HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 10b

Steam Cycle Power Conversion System

Outline

- Functions and requirements
- SCPCS configuration
- Key SCPCS components
- Steam cycle performance
- Experience

SCPCS Functions and Requirements

- **Key SCPCS functions for normal operation**
  - Transfer reactor heat to secondary circuit
  - Generate electricity for
    - Process user
    - Supply to grid
    - Reactor module house load
  - Provide process steam for end user
  - Support cogeneration
- **Key SCPCS functions for off-normal operation**
  - Residual heat removal during shutdown/maintenance
  - Provide potential residual heat removal path during accidents (non-safety)
- **Specific functions and requirements must be defined for each individual application**

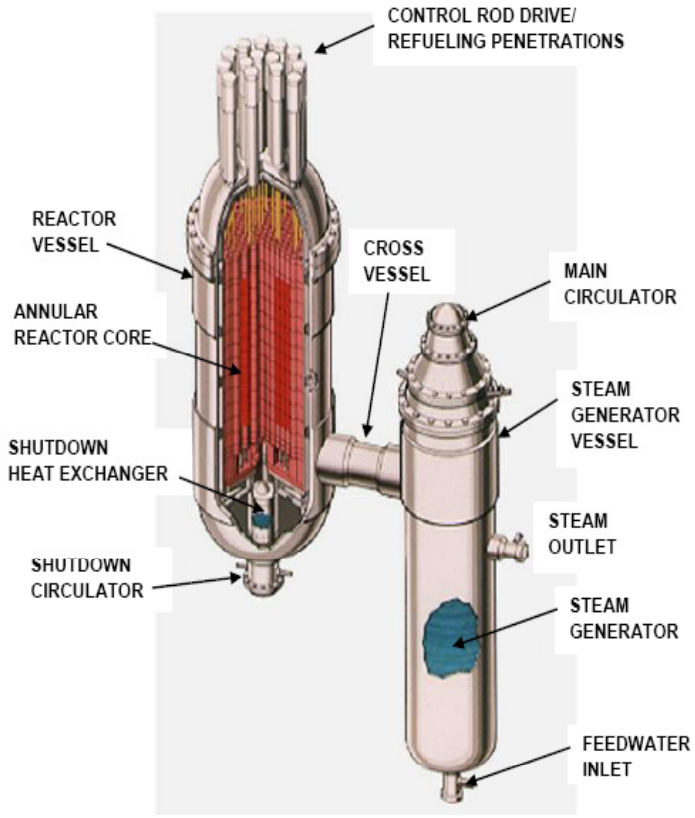
Outline

- Functions and requirements
- SCPCS configuration
- Key SCPCS components
- Steam cycle performance
- Experience

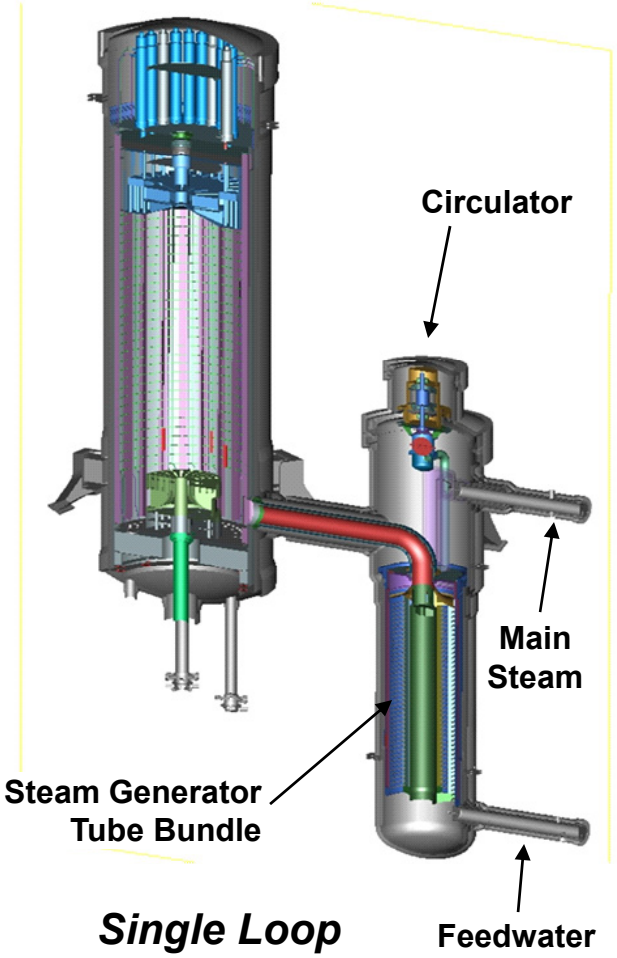
HTGR SCPCS Configuration Addresses Three Main Areas

- Basic steam cycle primary loop
- Basic secondary Rankine cycle
- Generic process steam and cogeneration configuration

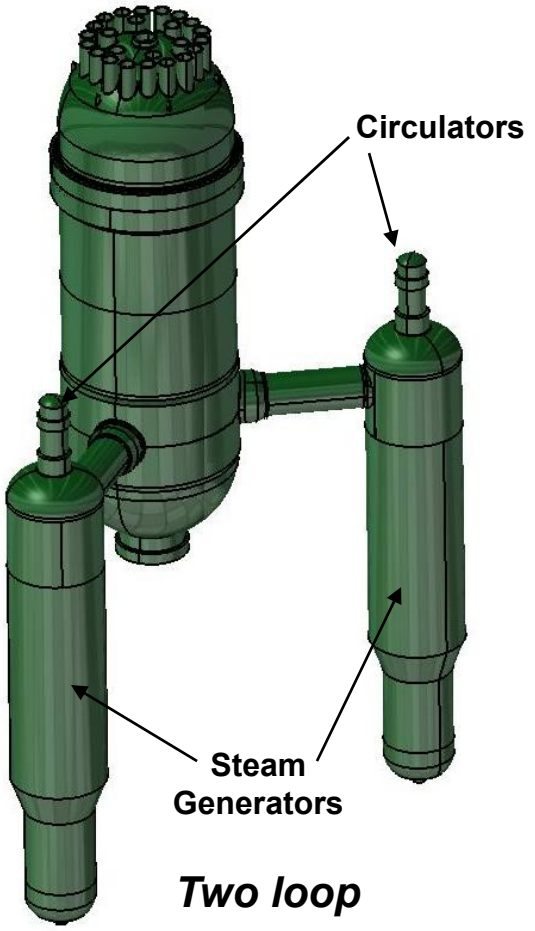
Example Modular HTGR Steam Cycle Primary Loop Configurations



Single Loop (MHTGR)

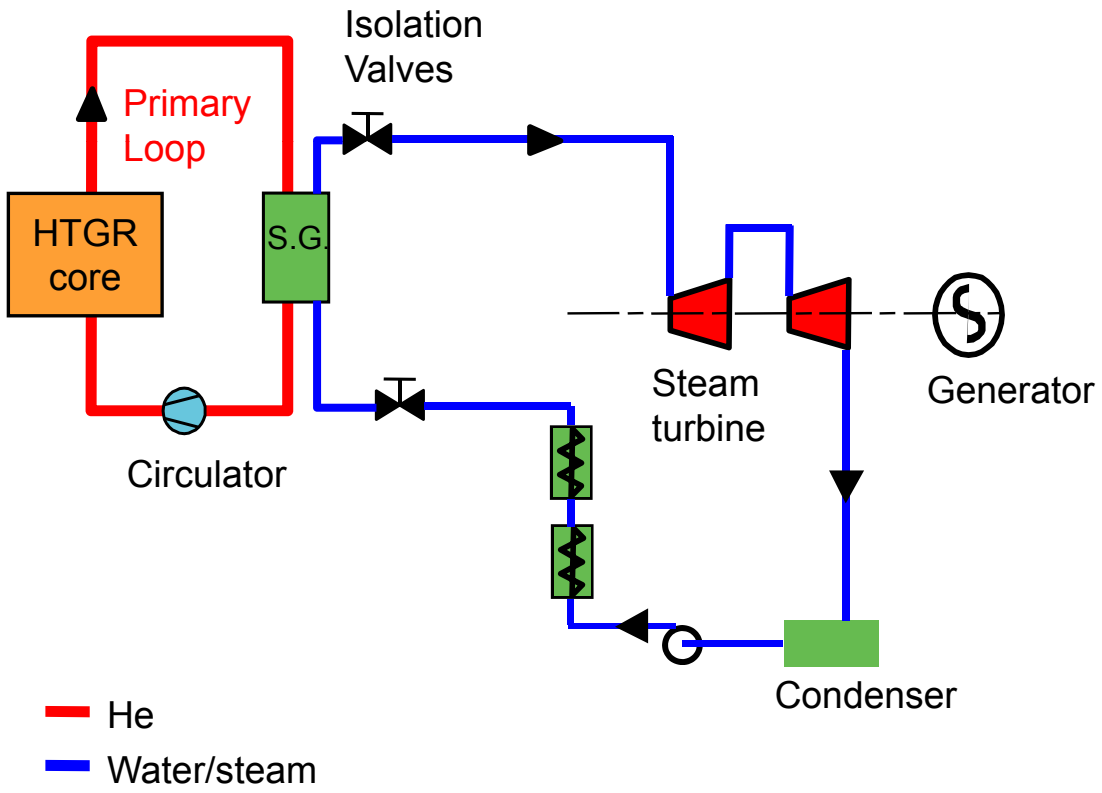


Single Loop (PBMR-CG)



Two loop (AREVA)

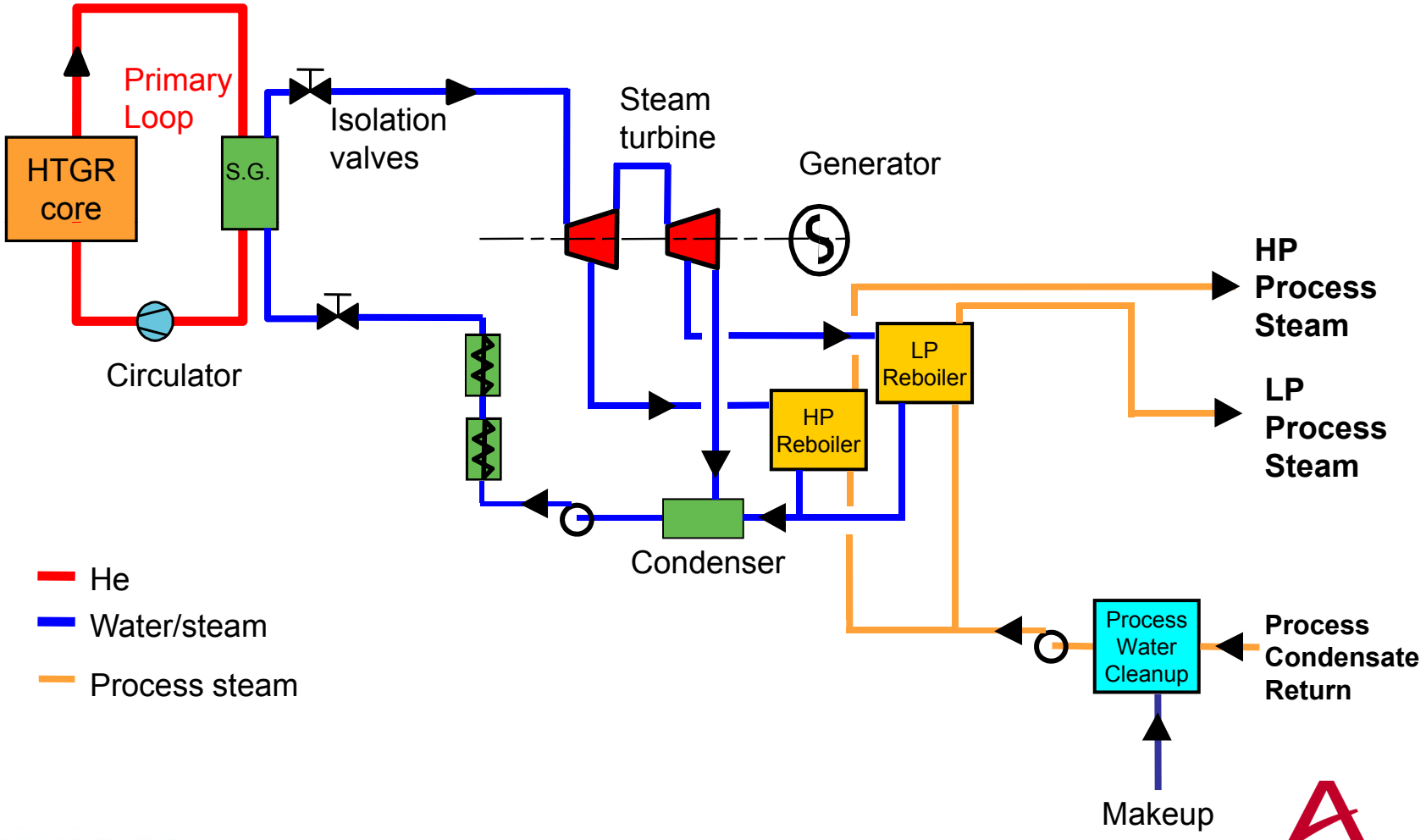
Conventional Rankine Cycle
Primary and Secondary Loop Configuration



Process Steam Supply Considerations

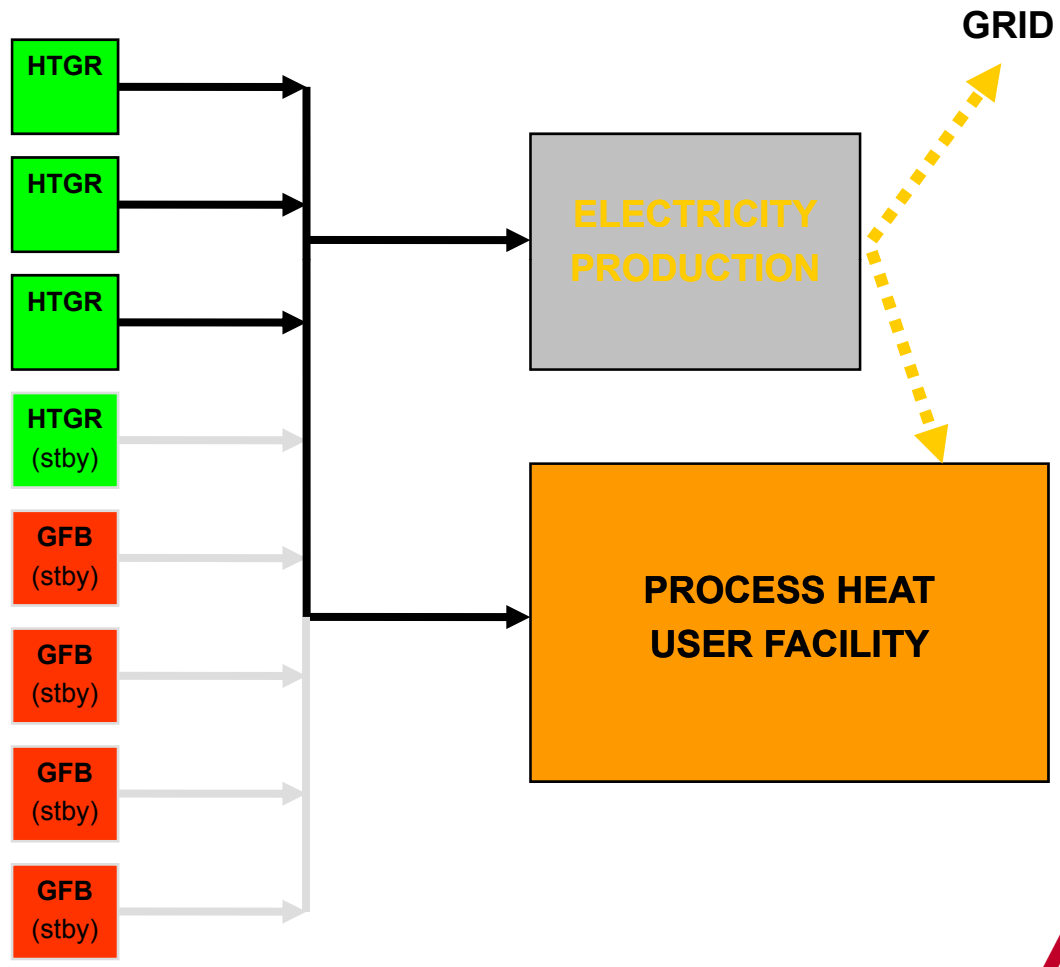
- **Process steam pressure/temperature**
- **Process steam quantity**
- **Operating flexibility**
  - Response to varying user steam demands
  - Flexibility for varying steam vs. electricity production
- **Operational interaction between steam supply units and process users**
- **Process steam contamination concerns**
- **Feedwater quality control**
- **Process steam reliability concerns**
  - Availability
  - Service interruption

Generic Process Steam Cogeneration Configuration



Modular Steam Supply System Conformed to Applications

- **Match to plant steam demand**
- **Optimized for customer priorities**
  - Nominal steam
  - Minimum steam
  - House electric
  - Grid capacity
- **Steam reliability requirements**



GFB = Gas-fired boiler

stby = Module in standby

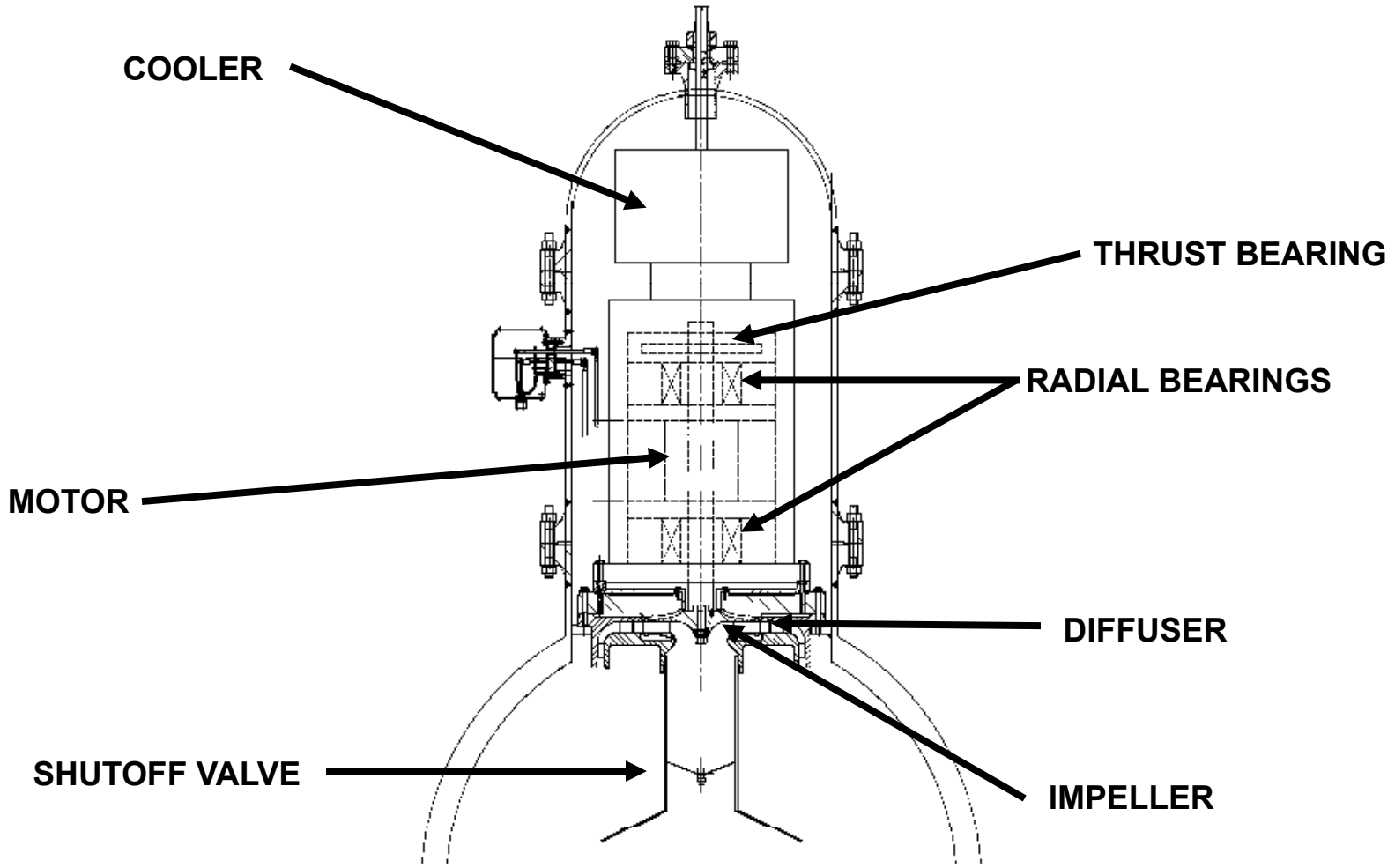
Outline

- **Functions and requirements**
- **SCPCS configuration**
- **Key SCPCS components**
  - Primary circulator
  - Steam generator
  - Steam turbine
  - Condenser
  - Electrical generator
  - Reboiler
  - Steam generator isolation valves
  - Steam/water dump system
- **Steam cycle performance**
- **Experience**

Primary Circulator Considerations

- **Circulator functions and requirements**
  - Circulate primary coolant
    - Normal operation
    - Maintenance
    - Some accidents (when SG is available as heat sink)
  - Variable speed
  - Pressurized and depressurized operation
  - Suppress natural convection and reverse flow
- **Options**
  - Electric drive
  - Submerged motor (most current designs)
  - External motor with shaft seal
  - Bearings (magnetic, oil, other)
  - Impeller type

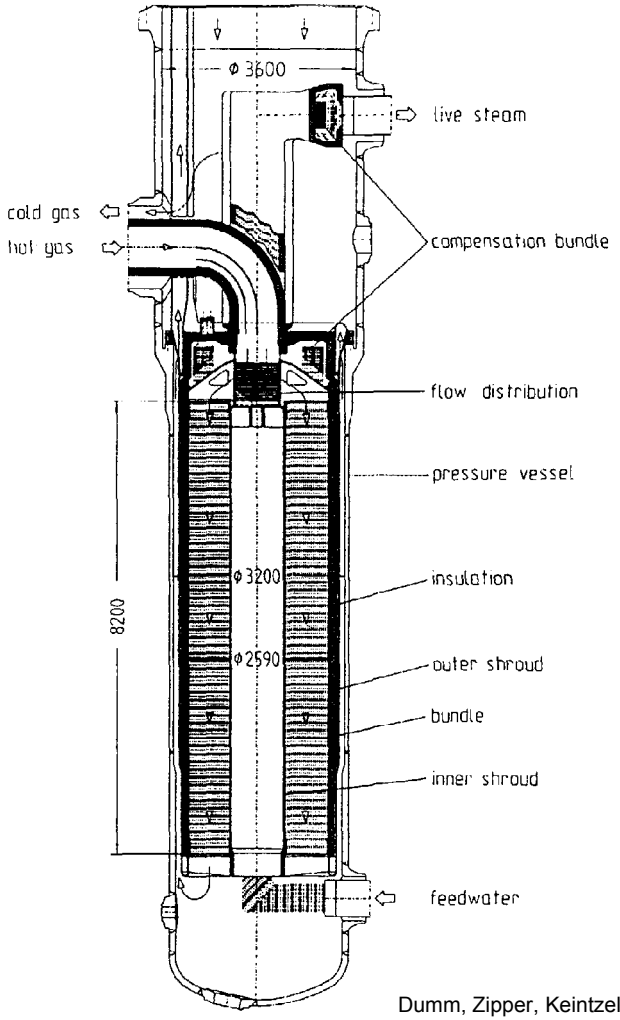
Typical Circulator Arrangement



Steam Generator Considerations

- **Steam generator functions and requirements**
  - Transfer heat from primary to secondary coolant
  - Produce steam at required temperature and pressure
  - Remove decay heat from primary coolant during shutdown and maintenance
  - Remove decay heat from primary coolant during some accidents (when available)
  - Provide primary coolant boundary
  - Control radionuclide releases
    - Circulating activity
    - Role in tritium control
  - Minimize water ingress into primary circuit (together with protection system which initiates isolation, etc.)
- **Options**
  - Heat exchanger geometry
    - Shell and tube HX (water on tube side)
    - Helical coil tube bundle
  - Upflow or downflow
  - Reheat or no-reheat

Typical Modular HTGR Steam Generator Configurations



Dumm, Zipper, Keintzel, 1987

"Uphill" boiling

-helium flows down

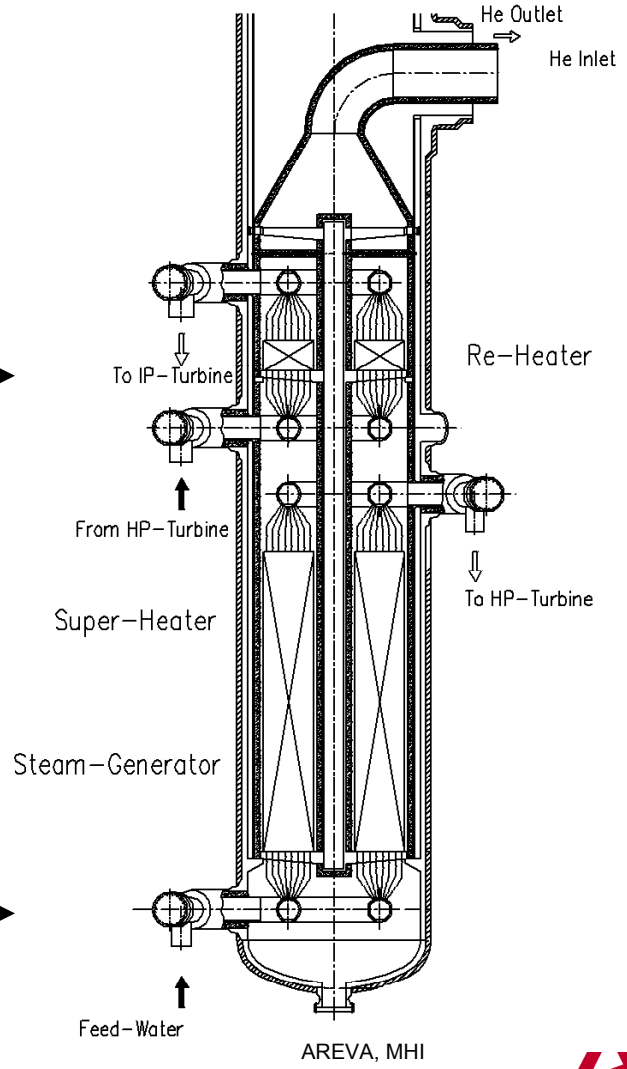
-Water/steam flows up

Reheat▶

◀No reheat

◀Tube sheets

Toroidal headers▶



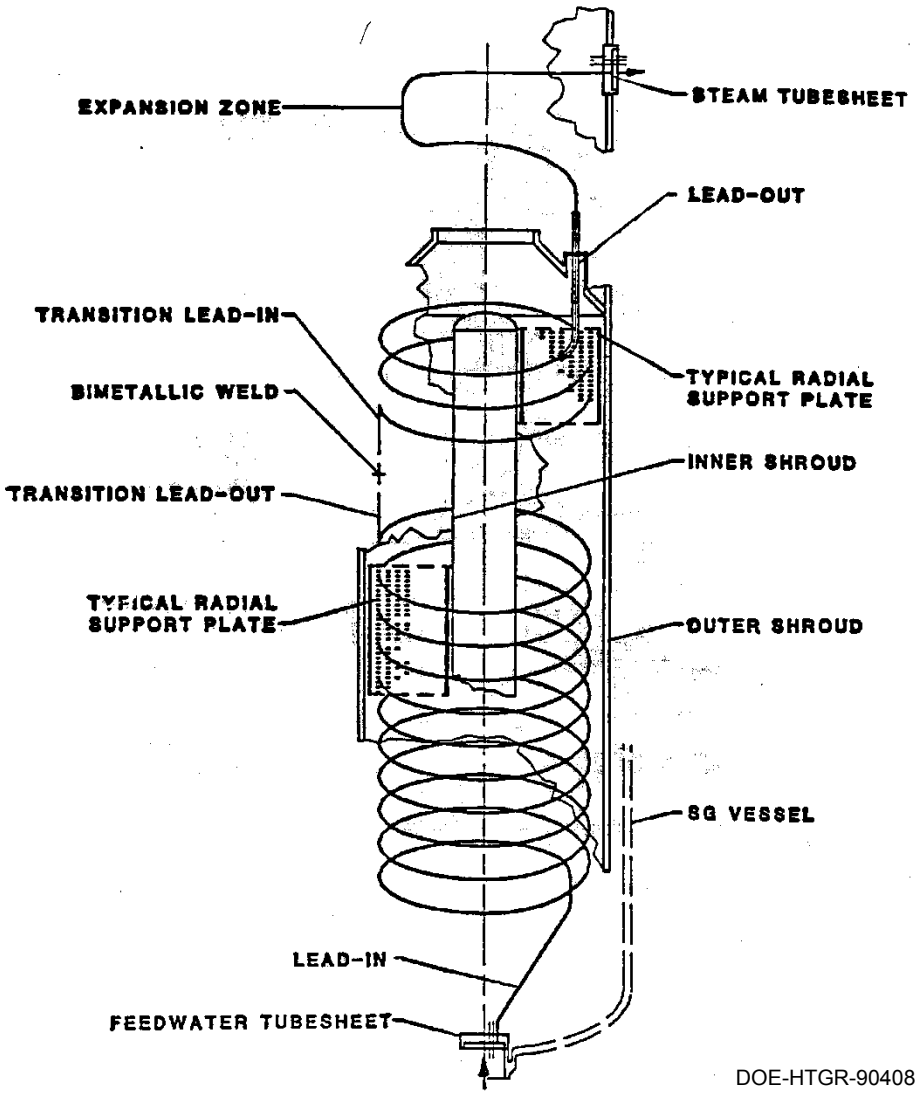
AREVA, MHI

Idaho National Laboratory

AREVA

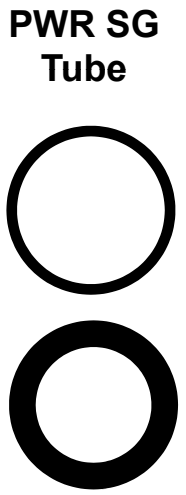
Key Elements of HTGR Steam Generator Technology

- Helical coil tube bundle
- Thick wall tubes
- Radial support plates
- Common tubing materials
  - 2.25 Cr – 1 Mo
  - 800 H



HTGR Steam Generator Reliability Considerations

- **HTGR steam generator applications demand high reliability**
  - HTGR cannot operate with sustained steam/water ingress into primary circuit
- **Steam generator leakage is easily detectable**
- **Steam generator environment is very benign**
  - Inert gas on shell side
  - High purity water on once-through tube side
  - Good thermal margins for materials
- **Steam generator design is very robust**
- **HTGR operating experience has been good**
- **Steam generator leak mitigation capability based on conservative assumptions**
  - Isolation
  - Steam/Water Dump System
  - Robust reactor design



Steam Turbine Considerations

- **Steam turbine functions and requirements**
  - Convert steam energy into mechanical energy
  - Reduce main steam to desired pressure/temperature for process applications
- **Options**
  - Standard fossil plant multi-stage steam turbine
  - Standard fossil plant back-pressure steam turbine

- **No significant considerations unique to HTGR applications**

Condenser Considerations

- **Condenser functions and requirements**
  - Condense turbine exhaust steam
  - Transfer waste heat to circulating water system
  - Collect condensate from turbine, reboilers, etc.
  - Maintain feedwater quality
- **Options**
  - Standard fossil plant condenser

- **No significant considerations unique to HTGR applications**

Electrical Generator Considerations

- **Generator functions and requirements**
  - Convert mechanical energy to electrical energy
- **Options**
  - Standard fossil plant generator
  - Air-cooled or hydrogen-cooled

- **No significant considerations unique to HTGR applications**

Reboiler Considerations

- **Reboiler functions and requirements**
  - Produce process steam from secondary steam heat
  - Pressure boundary between secondary and process steam loops
  - Minimize transfer of radionuclides from secondary loop to process steam
  - Minimize transfer of impurities from process feedwater to secondary loop
- **Options**
  - Standard process industry equipment
  - Wide variety of potential configurations depending on application
    - Shell and tube HX
    - Plate HX
    - Multi-stage or hybrid HX

Steam/Water Isolation Valve Considerations

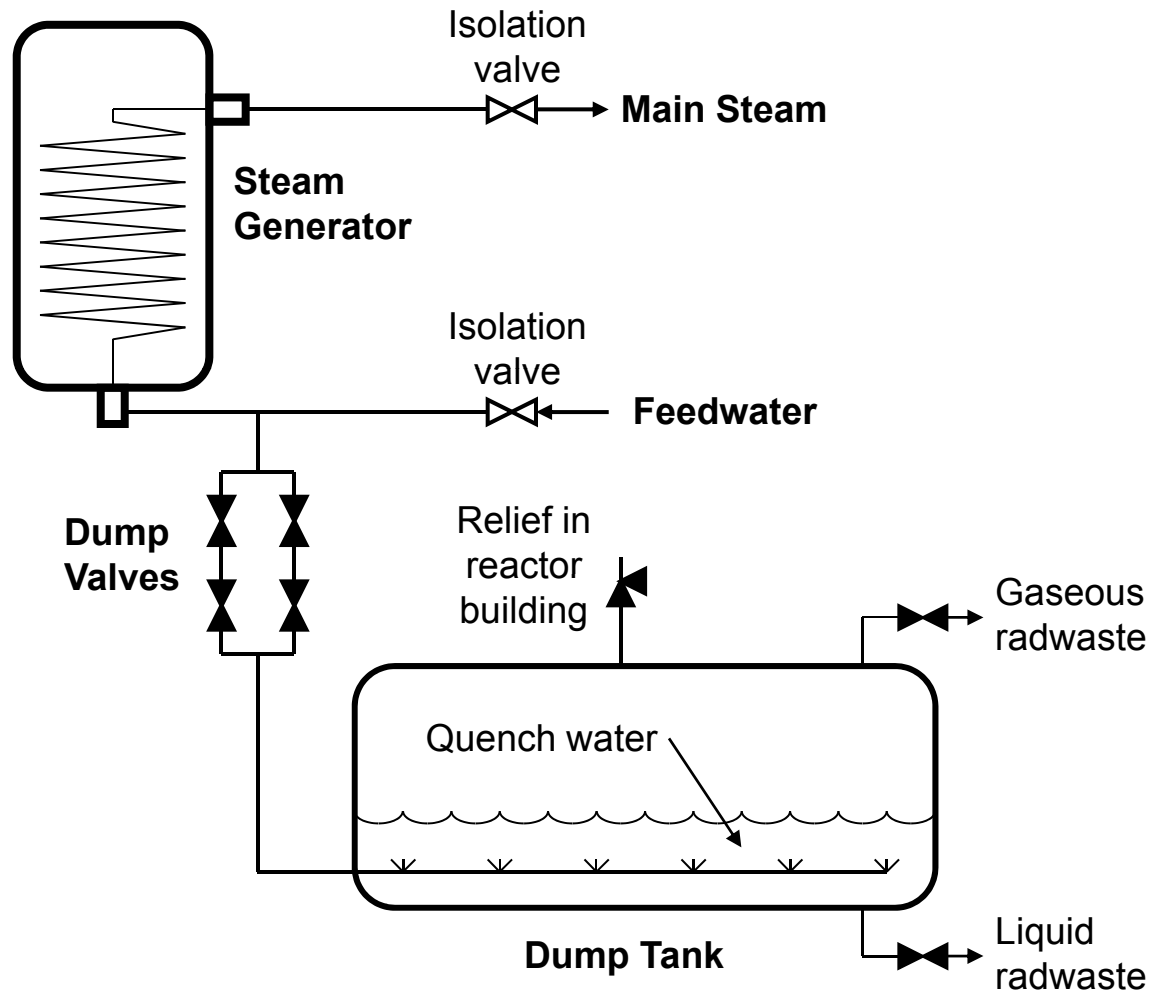
- **Isolation valve functions and requirements**
  - Separate SG from feedwater system for maintenance
  - Separate SG from main steam system for maintenance
  - Limit water ingress in case of steam generator leak
  - Maintain primary coolant boundary in event of steam generator leak
- **Options**
  - Standard industry equipment

Steam/Water Dump System Considerations

- **Isolation valve functions and requirements**
  - Limit water ingress in case of steam generator leak
  - Accept water inventory from steam generator and feedwater nozzle
  - Maintain primary coolant boundary in event of steam generator leak
- **Options**
  - Standard industry components

Steam/Water Dump System Configuration

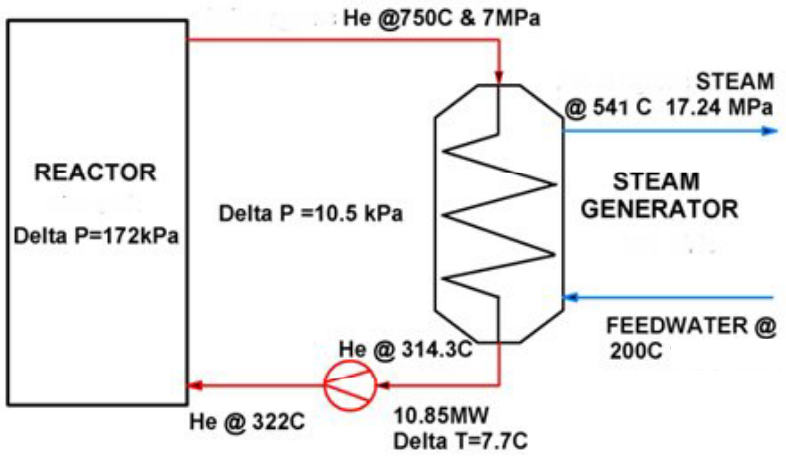
- **Dump valves actuated by protection system**
  - High moisture
- **Driving force**
  - Gravity
  - Steam pressure



Outline

- Functions and requirements
- SCPCS configuration
- Key SCPCS components
- Steam cycle performance
- Experience

Sample HTR Steam Cycle Operating Conditions



Reactor Outlet/SG Inlet Temp	750°C
SG He Outlet Temperature	314°C
Reactor Inlet Temp	322°C
SG Water Inlet Temperature	200°C
SG Steam Outlet Temperature	541°C
Steam Outlet Pressure	17.2 MPa

"Modern" fossil steam conditions (e.g., pulverized coal)

Outline

- Functions and requirements
- SCPCS configuration
- Key SCPCS components
- Steam cycle performance
- Experience

Overall Steam Cycle Experience

- **Most past HTGRs used conventional steam cycle power conversion system**
- **HTGR steam cycle conditions and hardware are similar to previous generation fossil-fired Rankine systems (e.g., pulverized coal)**
- **Steam cycle power generation is mature technology**
  - Used successfully around the world
- **Process steam distribution and use has been widely used for many years**
- **Remaining issue is coupling of HTGR steam system to process heat application**
  - SC/C 2240 MWt (HTGR concept)
  - Midland (PWR)

HTGR Circulator Experience

- **Good circulator performance in Magnox, AGRs, and HTGRs**
- **Except for bearing lubricant leakage into primary coolant**
  - Oil in Peach Bottom-1
  - Ingress from Fort St. Vrain water-lubricated bearings
- **Experience base for current circulator concepts**
  - Aerodynamic experience adequate
  - Magnetic bearing experience
    - Industry experience adequate for moderate size machine
  - Submerged motor experience available
  - Power supply industrially available
  - Electrical penetration experience available
- **NGNP circulator will be FOAK**
  - Vendor experience adequate for required extrapolation
  - Circulator of required size within experience base
  - Air testing of prototype would be performed

HTGR Steam Generator Experience

- **Past HTGRs have used steam generators in primary circuit**
- **HTGR steam generators have performed well**
  - Good thermal performance
  - Few leaks
- **Many years of successful AGR steam generator experience**
  - Early failures attributed to design and infant mortality
  - Experience improved over time
  - Overall failure rates modest
- **Relevance of PWR steam generator experience**
  - HTGR environment much more benign
  - Essentially no shell side corrosion or deposits
  - HTGR steam generators more robust than PWR steam generators
  - PWRs still being built

Rankine Cycle Component Experience

- **Steam turbine**
  - High pressure multi-stage steam turbines in wide use around the world
  - Back pressure and extraction turbines used in many process applications
  - Actual turbine for specific HTGR cogeneration application will likely be custom ordered based on mature technology
- **Condenser**
  - Broad experience exists
  - Size consistent with numerous existing applications
- **Electrical generator**
  - Broad experience exists
  - Size consistent with numerous existing applications

Reboiler Experience

- **Reboiler is new component for HTGR applications**
- **Reboilers used extensively in process industries**
  - Separate process streams
  - Recover excess heat from process streams
  - Reevaporate condensed process fluids
- **Existing units are tailored to the specific applications**
- **HTGR process steam supply reboilers will be customized units based on established technology**

Summary

- **Steam cycle power conversion system must**
  - Transfer heat from primary circuit
  - Generate electricity for internal and external use
  - Provide process steam at necessary conditions
- **Past HTGRs used conventional steam cycle successfully**
- **HTGR steam cycle technology is comparable to past generation of coal-fired steam cycle systems**
- **Planned system is based on solid technology experience**