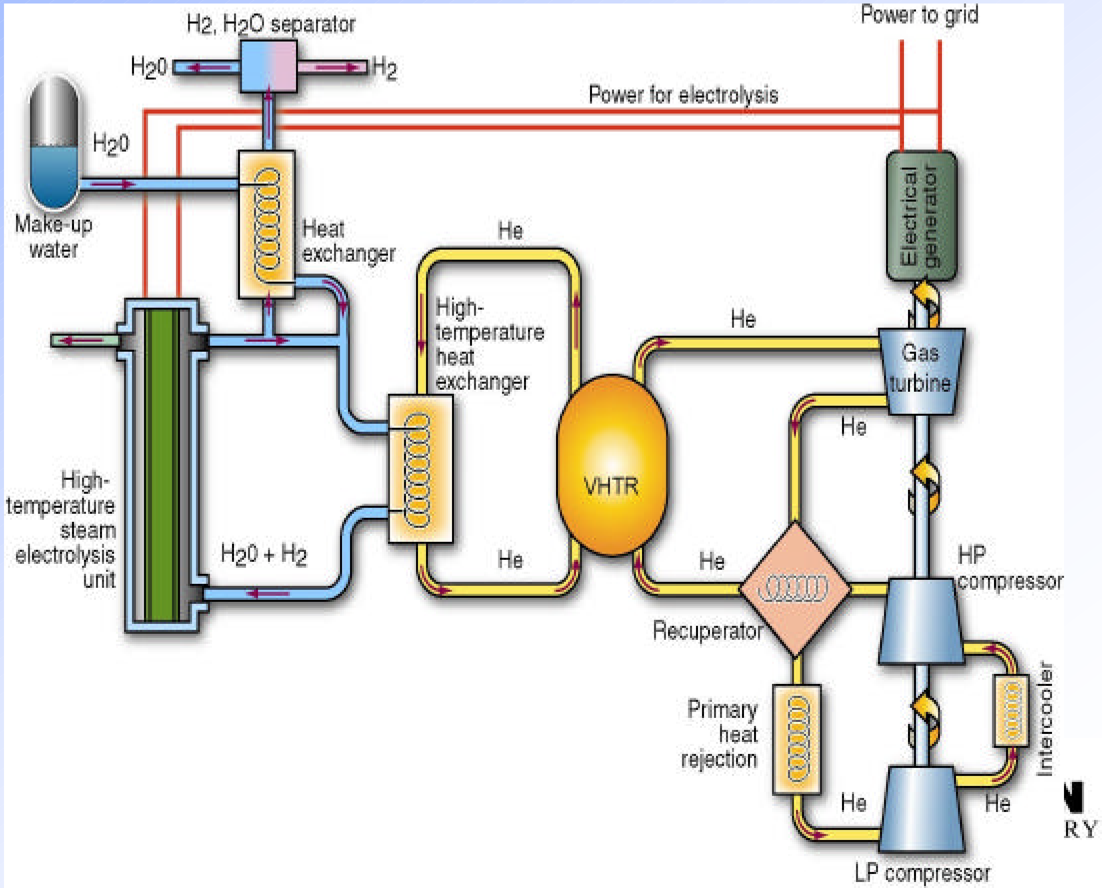
Fast neutrons & integral fuel cycle for high sustainability

VHTR FOR HYDROGEN PRODUCTION

- Hydrogen demand is already large and growing rapidly
  - Heavy-oil refining consumes 5% of natural gas for hydrogen production

- Energy security and environmental quality motivate hydrogen as an alternative to oil as a transportation fuel
  - Zero-emissions
  - Distributed energy opportunity

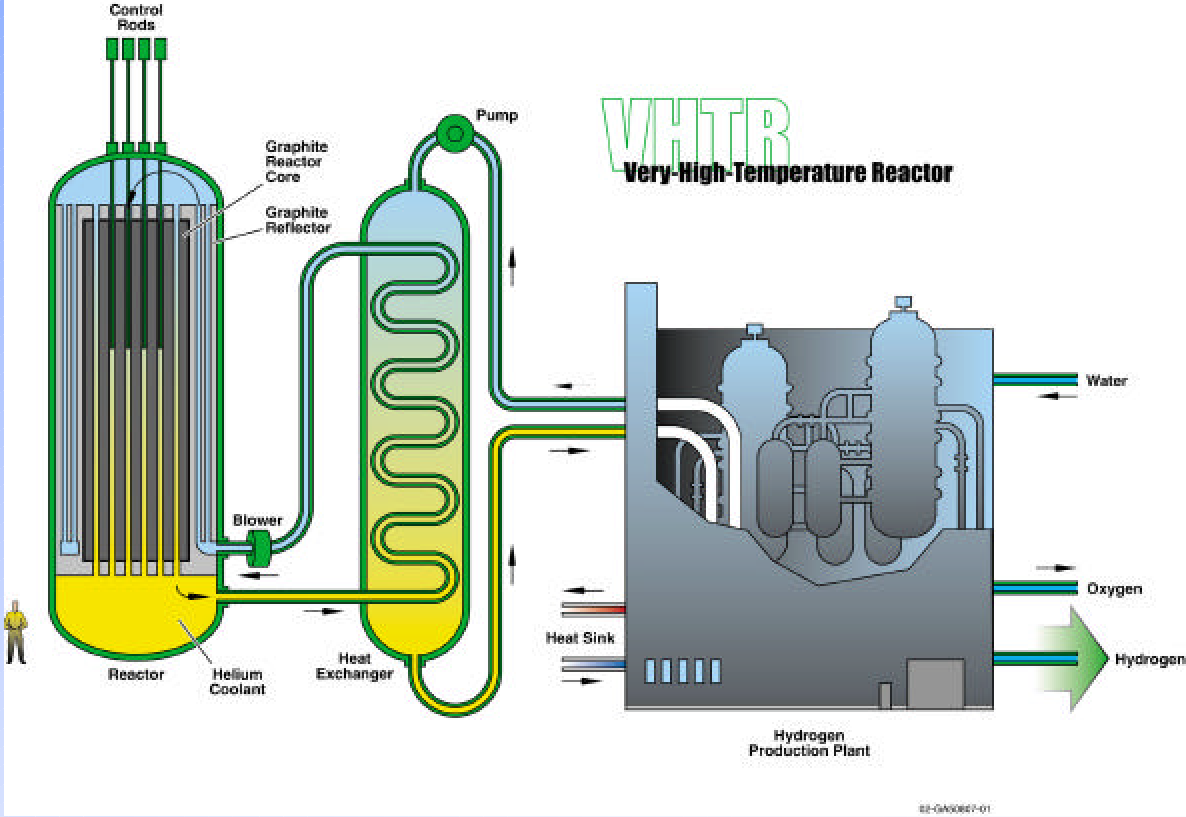
- Water is the preferred hydrogen "fuel"
  - Electrolysis using off-peak power
  - High-temperature electrolysis
  - High-temperature thermochemical water splitting



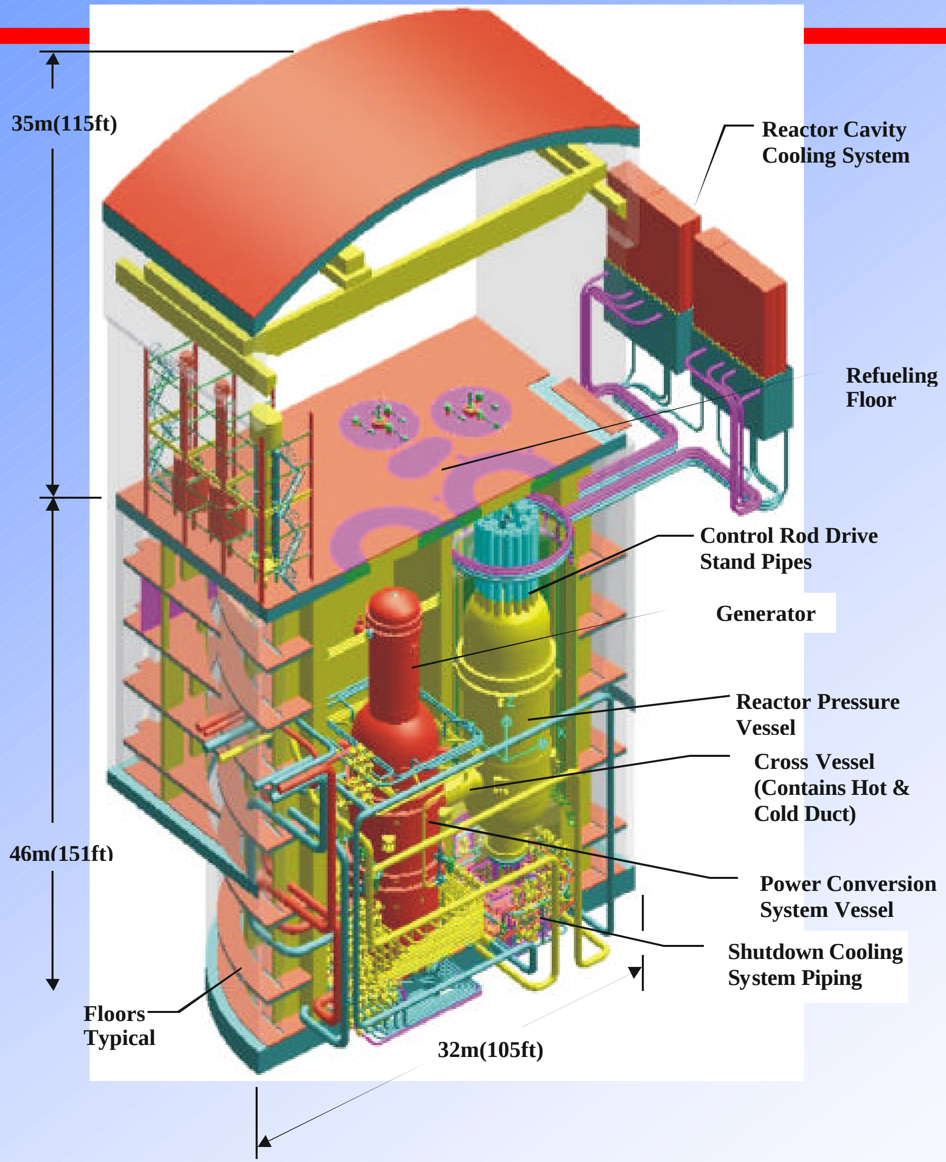
VERY HIGH TEMPERATURE REACTOR (VHTR)

Characteristics

- He coolant
- 1000°C outlet temperature
- Reactor coupled to H_2 production facility
- 600 MW_{th}, nominally based on MHTGR
- Coated particle fuel, graphite block (or pebble?) core



GT-MHR REACTOR BUILDING



GT-MHR

Upper plenum - hot plume mixing - "LOF"

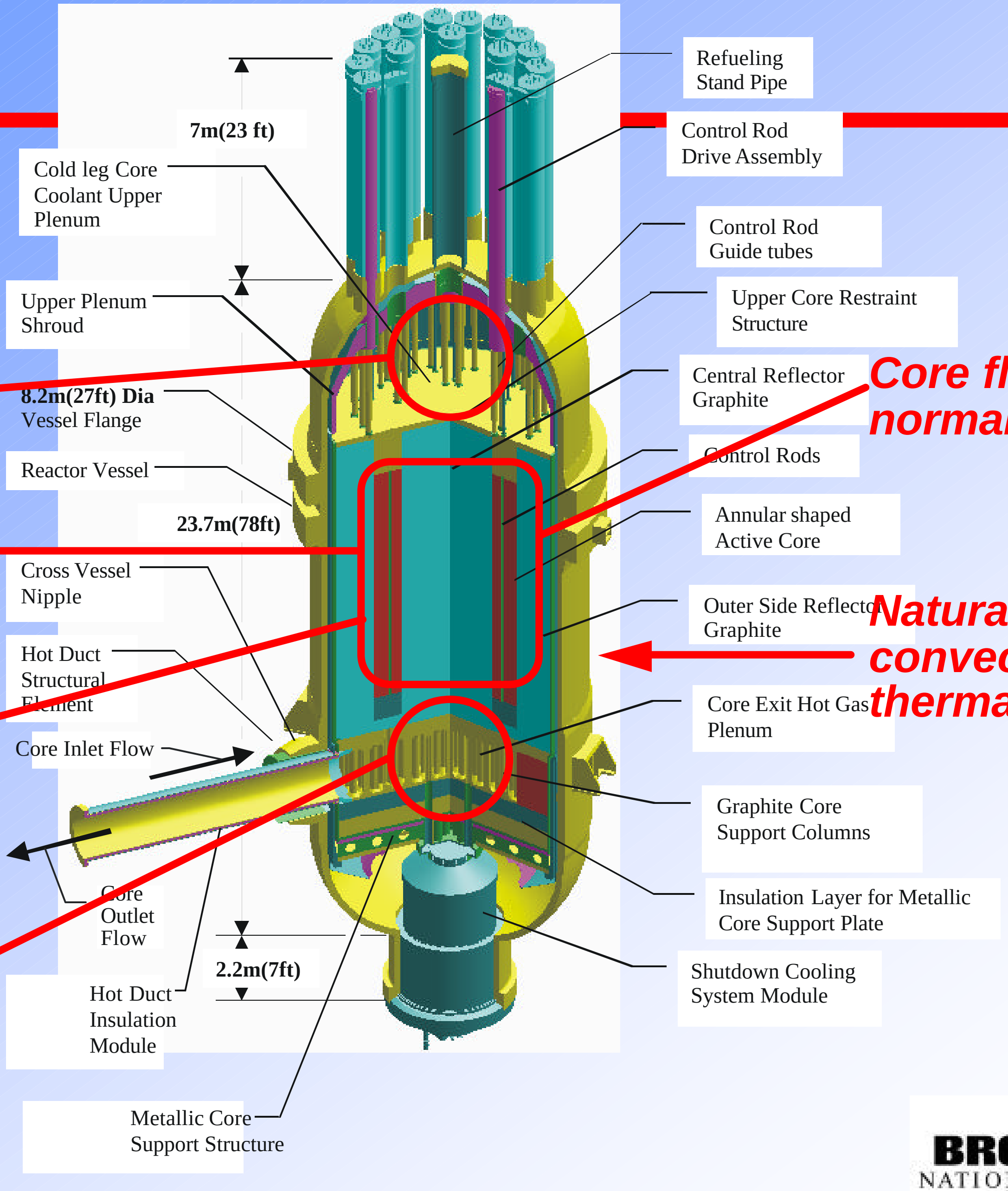
Core - depressurized cooldown

Flow between hotter/ cooler channels - "LOF"

Lower plenum - hot jet mixing

Core flow - normal operation

Natural convection and thermal radiation



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CORE FLOW ISSUES DURING NORMAL OPERATION

- **Calculation of the coolant channel temperatures during normal operation**
  - **Significant local variations in power occur across the core due the non-uniform location of the reflectors, control rods, and burnable poison assemblies and due to the fuel loading**
  - **Power variations are amplified in the hot channels due to the buoyancy resistance**
  - **Therefore the coolant temperatures can vary by more than + or - 200°C from the average**

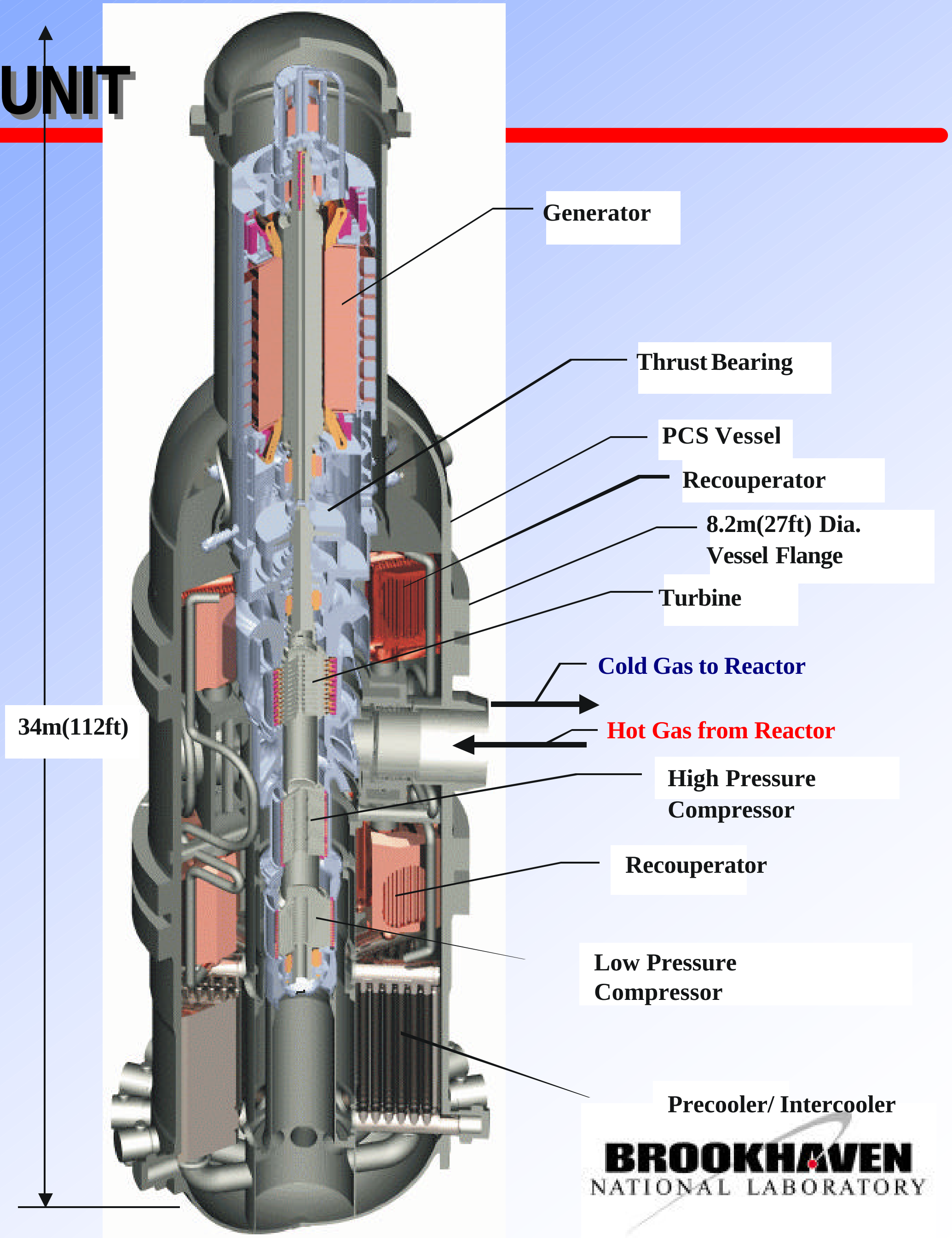
- **Calculation of the core lower plenum flow mixing and pressure drop**
  - **Hot jet mixing, complex 3-dimensional flow around the core supports, and the flow acceleration near the hot duct need to be calculated**

- **Calculation of the hot duct coolant mixing and insulation effectiveness**
  - **Permeation of the hot gas into the insulation is a concern**
  - **The entrance conditions are somewhat uncertain, but the flow must be well mixed by the time it reaches the turbine**

POWER CONVERSION UNIT

Thermal-hydraulic Issues

- Mixing of the gases during bypass events
- Flow distributions among the recuperators and recuperator efficiency
- Hot streaks at the turbine inlet



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THERMAL-HYDRAULIC ISSUES - ACCIDENT CONDITIONS

- Rejection of the heat by natural convection and thermal radiation from the reactor pressure vessel outer wall to the passive cooling system
  - Local effects around the hot duct need to be considered
  - Some separate effects proof testing may be needed

- Reliability, robustness, and effectiveness of the Reactor Cavity Cooling System

- Flow through the core during a loss of circulation accident
  - Up flow in the hot channels and down flow in the cool channels results in hot plumes in the upper plenum
  - The hot and cold channel flow distribution and the upper plenum mixing are uncertain
  - Low Reynolds number flow with turbulent, transitional, and/or laminar flow, buoyancy effects, and gas property variations

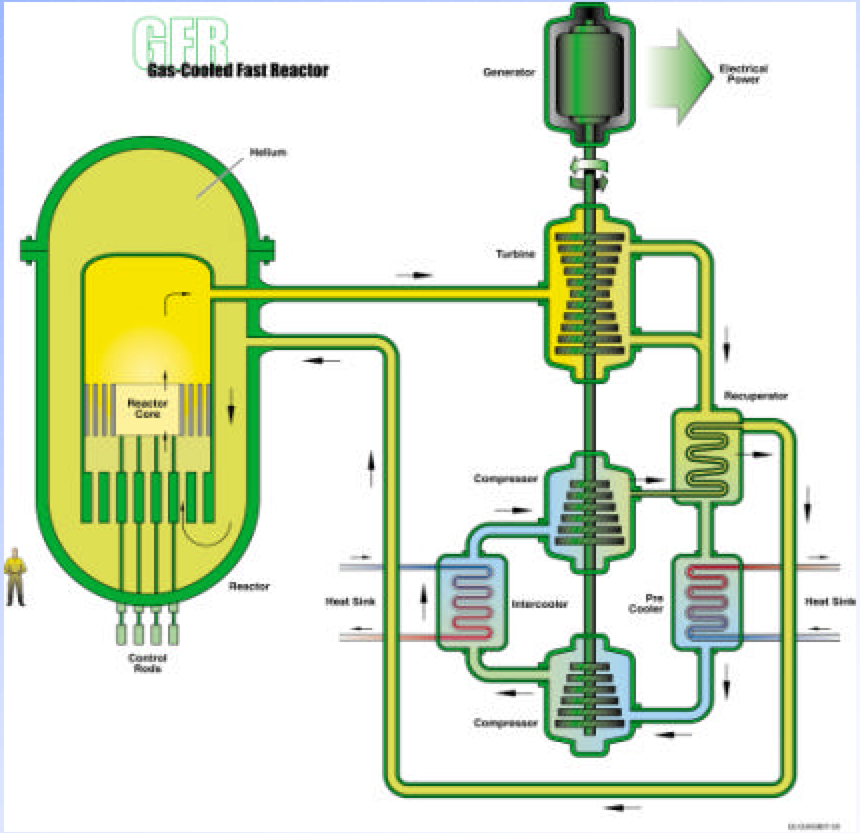
- Core cool down during a LOCA

- Air or water ingress during a LOCA

GAS-COOLED FAST REACTOR (GFR)

Characteristics

- He (or SC CO_2) coolant, direct cycle energy conversion
- 850°C outlet temperature
- 600 MW_{th}/288 MW_e
- U-TRU ceramic fuel in coated particle, dispersion, or homogeneous form
- Block, pebble, plate or pin core geometry
- Combined use of passive and active safety systems
- Closed fuel cycle system with full TRU recycle
- Direct Brayton cycle energy conversion



ADVANTAGES OF GFR

- GFRs share the sustainability attributes of fast reactors
  - Effective fissioning of Pu and minor actinides
  - Ability to operate on wide range of fuel compositions (“dirty fuel”)
  - Capacity for breeding excess fissile material

- Advantages offered by use of He coolant
  - Ease of in-service inspection
  - Chemical inertness
  - Very small coolant void reactivity ($<ß_{eff}$)
  - Potential for very high temperature and direct cycle conversion

- High temperature potential opens possibilities for new applications, including hydrogen production

GFR R&D NEEDS

- **Safety case difficult with low thermal inertia and poor heat transfer properties of coolant**

  - **Reliance on active and “semi-passive” systems for decay heat removal**
  - **Passive reactivity shutdown is also targeted**

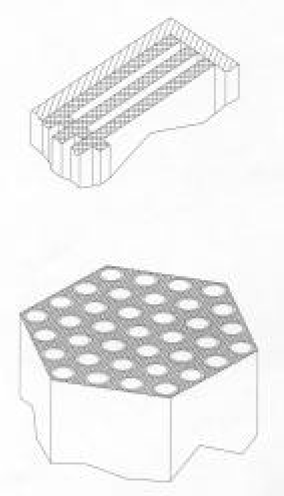
- **High actinide-density fuels capable of withstanding high temperature and fast fluence**

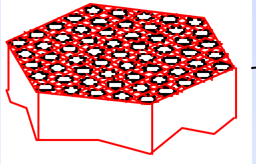
  - **Modified coated particle or dispersion type fuels, e.g.,**
    - **(U,TRU)C/SiC**
    - **(U,TRU)N/TiN**
  - **Fuel pins with high-temperature cladding, e.g., infiltrated kernel particle**

- **Core structural materials for high temperature and fast-neutron fluence conditions (ceramics, composites, refractory alloys)**

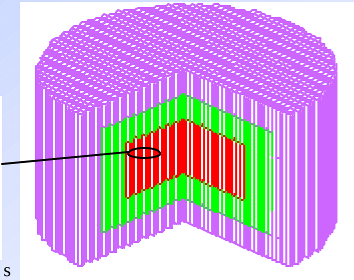
FUEL / CORE CONFIGURATIONS

- GFR
  - Metal or ceramic matrix (similar to prismatic)
  - Pin, plate types (ceramic, metallic)
  - Pebble/particle

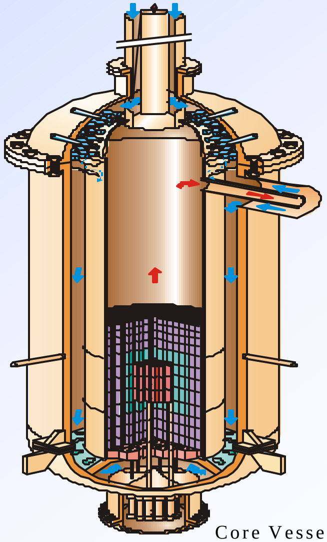




Composite Ceramics Fuel Element



Core Lay-out



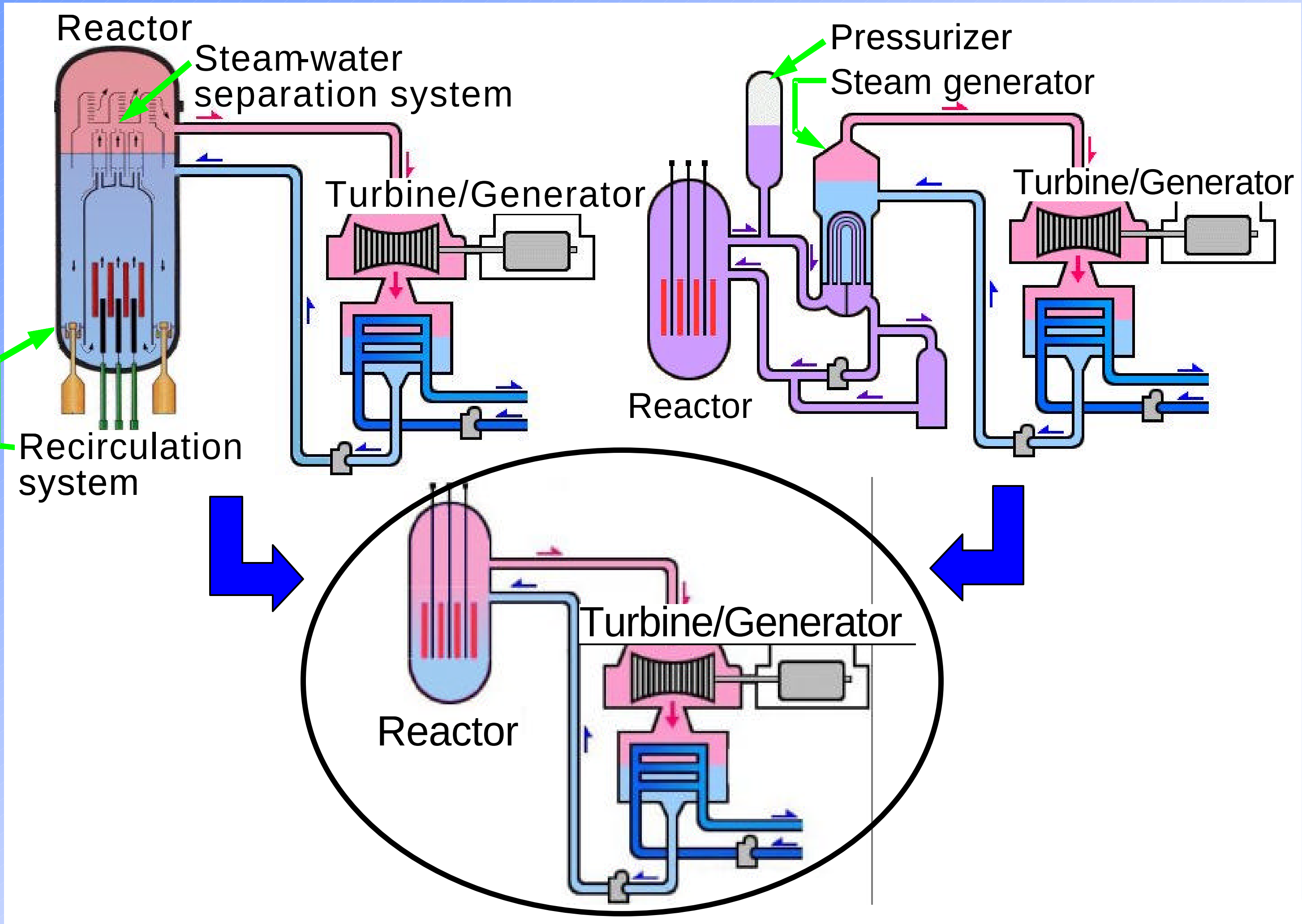
Core Vessel

SCWR: GENERAL CHARACTERISTICS

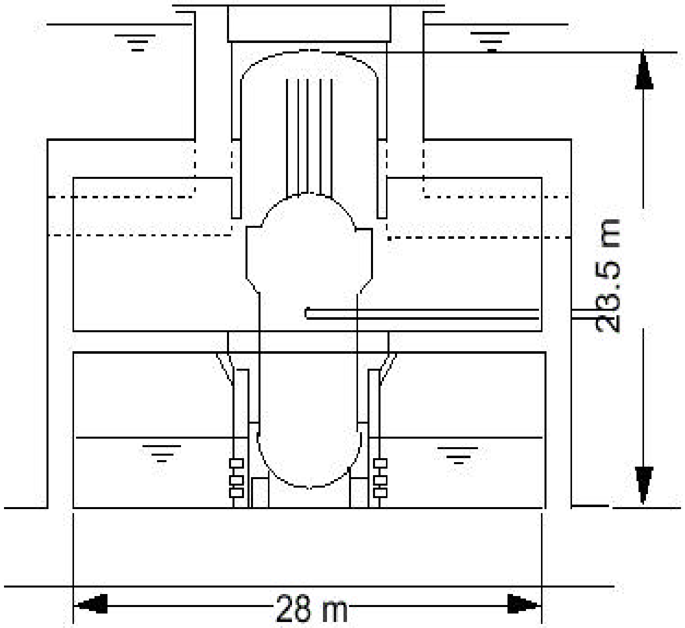
- LWR operating at higher pressure (>22.1 MPa) and temperature (280-550°C)
  - Operating conditions with fossil plant experience
- Higher thermal efficiency (44% vs. 33%)
- No change of phase
  - Larger enthalpy rise in core
  - Lower flow rate (~10% of BWR)
  - Lower pumping power (smaller pumps)
- Simplified direct cycle system
  - No recirculation
  - Smaller reactor pressure vessel/containment
- Thermal or fast spectrum possible
  - Fuel cycle flexibility

Improved Economics

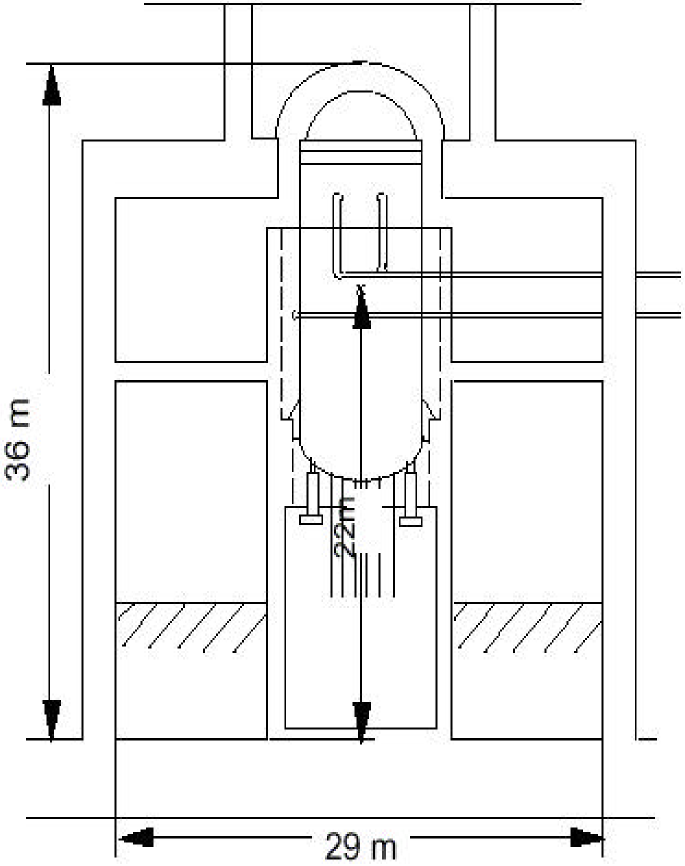
SCWR: OPTIMIZATION OF LWR TECHNOLOGY



SCWR: EFFECT OF SIMPLIFICATION



SCLWR-H (1700MWe)



ABWR (1350MWe)

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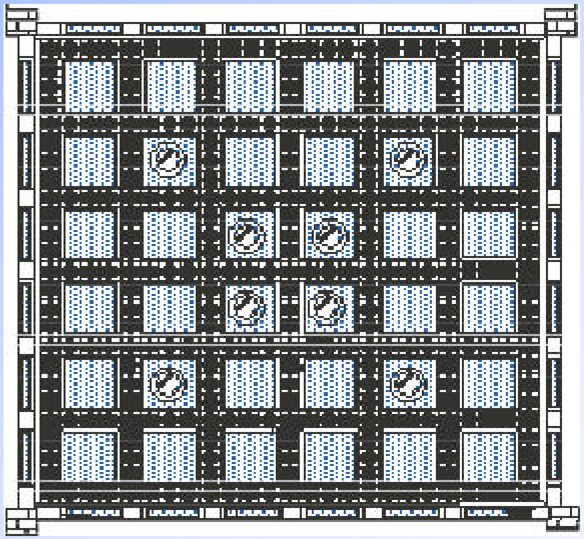
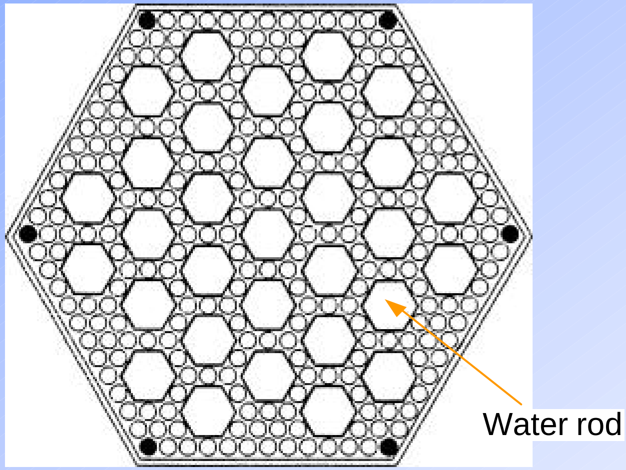
SCWR NEUTRONIC DESIGN

- Considerations with core design
  - Large change in density axially
  - Average coolant density higher than in BWR
  - Downward flow in water rods
  - Other moderators (BeO, ZrH_2)
  - Square or hexagonal geometry



Fuel assembly



- Safety consideration
  - Rod ejection accident
  - Negative moderator reactivity coefficient

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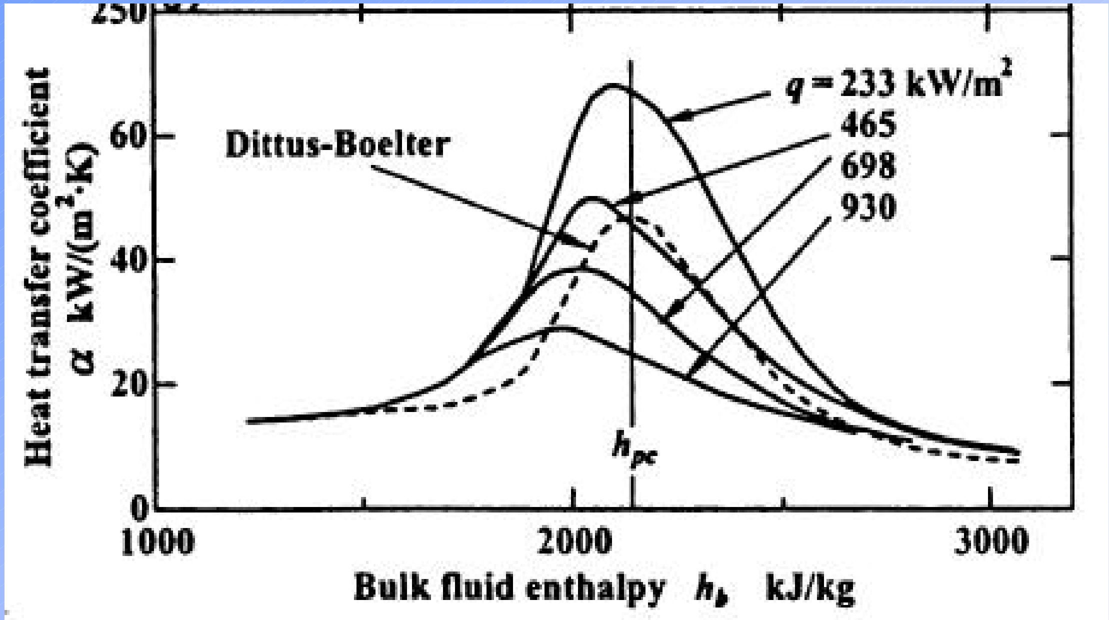
BASIC DATA - HEAT TRANSFER

Single-phase heat transfer:



Data exist for either simple round tubes and/or surrogate fluids. Existing SCW heat-transfer database and correlations are inconsistent.

Heat-transfer data at <u>prototypical SCWR conditions</u> (i.e., supercritical water, complex bundle geometry, high heat flux) are needed.

Existing correlations and models for SCW heat transfer exhibit large discrepancies and diverging trends

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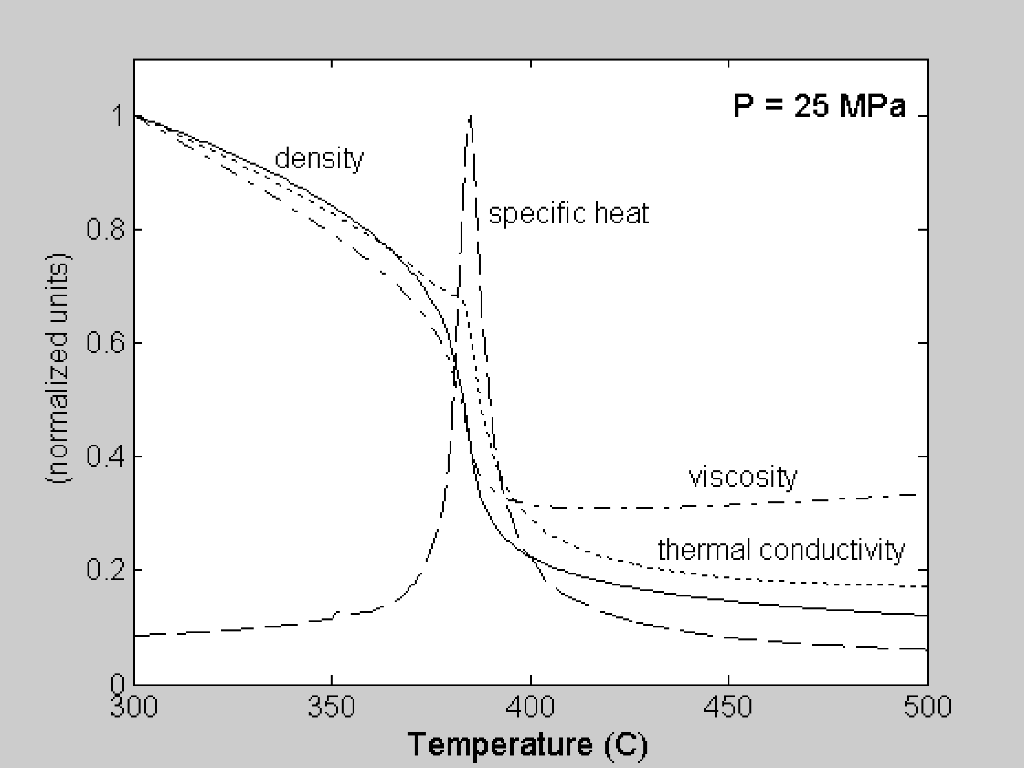
CODES - NUMERICAL INSTABILITIES

Large (albeit continuous) variation of the thermo-physical properties…

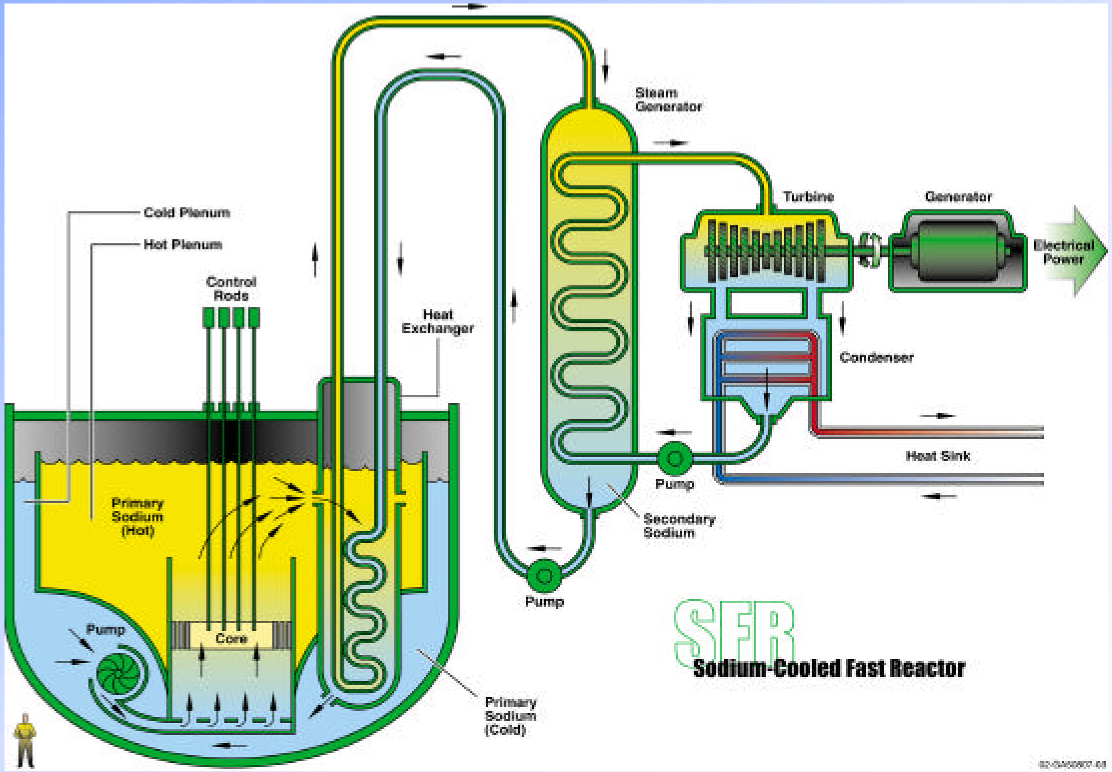


… may result in code execution failures.

SODIUM-COOLED FAST REACTOR (SFR)

Characteristics

- Sodium coolant, 550°C T_{out}
- 150 to 1500 MWe
- Pool or loop plant configuration
- Intermediate heat transport system
- U-TRU oxide or metal-alloy fuel
- Hexagonal assemblies of fuel pins on triangular pitch



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SFR SAFETY R&D NEEDS

- Demonstration of passive safety design: providing assurance that the physical phenomena and related design features relied upon to achieve passive safety are adequately characterized

  - Axial fuel expansion and radial core expansion
    - Experimental data plus deterministic models required for accurate core representation (particularly, minor-actinide-bearing fuels)
    - Reduce uncertainties in T-H quantities by using more detailed models
      - Multi-pin subassembly, full assembly-by-assembly, coupled neutronics-thermal-hydraulic calculation
      - Accurate duct-wall and load pad temperatures required for calculating bending moments in each subassembly to characterize core restraint and expansion
      - CFD tools for benchmark calculations or routine design calculations?

  - Self-activated shutdown systems
  - Passive decay heat removal systems
    - CFD models useful for resolution of complex natural circulation flow paths

SFR SAFETY R&D NEEDS (CONT'D)

- Accommodation of extremely low probability but higher consequence accident scenarios
  - Demonstrate that passive mechanisms exist to preclude recriticality in a damaged reactor
  - Show that debris from fuel failure is coolable within the reactor vessel
- Implication for safety analysis tools
  - Requires analytical and experimental investigations of mechanisms that will ensure passively safe response to bounding events that lead to fuel damage
    - e.g., out-of-pile experiments involving reactor materials are recommended for metal fuels
  - Local feedback and material motion modeling required

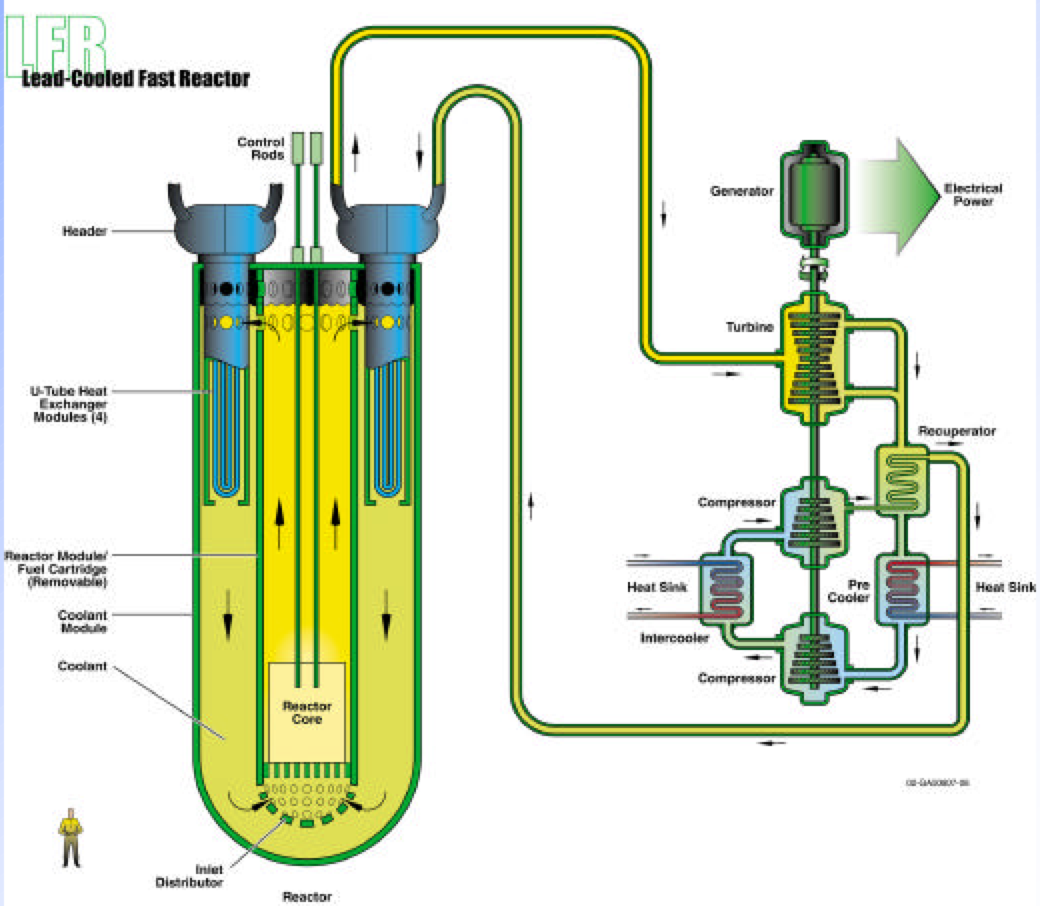
LEAD-COOLED FAST REACTOR (LFR)

Characteristics

- Pb or Pb/Bi coolant
- 550°C to 800°C outlet temperature
- Fast Spectrum
- Multi-TRU recycle
- 50–1200 MWe
- 15–30 year core life

Options

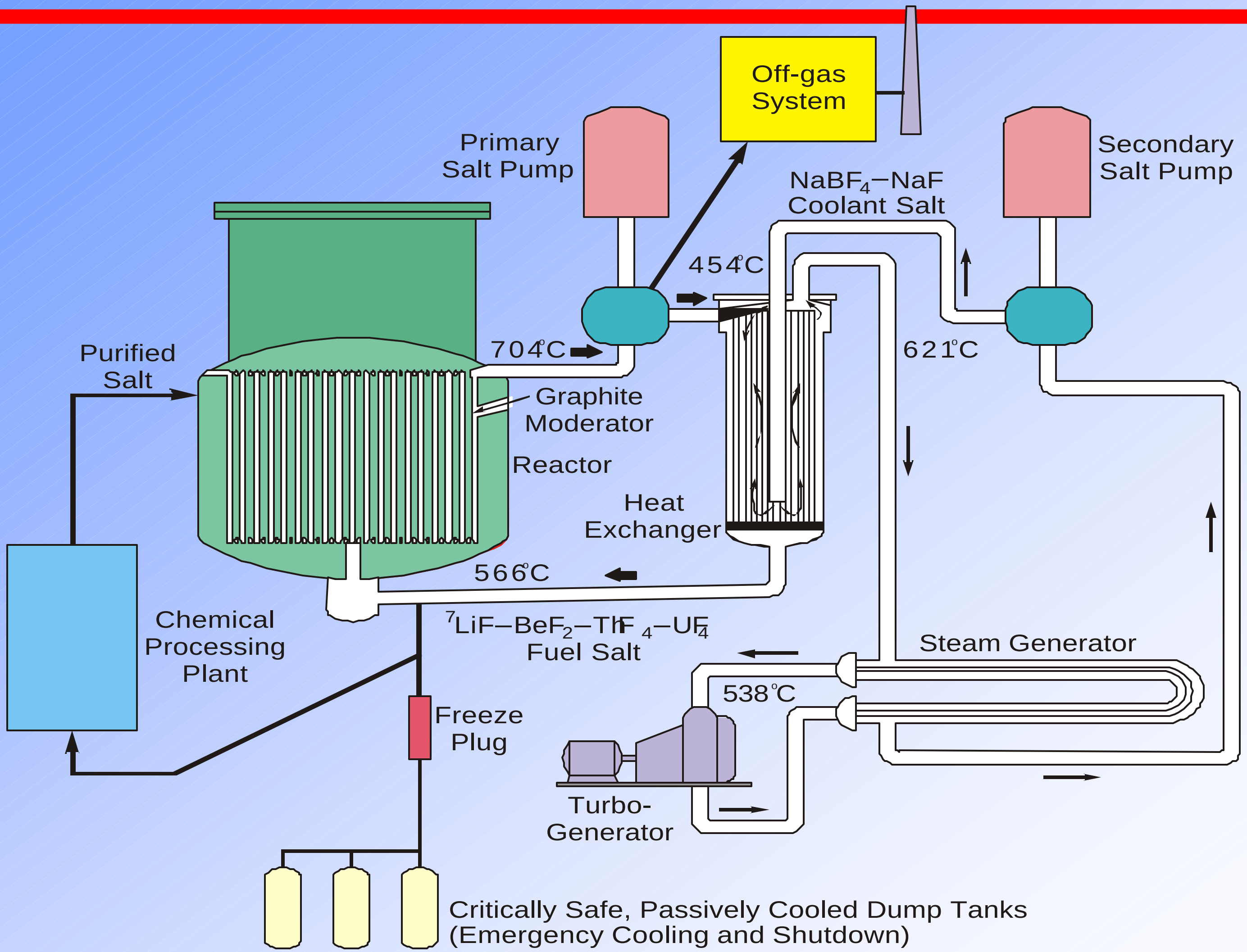
- Long-life (10-30 yrs), factory-fabricated *battery* (50-150 MWe) for smaller grids and developing countries
- Modular system rated at 300-400 MWe
- Large monolithic plant at ~1,200 MWe
- Long-term, Pb option is intended for hydrogen generation – outlet temperature in the 750-800ºC range



CHARACTERISTICS OF LEAD ALLOY COOLANT

- Low Neutron Absorption and Slowing Down Power
  - Allow to open the lattice, increase coolant volume fraction absent a neutronics penalty – pumping requirements also dictate open lattice
  - Facilitates natural circulation
- High Boiling Temperature at Atmospheric Pressure (~1700°C)
  - Unpressurized primary (precludes loss of coolant accident initiator)
  - Margins are available to employ passive safety – based on thermo/structural feedbacks
  - Potential to raise core outlet temperature (~800°C suitable for H_2 production and other process heat missions)
- Non-vigorous reaction with air and water
  - Potential to simplify heat transport circuits
  - Potential to simplify refueling approaches

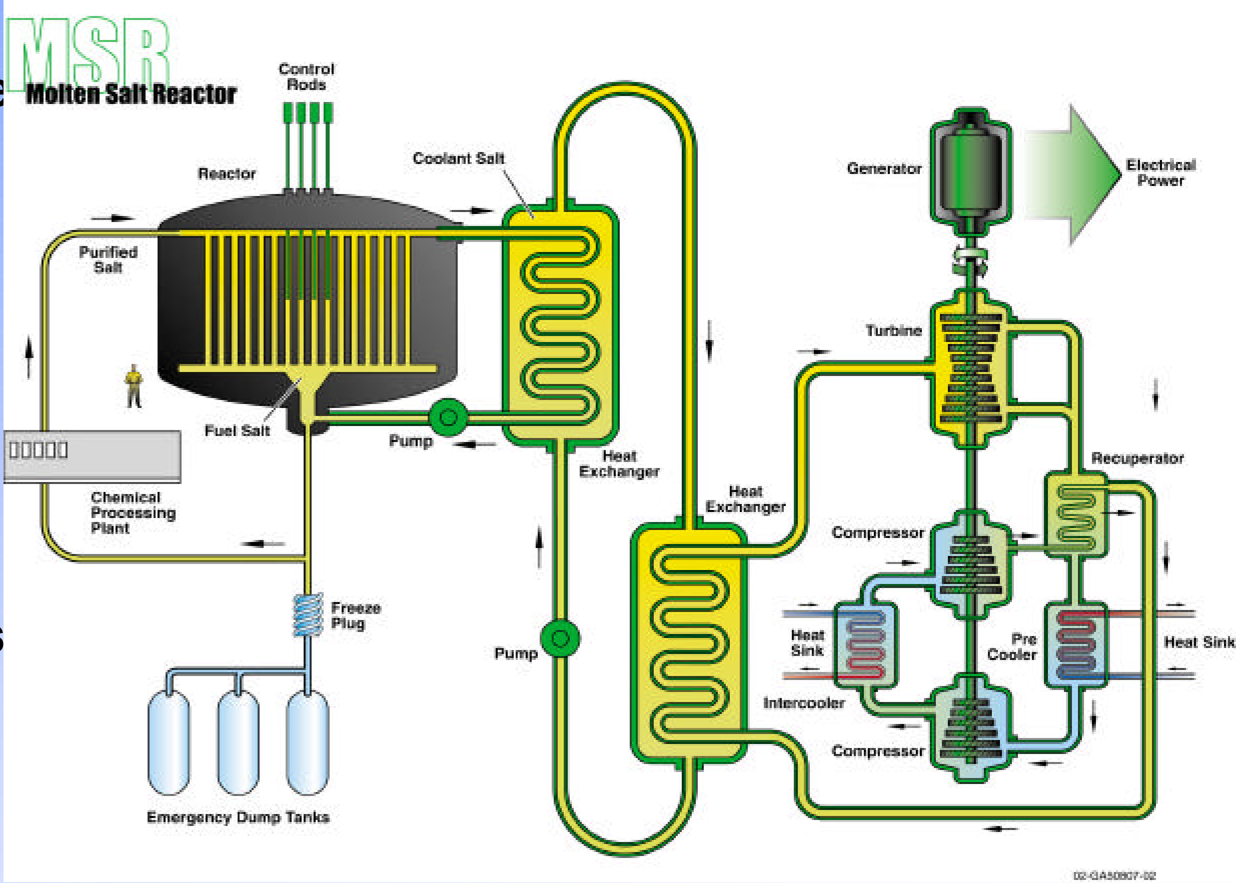
MOLTEN SALT REACTOR (MSR)



MOLTEN SALT REACTOR (MSR)

Characteristics

- Molten fluoride salt fuel
- 700–800°C outlet temperature
- Intermediate heat transport circuit
- ~1000 MWe or larger
- Low pressure (<0.5 MPa)
- Graphite core structure channels flow of actinide bearing fuel



Safety analysis issues

- Modeling of nuclear, thermal, & physio-chemical processes (e.g., FP and MA solubility, noble metal FP plate-out, …)
- Lack of established analysis capabilities
- Regulatory framework not defined