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Framatome Steam Cycle High-Temperature Gas-Cooled Reactors

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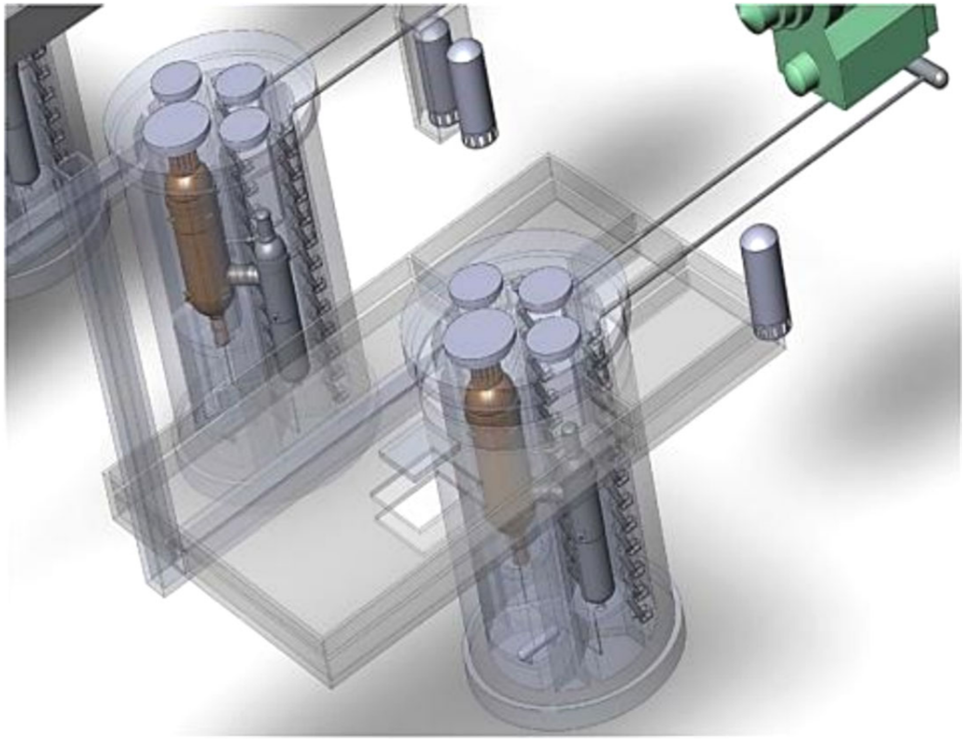
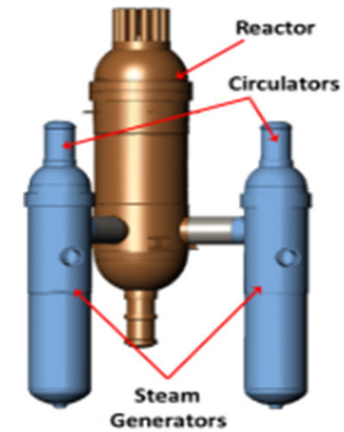
Topics

- Framatome Steam Cycle HTGR Design
- Resource Utilization – Fuel Cycle Flexibility
- Advanced Fuel Cycle Options and Nuclear Waste Management/Disposal
- Nuclear Security and Proliferation Resistance
- Passive & Inherent Nuclear Safety Features
- Market Benefits of the SC-HTGR
- Commercialization Challenges



Framatome History of HTGR Development

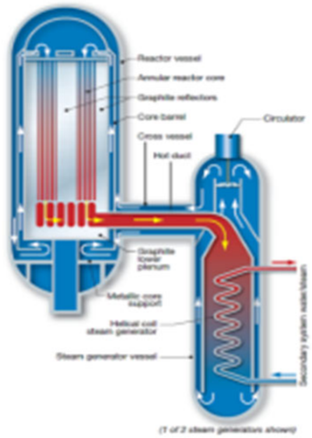


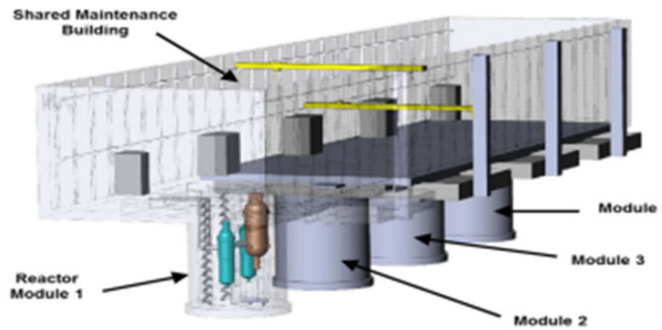
- **1960s, 70s, and 80s**
  - Framatome GmbH – Pebble Bed HTGRs
    - AVR – 46 MWth test reactor
    - THTR – 750 MWth cogeneration reactor
    - HTR-Module – 200 MWth (beginning of modular HTGR development)
- **1990s and early 2000s**
  - GT-MHR – 600 MWth prismatic core, Brayton Cycle.
  - Collaboration with Russian Federation and General Atomics
- **Mid to Late 2000s**
  - **ANTARES** Project - 600 MWth prismatic core, Indirect cycle with combined cycle gas turbine generation
  - **US DOE NGNP** project - Modified ANTARES design
- **Late 2000s to Present**
  - **Steam Cycle – HTGR reference plant**
    - **4 x 625 MWth, prismatic core, cogeneration of high temperature process steam and electricity**
    - **Optimized for passive safety and lowest cost of energy**
  - Scalability of reference concept provides variants for smaller markets (all use the same fuel)

625 MWth reference	**54 MWth** remote site
315 MWth single SG	**10 MWth** Micro-HTGR
180 MWth EU steam only	**7 MWth** mobile micro HTGR

Framatome 625 MWt SC-HTGR
A modular High Temperature Gas-cooled Reactor

- **Nominal core power 625 MWt / module**
- **Output**
  - **All electric mode: 272 MWe / module (43.5% net)**
  - **100% process heat mode: 630 MWt / module**
- **Reactor module configuration**
  - **Helium coolant**
  - **Graphite moderator**
  - **TRISO fuel**
  - **102 column prismatic block annular core**
  - **Two loop (2 steam generators per reactor module)**
- **Reactor conditions**
  - **Core inlet/outlet: 325°C / 750°C**
  - **Primary coolant pressure: 6 MPa**
  - **Reactor flow rate: 282 kg/s**
- **Nominal steam conditions**
  - **566°C, 16.7 MPa**





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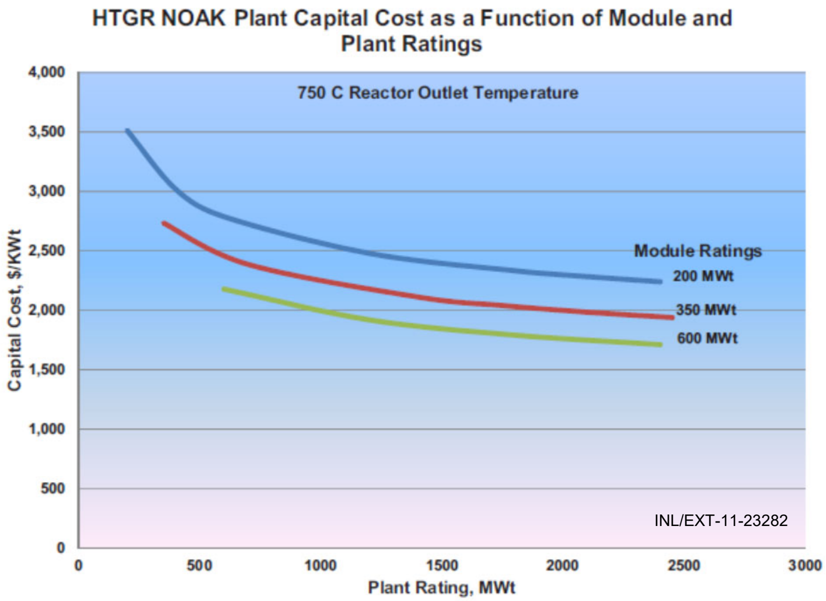
Why Did Framatome Select the 625 MWt SC-HTGR?

- Minimized technical risks to allow completion of the FOAK demo plant in ~2030
- High temperature steam satisfies large portion of the process heat market
- 625 MWt prismatic HTGR has lowest unit energy cost
- Excellent safety characteristics
  - Safety does not require AC power
  - Safety does not require reactor coolant
  - Safety does not require operator action
- Excellent investment risk profile
  - Plant can be restarted after any Design Basis Accident
- SC-HTGR is the most flexible and economical modular HTGR for near-term deployment
- Provides path for improving technology incrementally for future higher temperature process heat needs and industrial scale hydrogen generation

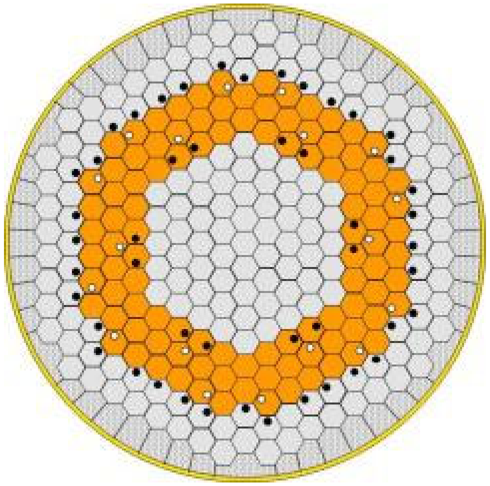


Reference SC–HTGR Fuel Cycle

- **Reference cycle chosen for rapid deployment to address most pressing sustainability needs**
- **UCO kernel TRISO coated particle fuel is best in class for SC-HTGR and VHTRs**
  - HA-LEU (14.5% U-235)
  - Low power density provides passive safety
  - High burnup (160,000 MWD/MT) provides efficient resource utilization
- **Cycle length**
  - 18-24 month refueling interval
  - One half of core replaced at each refueling outage
  - Automated refueling – precise control of each element location in reactor (and in storage)
- **Once-through disposal options**
  - Full block disposal
  - Separate compacts from graphite blocks

Prismatic HTGR Characteristics Provide Unique Fuel Cycle Flexibility

- **Inherent HTGR prismatic annular core characteristics**
  - Decoupling of coolant, moderator, and fuel geometries – increased core design flexibility
  - Graphite moderator yields more intermediate energy neutrons
  - Longer prompt neutron lifetime – increased control stability for cycles with reduced delayed neutron fractions
  - Lower absorption in moderator provides more neutrons for non-fission events
- **Flexible core design**
  - Allows segregation of multiple fuel types in single fuel element
  - 3-D fuel shuffling of fuel provides additional level of core optimization
- **Improved cycle options**
  - Increased Pu and actinide content possible (up to 100% Pu)
  - Deep Burn
  - Thorium cycles



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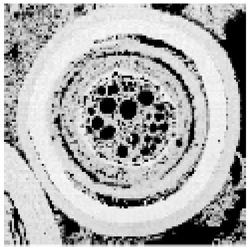
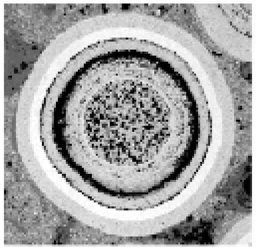
Long-Term Fuel Cycle Flexibility

- **Alternate cycles provide benefits for long-term sustainability**
  - Improved resource utilization
  - Reduce HLW quantity
  - Reduce waste longevity
- **Other TRISO fuel options are available**
  - Plutonium, Thorium, MOX, actinides
  - Plutonium and thorium particle fuels suitable for HTGR have been demonstrated successfully
- **Recycling options**
  - Actively developed in 1980s by General Atomics and ORNL
  - Mechanical crushing to expose kernels (chemical and electrical options also available)
  - Crushed kernels feed to national recycling scheme



Pu Oxide
747,000 MWdays/tonne
>95% Pu-239, and
>65% all Pu transmuted



Th-Pu Oxide
183,000 MW-days/tonne
>95% Pu-239 Transmuted

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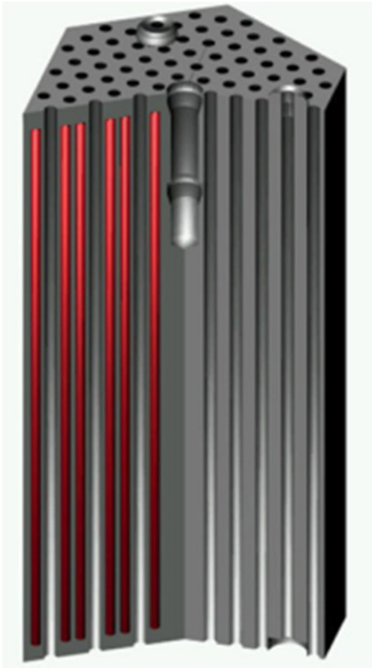
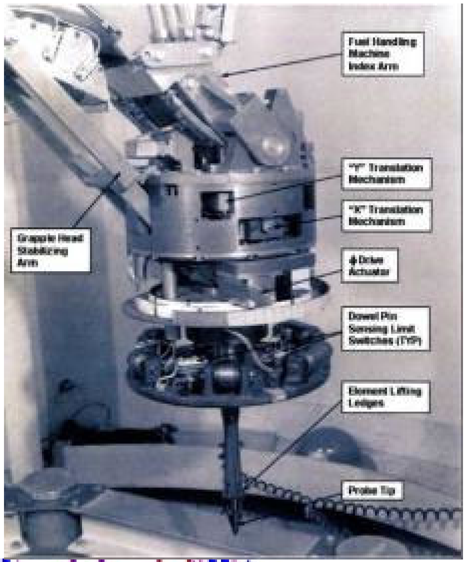
Multiple Disposal Options for Prismatic Block Fuel

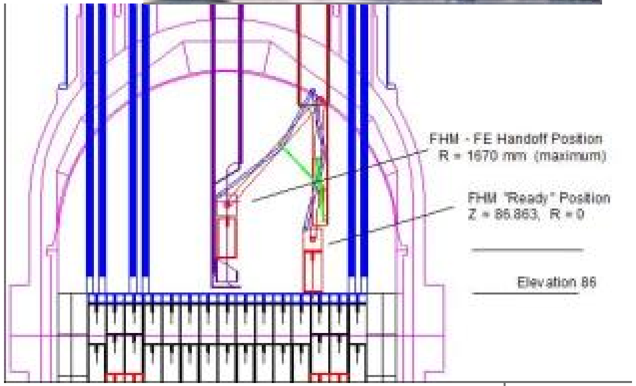
- **TRISO fuel is well suited for long-term storage and disposal**
  - Stable in both interim storage and permanent disposal environments
- **Preferred disposal path depends on selected fuel management strategy and repository options and limitations**
- **Options for block disposal**
  - Full block disposal
  - Compact separation and disposal to minimize volume
- **Fuel recycling**
  - Required industrial technologies have been demonstrated
- **Options for graphite disposal**
  - Direct disposal of reflector blocks and defueled fuel elements
  - Recycle crushed blocks as feedstock for graphite production
  - Potential reuse



Automated Prismatic Core Refueling Based on Established Technology

- **Basic refueling hardware is based on Fort St. Vrain Refueling Machine**
  - Operated successfully during FSV refueling campaigns
- **Coupled with more advanced automation and control technology available today**
  - Optimization of movement sequences
  - Preprogrammed handling sequence minimizes refueling time
- **Full operator oversight is maintained**
  - Direct display of current and pending fuel movements
  - Video record of all fuel placements
- **Automation eliminates potential for fuel loading errors**
  - Movements are preplanned and uploaded prior to refueling campaign
  - All movements are monitored in real time
  - Full log of all movements is automatically generated





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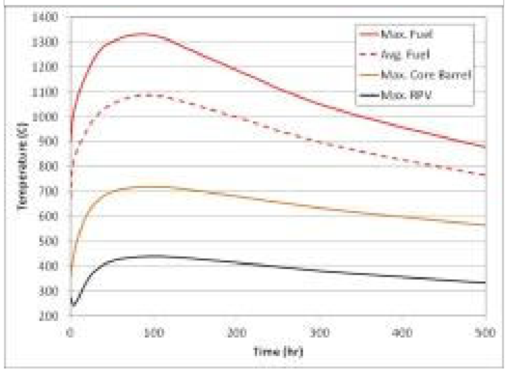
Security and Proliferation Resistance

- **Underground (silo) installation with limited need for human access**
- **Graphite fuel blocks**
  - Fuel elements are too large for clandestine theft (~ 300lbs per block)
  - Individual fuel element inventory is limited
  - Bar-code accountability system
  - Fuel is fully burned before removal from reactor
  - Spent fuel isotopic makeup is unattractive for diversion
  - TRISO fuel requires industrial recycling technology to retrieve usable material
- **Remote semi-automatic refueling**
  - Operator oversight and video surveillance
  - Fuel cannot be removed mid-cycle without reactor shutdown and depressurization

Passive and Inherent Safety Features

Nominal DLOFC response



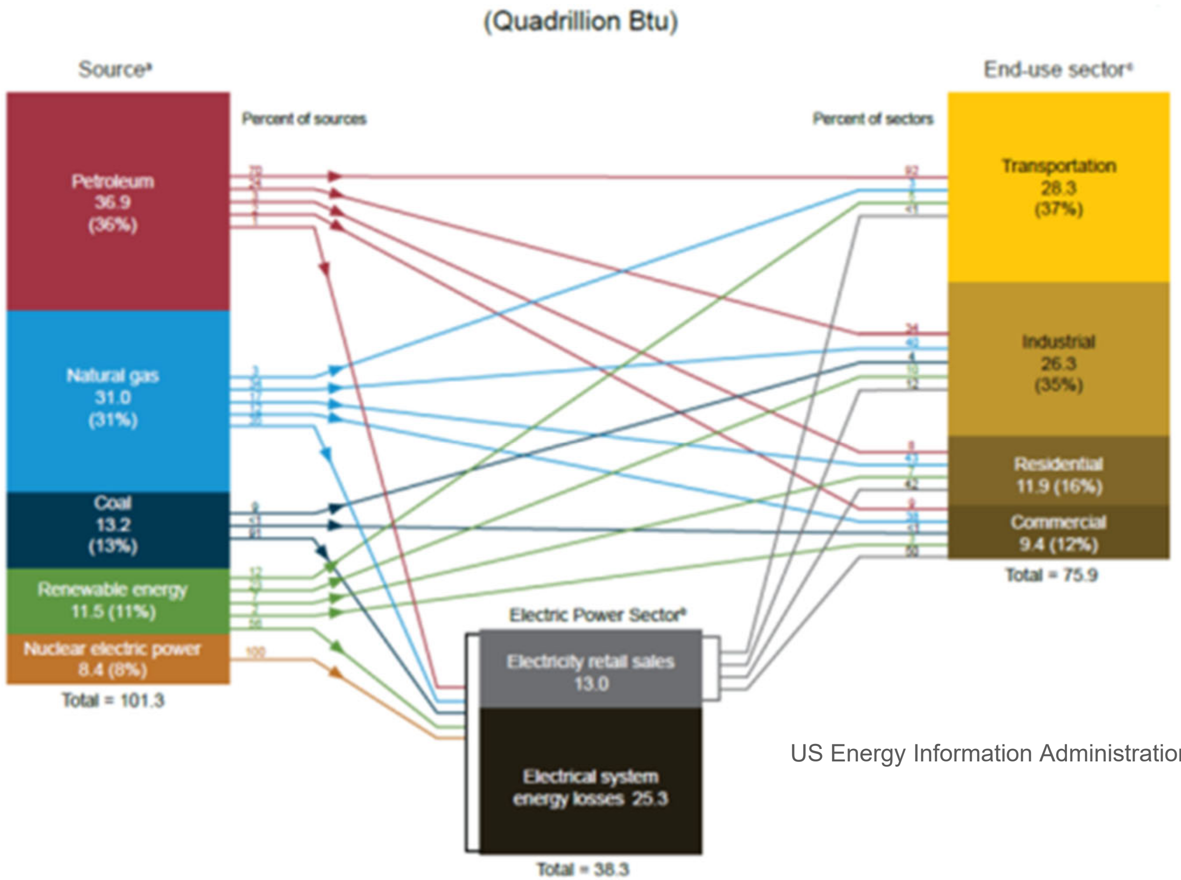
- **TRISO coated particle fuel proven radionuclide retention characteristics**
  - Fuel temperatures well below fuel failure limits for all accidents
- **Passive decay heat removal**
  - Low power density (~6 w/cc) allows passive decay heat removal
  - Very large thermal inertia of graphite core
  - Passive Reactor Cavity Cooling System (water-based natural circulation)
  - Continuous RCCS operation (no need for activation, performance continuously monitored)
- **Multiple reactivity control and shutdown systems**
  - Control rods, absorber elements, and high negative reactivity coefficient
- **Inert primary coolant**
  - Does not react chemically or neutronically
- **No reliance on powered safety systems**

Design Decisions Support Near-Term Deployment

• Fuel (UCO kernel TRISO coated particle)	AGR irradiation data and NRC topical
• Core Graphite (SGL-Carbon NBG-17, Toyo-110)	AGC characterization, ASME Sec. III Div. 5
• Vessels (SA-508/533)	ASME Section III, (no SS cladding required)
• Reactor Internals (Alloy 800H, Graphite)	ASME Section III Div. 5
• Steam Generator (Alloy 800H, 2.25Cr-1Mo)	Helical coil tubes (He-to-steam), TEMA
• Instrumentation and Controls	IEEE Standard (analog or digital)
• Decay Heat Removal (RCCS)	Steel panels (ASME Section III)
• Circulator (submerged motor, magnetic bearings)	ASME Section III (housing)
• Reactor Building (concrete)	ACI standard
• Refueling Machine	Semi-automated refueling

Market Demand

- Demand for carbon free process heat exists today
- The process heat market is solely powered by fossil fuels (mainly natural gas)
- SC-HTGRs can replace fossil fuels in the process heat markets
- SC-HTGRs can be integrated with intermittent energy sources and thermal storage systems in an integrated energy park to supply cost efficient electricity and process heat.



US Energy Information Administration

Process Heat

HTGRs can generate heat at higher temperatures necessary for certain industrial processes

Potential to Displace Fossil Fuels

HTGR technology is the near-term energy source capable of displacing the use of fossil fuels for high-temperature process heat and/or electricity generation while emitting almost no CO_2.

- Process heat and electricity can be supplied for petrochemical refining, chemical processes and extraction, upgrading of bitumen from oil sand and shale, replacing or supplementing premium fossil fuels.
- Low CO_2 emissions enable premium fossil fuels to be used as feedstock for higher-value products, such as chemicals and synthetic fuels that add multiples of gross returns instead of simply burning as fuel.

Near-Term Market Potential

- North America/USA:

  250-500°C = 75,000MWt (or 150-300 reactors)
- Mostly Petroleum products:

  500-700°C = 65,000MWt (or 130-260 reactors) (Petroleum + Ammonia). Easily achievable today.

Allows flexibility of operation, switching between electricity and process heat

Temperatures required for various industrial processes

Cogeneration of Electricity & Steam

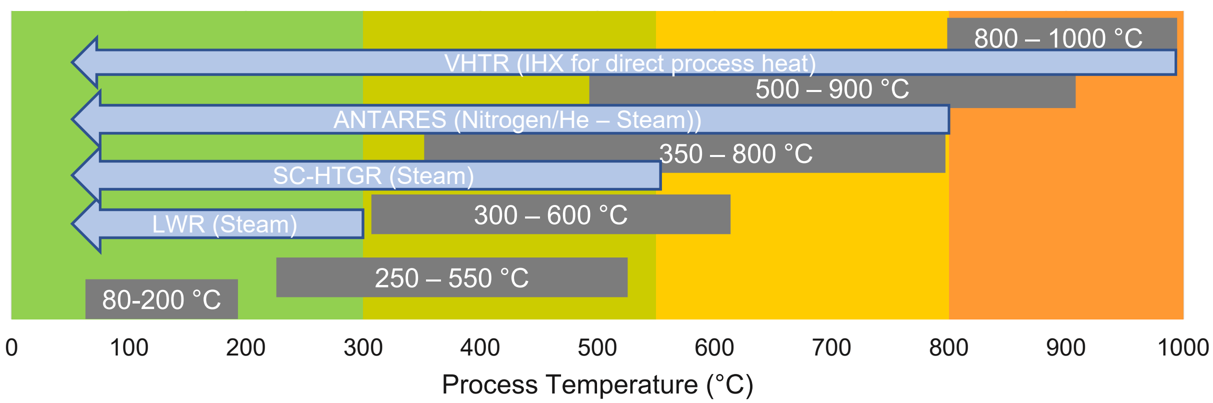
HTSE, Thermo-Chemical Hydrogen -- >>>>>>>
Production, Coal Gasification -- >>>>>>>>>>>>

Steam Reforming of Natural Gas Biomass -- >>
Hydrothermal Gasification -- >>>>>>>>>>>>>>

Oil Shale & Oil Sand Processing -- >>>>>>>>>

Petroleum Refining -- >>>>>>>>>>>>>>>>>>

Ethanol Concentration Seawater -- >>>>>>>>>
Desalination District Heating -- >>>>>>>>>>>



SC-HTGR is Optimized to Provide Maximum Benefit to the Overall Energy Mix in the Near-Term

- **Process steam market exists now**
  - **Largest segment of the process heat market**
  - **Depends entirely on fossil fuels**
  - **Requires no modification of existing chemical plants to use high temperature steam from SC-HTGR**
- **Market for direct very high temperature heat is longer-term**
  - **Smaller than high temperature steam market**
  - **More fragmented – requires customized interface for different applications**
  - **Existing chemical processes require further development for integration with heat from very high temperature reactor**
- **Reactor technology similar between steam cycle HTGR and VHTR**
  - **Largest VHTR challenge is high temperature energy transfer interface**
- **Focusing on steam cycle HTGR provides best short-term and long-term solution**
  - **Partitioning risk between HTGR and VHTR projects reduces risk for each project**

Required Development	SC-HTGR	Future VHTR
Fuel Qualification	X	
HTR Siting	X	
HTR Licensing	X	
Process Interface Issues	X	
Safety Case Validation	X	
Very High Temperature Materials (metals, ceramics)		X
IHX Development		X
Very High Temperature Process Interface		X

Dual Market Demand

Electricity and Process Heat

Process Heat is 40% of total energy market (same as electricity).

Process Heat is 100% dependent on fossil fuels.

LWRs are only relevant for low temperature process heat.

Wind and solar cannot displace fossil fuels from PH market.

HTGRs are the alternative to fossil fuels in this market.

- Required temperature range.
- Required risk profile for collocation with $20B chemical plant (both safety and investment risk).

Cost advantage of CO2-free process heat production

Carbon tax estimate $105/ton CO2 by 2028

For every $10 per ton of CO2, the cost effectiveness of the HTGR improves by $0.50/MMBTU equivalent natural gas price.

A $50 price per ton of CO2 improves the competiveness of the HTGR from $6/MMBTU to $3.50/MMBTU

Ref: gas is currently $2.80/MMBTU

The North American potential market for >300 °C steam
(600 MWt modules assuming conservative market penetration*)

Co-generation
Petrochemical, refinery, fertilizer/ammonia plants and others
75 GWt (~125 modules)

Oil Sands / Oil Shale
Steam, electricity, hydrogen & water treatment
18 GWt (~30 modules)

Hydrogen Merchant Market
36 GWt (~60 modules)

Synthetic Fuels & Feedstock
Steam, electricity, high temperature fluids, hydrogen
249 GWt (~415 modules)

IPP Supply of Electricity
110 GWt (~180 modules)

*Based on NGNP Program and Framatome studies.

Going forward ----
Challenges and keys to a successful deployment

- **Sustainability demands a non-fossil process heat alternative**
- **The competition for our reactor is the abundance of domestic low cost natural gas without a carbon penalty**
- **Wind and solar alone cannot supply this market**
- **The financial incentives for nuclear energy is needed to promote entry into the process heat market**

- **Near-term goal for SC-HTGR development → Focused studies to:**
  - **Integrate with industrial process heat systems**
  - **Integrate with other CO_2 free energy sources and storage schemes**
  - **Key system design studies**
  - **Further optimize the design to reduce CAPEX and OPEX**

Commercialization Challenges

To succeed in the future process-heat and power-generation markets, SC-HTGR and other advanced reactors will need:

- **Financial incentives** to drive customers towards this clean energy solution (e.g., investment tax credits, production tax credits, carbon tax, electricity market recognition of nuclear's clean-energy value)
- **Qualified TRISO fuel,** starting with completion of the TRISO qualification program
- **High-level waste management solution** (recycling, interim storage, permanent disposal)
- **A supply chain** that can deliver the components and fuel needed

SC-HTGR Provides a Flexible Solution to Our Most Pressing Energy Needs

- SC-HTGR provides high temperature steam which is the most flexible intermediate energy medium
  - Large scale process heat
  - High efficiency electricity generation
  - Repowering of fossil-fired power generation
  - Today these markets are completely dominated by fossil fuels
- SC-HTGR inherent safety characteristics meet customer expectations
  - Passive safety
  - No evacuation required for any design basis accidents
  - Negligible investment risk profile (plant restart possible after any design basis accident)
    - For both the SC-HTGR and for the neighboring process heat user
- SC-HTGR provides flexible fuel cycle options
  - Once through cycle for rapid near-term deployment
  - Flexible options for more advanced future cycles to maximize long-term sustainability
- Commercialization challenges must be overcome to enable near-term deployment

Questions

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