Status Report – Steam Cycle High Temperature Gas-Cooled Reactor (SC-HTGR) (Framatome Inc.))
United States of America (30/November/2019)

This reactor design is a new concept with a projected earliest deployment (start of construction) time of 2027.

The reference plant is a four module Steam Cycle High Temperature Reactor (SC-HTGR) and has a net power output of 272 MWe per module in a full electric mode [or up to 625 MWth of high temperature steam in a steam/electricity co-generation mode]

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [x] SMR [ ] FR

The Framatome SC-HTGR is a modular, graphite-moderated, helium-cooled, high temperature reactor with a nominal thermal power of 625 MWth and a nominal electric power capability of 272 MWe. It produces high temperature steam suitable for numerous applications including industrial process heat and high efficiency electricity generation. The safety profile of the SC-HTGR allows it to be collocated with industrial facilities that use high temperature steam. This can open a major new avenue for nuclear power use. The modular design allows plant size to be matched to a range of applications.

The SC-HTGR concept builds on Framatome's past experience of HTGR projects, as well as on the development and design advances that have taken place in recent years for modular HTGRs. The overall configuration takes full advantage of the work performed on early modular HTGR concepts such as the General Atomics MHTGR and the HTR-MODUL.

Development Milestones

2022 Conceptual Design
2024 Preliminary Design
2024 Start of pre-licencing vendor design review in the U.S.A.
2027 FOAK plant engineering design complete
2027 Secure necessary licenses in the U.S.A.
2027 Start construction of a first full-scale NPP module in the U.S.A.
2033 Commercial operation

Design organization or vendor company (f.shahrokhi@framatome.com)

Links (www.framatome.com):

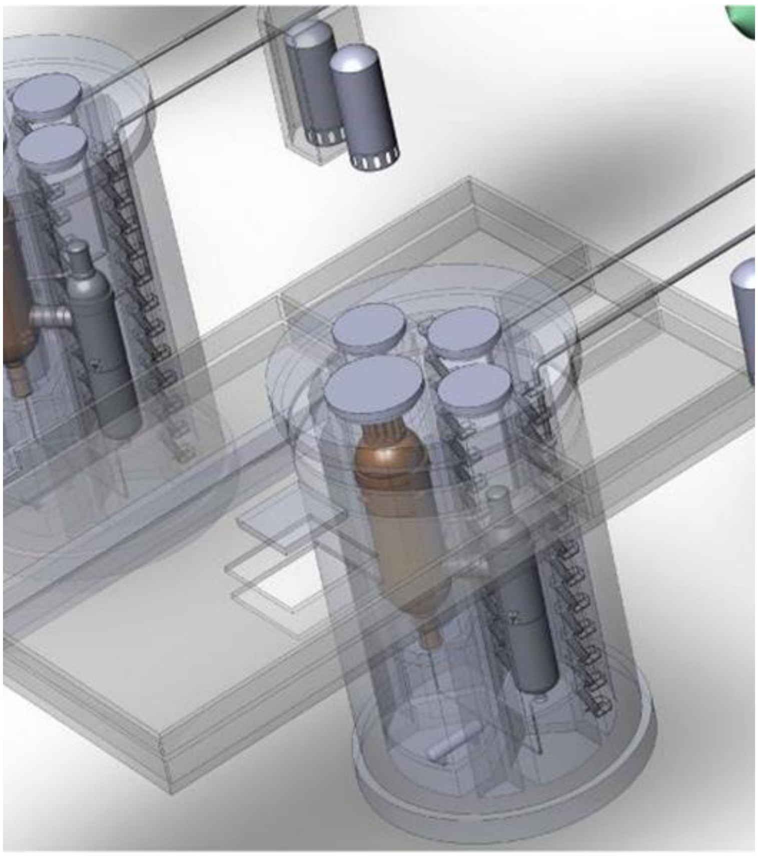

Figure 1 : Standard Reactor Building Configuration

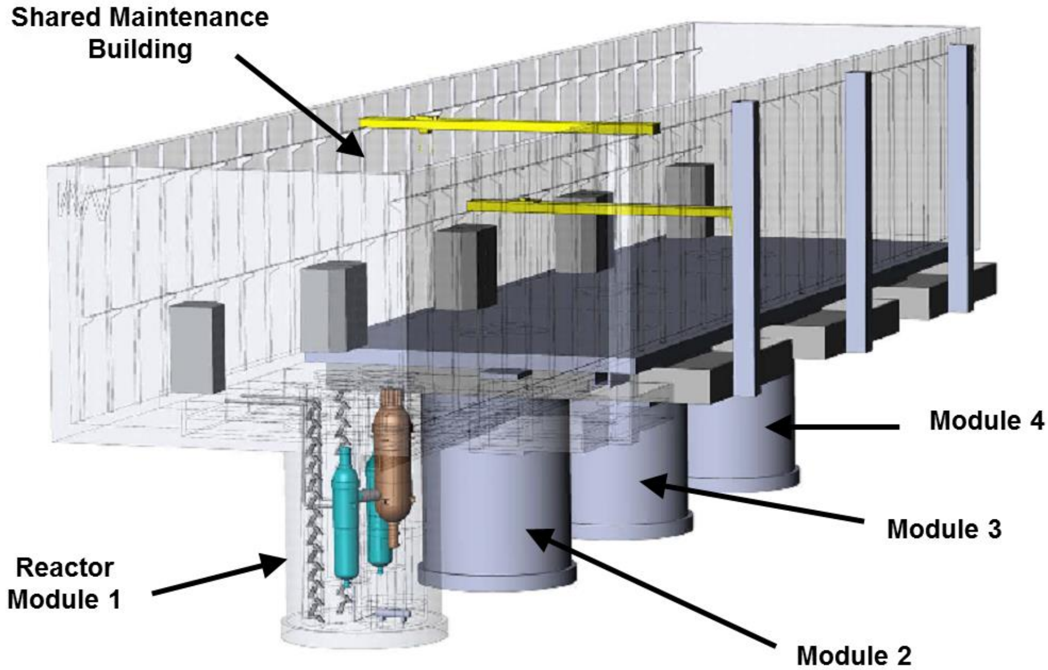

Figure 2 : Multiple Reactor Building Configuration

Table 1 : ARIS Category Fields (see also Spreadsheet “Categories”) for Booklet

ARIS Category	Input	Select from
Current/Intended Purpose	Commercial FOAK Demonstration	Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload with load switching and load follow capability	Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Below ground installation	On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Four module plant	Single Unit, Dual Unit, Multiple Unit (# units)
Reactor Core Size (1 core)	Small 625 MWth per module	Small (<1000 MWth), Medium (1000-3000 MWth), Large (>3000 MWth)
Reactor Type	GCR (HTGR in the USA)	PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Core Coolant	Helium	H_2O, D_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Neutron Moderator	Graphite	H_2O, D_2O, Graphite, None, (Other-specify)
NSSS Layout	Loop Type Two Loops	Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced circulation	Forced (# pumps), Natural
Thermodynamic Cycle	Rankine Cycle	Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	H_2O	H_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	UCO kernel TRISO coated particle fuel	Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Hex Blocks	Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	1020 fuel graphite fuel blocks	#, n/a
Fuel Material Type	UCO (HA-LEU kernel)	Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual	Conceptual, Detailed, Final (with secure suppliers)
Licensing Status	Pre-application 10CFR50 US NRC Prototype	DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)

Table 2 : ARIS Parameter Fields (see also Spreadsheet "Data") for Booklet

ARIS Parameter	Value	Units or Examples
Plant Infrastructure		
Design Life	80 years	years
Lifetime Capacity Factor	>93%	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	18-24 months ½ core replacement	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	/	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design	4-module Reference Plant	n Units/Modules
Capacity to Electric Grid	4 x 272 (MWe) In full electric mode	MWe (net to grid)
Non-electric Capacity	4 x 625 MWth Steam @ 560ºC	e.g. MWth heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	10MWe	MWe
Plant Footprint	10,000	m^2 (rectangular building envelope)
Site Footprint	200,000	m^2 (fenced area)
Emergency Planning Zone	0.4	km (radius)
Releases during Normal Operation	<0.01 mrem	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	20 – 100 5% per min	x – 100%, % per minute
Seismic Design (SSE)	0.5g	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	6MPa/16MPa	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)	He (TBD)	kg
Nominal Coolant Flow Rate (primary/secondary)	He (TBD)/Steam (TBD)	kg/s
Core Inlet / Outlet Coolant Temperature	325 ºC / 750 ºC	ºC / ºC
Available Temperature as Process Heat Source	560 ºC	ºC
NSSS Largest Component	1xRPV, 2xSGs, 2xCross Vessels	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- dimensions	24m/8.5m/880tonnes	m (length) / m (diameter) / kg (transport weight)
Reactor Vessel Material	SA-508/533	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	Vertical Helical Coils	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow

ARIS Parameter	Value	Units or Examples
Secondary Coolant Inventory	Water/Steam	kg
Pressurizer Design	N/A	e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	NA/NA	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	Vented Reactor Building	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume	10 years	years of full-power operation / m^3
Fuel/Core		
Single Core Thermal Power	625 MWth	MWth
Refuelling Cycle	18 or 24 months ½ of the core	months or "continuous"
Fuel Material	UCO (TRISO)	e.g. UO_2, MOX, UF_4, UCO
Enrichment (avg./max.)	14.5/18.5	%
Average Neutron Energy	Epithermal core	eV
Fuel Cladding Material	TRISO coated particles	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel "Units"	1020 fuel Blocks	specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	~140	kg
Total Fissile Loading (initial)	TBD	kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	N/A	applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge	15%	%
Core Discharge Burnup	165,000	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	165,000	MWd/kgHM
Breeding Ratio	N/A	Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	Possible (not allowed in USA)	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	B_4C canisters and B_4C absorber balls	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber	Gd_2O_3 Future core designs	e.g. Gd_2O_3,
Core Volume (active)	TBD	m^3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	TBD	N/m^2-s
Max. Fast Neutron Flux	TBD	N/m^2-s

ARIS Parameter	Value	Units or Examples
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	1/2	100/%100%
- core injection	N/A	/
- decay heat removal	2/2	100%/100%
- containment isolation and cooling	Not Required	/
- emergency AC supply (e.g. diesels)	Not Required	/
DC Power Capacity (e.g. batteries)	Batteries	7 days for monitoring and data collection – not safety related
Events in which ***Immediate Operator Action*** is required	None	e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time	7 -days	Refill RCCS tank with tap water
Severe Accident Core Provisions	None No core melt	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	Not Applicable	x / reactor-year (based on reference site and location)
Severe Accident Containment Provisions	Not Applicable	e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency (LRF)	< 1REM 30 day site boundary	x / reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (n^{th} of a kind)	24 months/module	months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort	TBD	person-years (PY) [DP&P]
Construction and Commissioning Effort	TBD	PY [C&C]
Material and Equipment Overnight Capital Cost	$3,900/MWe NOAK	Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	
- Site Development before first concrete	30/10	(e.g. 25 / 10) (30 / 40) (20 / 25) (20 / 10) (5 / 15) (-----------) (to add up to 100 / 100)
- Nuclear Island (NSSS)	30/40	
- Conventional Island (Turbine and Cooling)	20/25	
- Balance of Plant (BOP)	15/15	
- Commissioning and First Fuel Loading	5/10	
Factory / On-Site split in [C&C] effort	35/65	% / % of total [C&C] effort in PY (e.g. 60 / 40)

1. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

Each reactor module is located in a separate reactor building. The standard configuration uses a fully embedded below grade reactor building design (See Figure 1). This provides structural design advantages and superior protection from external hazards. An alternative partially embedded configuration can be used for sites where a fully embedded structure is not appropriate. The primary functions of the reactor building are to support the NSSS primary circuit components and to protect the system from external hazards. The SC-HTGR reactor building uses a vented confinement system. The building provides supplemental fission product retention in the event of an accident.

The modular design of the system allows multiple reactor modules to be grouped together on a single plant site. See Figure 2. A typical plant layout might have four reactor modules, although the specific number of modules in an actual plant, and the timing of construction of each individual module, will depend on the nature of the application and the customer's needs. Reactor modules share auxiliary and supporting systems during normal operation, but safety systems, including the RCCS and Reactor Protection Systems, are independent.

Steam headers and switch gear are provided to interface with the customer steam distribution system, local or national electrical grid.

The SC-HTGR site layout is arranged in accordance with effective process system layout, material and equipment handling and personnel access. Buildings are located to minimize the distances required for interconnecting utilities (e.g., ductwork, piping, electrical conduit, etc.), as well as minimizing the travel distance between buildings, and still meeting personnel safety requirements.

The SC-HTGR site layout design ensures a proper arrangement for performance of all required facility functions safely and efficiently. This is accomplished through master planning of the site layout, including environmental orientation, and access provisions to structures, systems, and components (SSCs). The SC-HTGR site consists of security fencing, roads, rail lines, seismic and non-seismic buildings, power generation structures and components, circulating water pump house and cooling towers, a switchyard, a spent fuel storage facility, and multiple gas storage facilities. The orientation of the facilities is selected for each SSC, relative to all other SSCs, so that the flow of material and personnel facilitate plant functions and overall plant costs are minimized. All facilities, with the exception of the ancillary production facilities (e.g., hydrogen production), are located within the site boundary security fence. The production facilities are located outside of the security fence to minimize the potential for adverse interactions with the reactor facility. A "Protected Area" is defined within the site boundary area. Facilities and buildings that require protection from sabotage are located within the Protected Area. The support and industrial services are comprised of the vehicle access portal, the receiving warehouse material receipt area, domestic water utilities distribution system, demineralized water, steam, conventional wastewater, sanitary waste, and fire protection distribution systems. All facilities are accessible via paved roads and are supplied with nearby parking and sidewalks.

The reactor building (silo) and the reactor service building constitute a principal portion of the reactor complex. A steel-framed maintenance enclosure with metal roofing and siding shelters the entire operating floor formed by the common at grade top slab of these buildings. Other buildings and areas at grade, which constitute the balance of the reactor complex, are the radioactive waste handling building, the reactor auxiliary building, the personnel service building, and an equipment module area. The Reactor Complex has a single foundation. Major equipment within the underground (silo) reactor building include the reactor vessel, cross-vessels, steam generators and circulators, reactor cavity cooling system, shutdown cooling system, and the control assembly drives. The reactor services building, located at grade level, houses facilities, systems, and components relating to fuel handing and maintenance.

The power conversion complex consists of the boiler feed pump buildings, the steam turbines and generators, and the boiler blowdown tanks. The power conversion complex also includes the generator breakers, startup transformers, unit auxiliary transformers, and unit transformers. The steam turbines and generators will be located on support structures above the steam condenser which will be located approximately at grade level. The plant also includes other buildings and facilities that house equipment in support of the reactor complex and the power conversion complex.

1.1.Site Requirements during Construction

The SC-HTGR site layout considers specific design criteria to enhance constructability. Construction materials staging and crane placement shall be reviewed during specific site layout. Construction activities will require a significant number of craft shops and will required coordination with the construction contractor for construction facility requirements. Plant layout considers construction sequence and staggered reactor module startup to minimize the potential for interference with operating units as subsequent modules are constructed. Modular construction methods are anticipated to be utilized to the extent practicable to shorten the construction schedule. Consideration will be given in the design of service facilities to account for future site expansion. A temporary on-site facility may be considered for the reactor vessel fabrication and heat treatment. The heavy load haul route (underground and overhead utilities) for moving vessels into place will be addressed during the specific site layout.

1.2. Site Considerations during Operation

The SC-HTGR safety characteristics result in enhanced public safety and increased siting flexibility. They also minimize investment risk for both the plant operator and for any adjacent industrial facilities and process heat users. As a result of the extremely low accident doses, industrial facilities can be located very close to the reactor, essentially at the Exclusion Area Boundary (EAB) (e.g., 400 m from the reactor). No public evacuation is required beyond the EAB for Design Basis Events.

1.3. Grid Integration

The enhanced level of safety also makes the SC-HTGR attractive for repowering of retiring fossil process heat and electrical generation stations in locations where the density of surrounding industry, commercial facilities, and population have increased since initial siting. This requirement for a high level of safety could well prevent siting of another reactor type in these locations.

2. *Technical NSSS/Power Conversion System Design*

SUMMARY FOR BOOKLET

Design Philosophy- The SC-HTGR is designed around proven helium-cooled, graphite moderated reactor technology, and passive decay heat removal, the heart of which is the TRISO coated fuel particles.

Reactor and Power Conversion System -The reactor inlet and outlet temperatures are 325°C and 750°C, respectively. These temperatures were selected primarily to support the desired steam outlet conditions for the target markets. These temperatures also allow the use of SA-508/533, a standard PWR vessel material, for the primary vessels without requiring separate cooling or special thermal protection. For the reference plant steam cycle concept, the reactor power level is 625 MWth.

Fuel Characteristics - The TRISO coated fuel particle consists of a uranium oxycarbide (UCO) fuel kernel surrounded by multiple ceramic coating layers that provide the primary fission product retention barrier under all design basis accident conditions. The total fuel inventory includes roughly 10 billion such particles per core. The particles are distributed in graphitic cylindrical compacts. Multiple compacts are contained within hexagonal nuclear grade graphite fuel blocks. The compacts are stacked in fuel holes drilled into the blocks.

Reactor Core Layout - In the reference plant the fuel blocks are configured into a 102 column annular core surrounded by graphite reflector elements. The inner or central reflector also contains graphite reflector elements. Hence the basic core structure is entirely ceramic. This configuration maximizes the reactor's passive heat removal capability. The active core is 10 blocks high. The reference reactor module can be scaled from 625 MWth to 50 MWth using the same fuel blocks in scaled arrangements.

Reactivity Control - The large negative temperature coefficient of the modular SC-HTGR, along with its large thermal margins, provide for an inherent shutdown capability to deal with failures to scram the reactor. Gravity-driven and diverse reactivity control systems provide further confidence of the ability to shut down the reactor.

Fuel Handling System - Refueling is performed using robotic systems with the primary coolant boundary intact. Following shutdown, the primary system temperature is reduced and then the helium inventory is reduced to slightly sub-atmospheric. Refueling access is then gained through the control rod drive penetrations at the top of the reactor vessel. The robotic refueling equipment is computer controlled using predetermined block movement sequences.

Reactor Pressure Vessel and Internals - The Reactor Vessel is part of the Vessel System which is the primary pressure-retaining components and also includes the Cross Vessels and Steam Generator Vessels. The reactor core, reflector elements, core support structure, and core restraint devices are installed in the reactor vessel. The reactor core components, together with elements of the reactor internal components, constitute a graphite assembly that is supported on a graphite core support pillars and restrained by a metallic core support assembly. The reactor internal components consist of the upper core restraint elements, permanent graphite side reflector elements, graphite core support pillars, metallic core support assembly, and the upper plenum shroud.

2.1. Primary Circuit

The SC-HTGR reactor is a two-loop modular steam supply system. Each module consists of one reactor coupled to two steam generators Figure 3. The steam generators are configured in parallel, each with a dedicated main circulator.

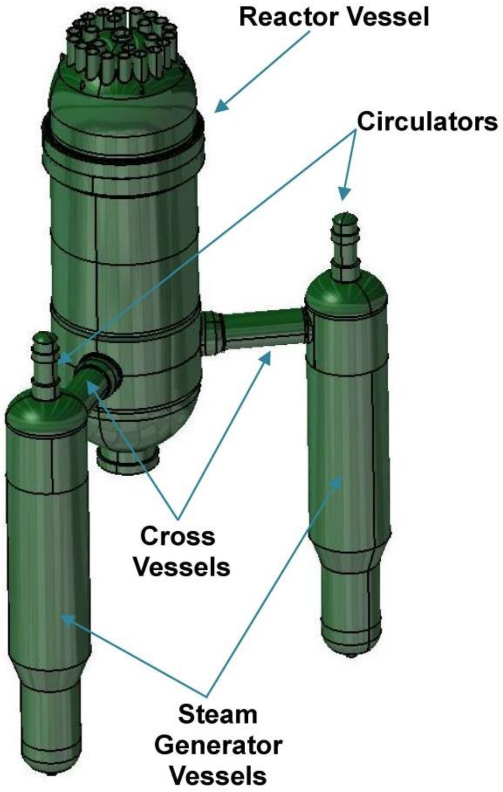

Figure 3 : Nuclear Process Steam Supply System

A steel vessel system houses the entire primary circuit. The reactor vessel contains the reactor core, reactor internals, and control rods. Each steam generator is housed in a separate steam generator vessel. A separate cross vessel connects each steam generator to the reactor vessel. Each cross vessel contains a hot duct that channels hot gas from the reactor outlet to the steam generator inlet. Cool return gas flows in the outer annulus between the hot duct and the vessel wall. The entire vessel system inner surfaces are bathed in cool reactor inlet gas, so conventional LWR vessel material can be used. This configuration is shown in Figure 4.

Each steam generator is a helical coil tubular heat exchanger. Feed water enters the bottom of the steam generator and flows upward inside the tubes, while hot primary coolant flows downward over the tube bundle. This steam generator builds upon the lessons learned at previously operated gas-cooled reactors (e.g., Fort St. Vrain, AVR, and THTR). The SC-HTGR steam generator uses similar technology including once-through helical coil tubes supported by radial support plates. The primary design difference between the current design and past operating reactors is the size of the tube bundle. However, the 315 MWth steam generator module is well within the size envelope of the larger steam generator designs used for the large HTGRs developed in the 1970s.

Electric motor-powered main circulators provide the primary coolant flow. The main circulator for each loop is located at the top of the associated steam generator vessel. The variable speed circulators use submerged motors with active magnetic bearings for simple operation and high reliability. Magnetic bearings are already in service on numerous commercial applications that envelope the SC-HTGR circulator requirements (e.g., many large industrial electric motor driven pipeline compressors). Private discussions with circulator vendors confirm that the required SC-HTGR circulators can be procured using existing technology.

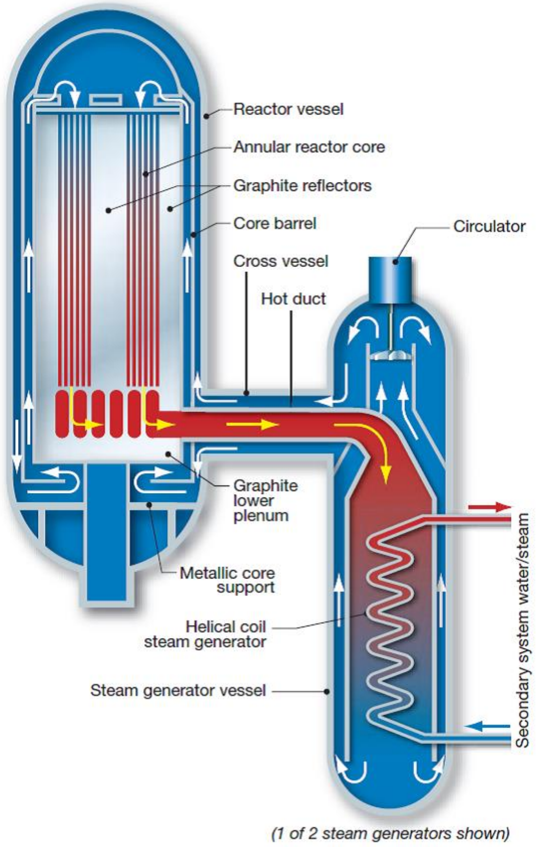

Figure 4 : Primary Circuit Layout

2.2. Reactor Core and Fuel

The SC-HTGR is designed around proven helium-cooled reactor technology, the heart of which is the Tri-Isotropic, or TRISO, coated fuel particle. Each fuel particle consists of a fuel kernel surrounded by multiple ceramic coating layers that provide the primary fission product retention barrier under all design basis accident conditions. The total fuel inventory includes roughly 10 billion such particles per core. As shown in Figure 5, the particles are distributed in graphitic cylindrical compacts. Multiple compacts are contained within hexagonal nuclear grade graphite fuel blocks. The compacts are stacked in fuel holes drilled into the blocks, which provide spacing and support for the compacts.

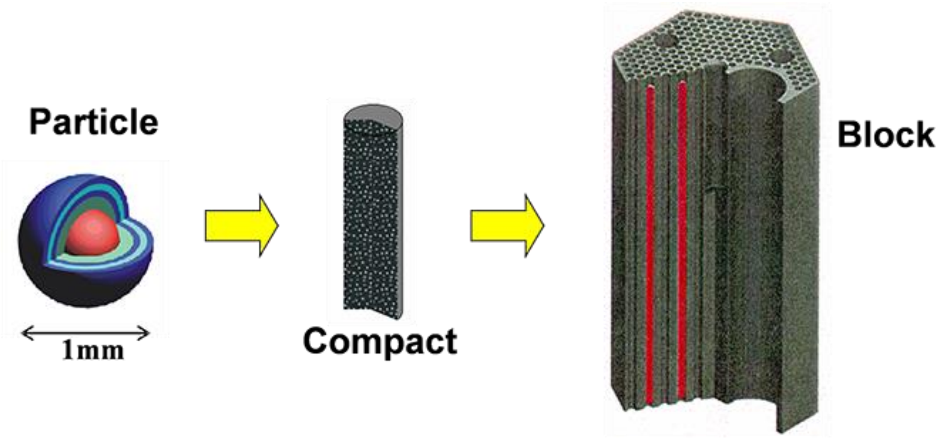

Figure 5 : TRISO Fuel Particle, Fuel Compact, and Fuel Block

The fuel blocks are configured into a 102 column annular core, Figure 6. The rest of the core is made up of stacked unfueled nuclear grade graphite reflector blocks. Hence the basic core structure is entirely ceramic. This composition and geometry provides an optimized total heat capacity and an efficient radial heat conduction to maximize the performance and benefits of passive decay heat removal. The active core is 10 blocks high.

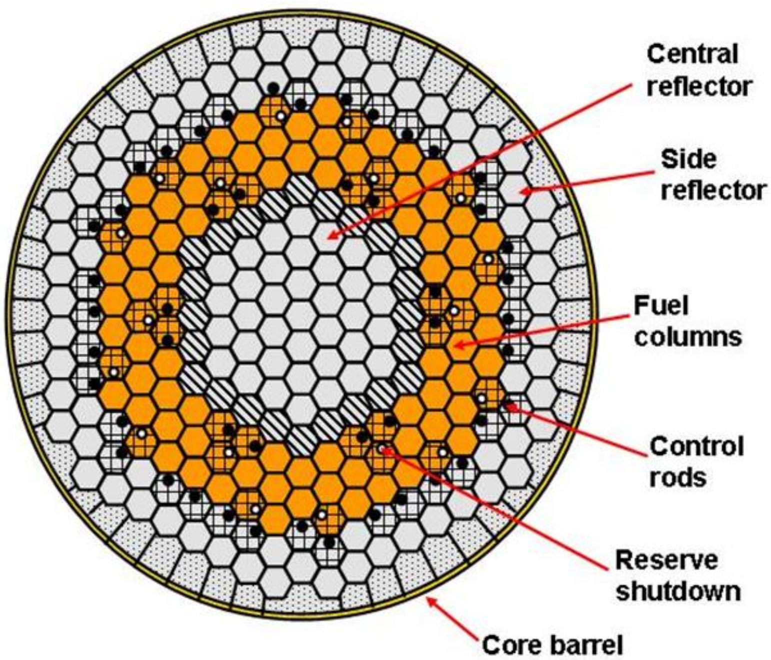

Figure 6 : Annualar Core Layout

The reactor inlet and outlet temperatures are 325°C and 750°C, respectively. The core inlet and outlet temperatures are selected to support the high efficiency Rankine cycle chosen for the plant steam cycle, which does not need the higher temperature of other power generation options, such as a combined cycle gas turbine.

The selected core inlet and outlet temperatures provide several benefits. They allow the use of SA-508/533, proven PWR vessel material, for the primary vessels without requiring separate cooling or special thermal protection. This also brings the core inlet temperature within the experience base developed by the LWR fleet, some of which operate with core exit temperatures as high as 328°C.

2.3. Fuel Handling

The Fuel Charge and Discharge System, that is used to shuffle the fuel in the core, is based on the same concept as the successful Ft. St. Vrain refueling system. It is made up of four main components; the Fueling Adaptor, the Fuel Handling Machine, the Fuel Elevator, and the Fuel Storage Server.

The Fueling Adaptor is a mechanical device that extends the CRDM nozzles. It is a welded steel structure that fits over the CRDM nozzles and creates a soft seal around each nozzle, to permit the removal of CRDMs and insertion of the Fuel Elevator and Fuel Handling Machine without opening the reactor coolant boundary.

The Fuel Handling Machine (FHM) is a robotic manipulator that is inserted into an inner control rod drive penetration. It is equipped with a grapple probe that can be inserted into the handling hole in the top of any hexagonal block. The probe can be expanded to engage the block so the machine can lift it. The FHM is equipped with a pantograph-like mechanism giving it the capability to extend the grapple to reach all the blocks within a sector, including all replaceable reflector blocks. The FHM can rotate, extend, and raise/lower, so that it can access all the hexagonal blocks in a sector from an inner CRDM nozzle.

The Fuel Elevator is a machine that is inserted through the central penetration in the reactor head into the reactor vessel and is used to move the Fuel Elements vertically from the core to the Fuel Storage Server.

The Fuel Storage Server is a movable shielded tunnel, supported on wheels and rails, which provides a shielded pathway between the Fuel Elevator and the nearby fuel storage facility. The Fuel Storage Server includes an internal track-mounted car with a grapple mechanism to facilitate Fuel Element transfer.

2.4 Reactor Protection System

The Reactor Protection System (RPS) is safety-related and is relied upon to shut down and maintain the reactor in a safe state to protect the public safety during design basis accidents (DBAs). The RPS initiates a reactor trip to control heat generation, and it initiates main loop trip and steam generator (SG) isolation to minimize water ingress into the primary. These engineered safeguards actions limit chemical attack of the graphite components. The RPS is independent from the Investment Protection System (IPS), the Plant Instrument and Control System (PICS), and the Plant Monitoring System (PMS). There is one RPS for each reactor module.

2.5 Secondary Side

The HTGR steam cycle concept is extremely flexible. Since high pressure steam is one of the most versatile heat transport mediums, a single basic reactor module configuration designed to produce high temperature steam is capable of serving a wide variety of near-term markets. As a result, the SC-HTGR is well suited to supply a wide variety of process heat facilities.

The SC-HTGR can also generate electricity very efficiently. Using the conventional Rankine cycle with high temperature steam, a net efficiency of over 43% can be achieved in the full electricity generation mode. This makes the concept an attractive option in markets with limited grids and markets requiring incremental capacity addition, particularly for repowering existing fossil-fired facilities that are being retired.

Most important, the steam cycle is well suited to cogeneration of electricity and process heat. Steam system equipment can be configured in a variety of ways depending on the specific needs of the facility for high temperature process steam, low temperature process steam, and electricity. Figure 7 illustrates one possible cogeneration plant configuration in which high pressure extraction steam is used to supply tertiary process steam either directly or via a reboiler. This configuration is only intended to illustrate potential flexibility of the system. The secondary and tertiary system of the plant can be easily customized for each end-user energy application.

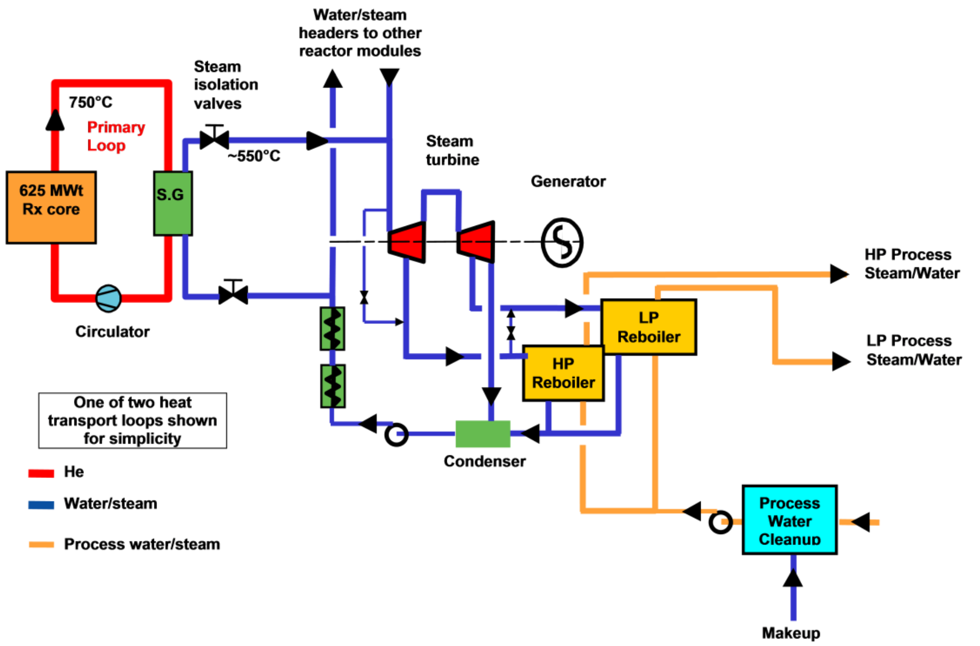

Figure 7 : Typical Co-Generation Plant Configuration

The steam cycle plant also has good load following characteristics. Reactor module power level and steam production can be increased or decreased relatively easily. Systems can also shift energy between electricity generation and heat supply dynamically as load and market conditions vary, all while keeping reactor power constant. This provides the maximum utilization of the HTGR nuclear heat source.

2.6 Radionuclides Containment/Confinement

The SC-HTGR functional safety approach is to: a) retain radionuclides as close to the fuel particle as possible during design bases events, anticipated operational occurrences, and normal operations, b) require no operator action or active system response to provide safety, c) design a truly “walk away” and more importantly “walk back again” safe plant, and d) require no evacuation or adverse radiological impact beyond the plant boundary.

The design features SC-HTGR that provide the above functional safety are as follows:

1. Inert coolant – the single phase helium gas was selected to transport the fission heat produced in the core to the secondary steam/water traditional energy delivery system
2. Ceramic core – the ceramic core nuclear grade graphite provides a solid moderator, heat sink, and core structural element that can withstand the high temperature condition during normal and accident conditions without loss of expected performance
3. Robust fuel – The TRISO coated particle fuel has proven characteristics to retain the fission products and maintain structural integrity during normal and accident conditions
4. Passive cooling – In an accident scenario the decay heat can be dissipated through an highly efficient, passive system without power, component mode change, or any active or passive actuation signal. Operability of this system (the RCCS) is continuously monitored and verified operable during all plant modes of operation.
5. Negative temperature coefficient – The choice made for the ceramic core material provides an additional neutronic benefit of providing a negative temperature coefficient. This core neutronic characteristic will shut down the fission reaction as core temperature rises above its design limit in case neither the control rods nor the backup absorber elements fail to actuate and shut down the reactor.
6. Loss of power – The SC-HTGR does not depend on any electrical system (AC or DC) to activate its safety systems. It is anticipated that safety related DC power will be required to provide monitoring of key systems to verify plant conditions.

The SC-HTGR has five barriers to radionuclide release to the environment that form its functional containment system. These barriers are as follows:

1. The fuel particle kernel,
2. The fuel particle coatings (silicon carbide and pyrocarbon coatings),
3. The core graphite and carbonaceous materials,
4. The helium pressure boundary, and
5. The reactor building.

The effectiveness of these barriers in containing radionuclides depends upon a number of factors including the chemistry and half-lives of the various radionuclides, the service conditions, and irradiation effects. The effectiveness of these release barriers is also event specific.

The safety characteristics of the SC-HTGR rely on inherent and passive safety features of the design. It uses the inherent high temperature tolerant characteristics of TRISO-coated fuel particles, graphite moderator, and helium coolant, along with passive heat removal capability of a low power density core with a relatively large height-to-diameter ratio within an uninsulated steel reactor vessel to assure sufficient core residual heat removal under loss-of-forced cooling or loss- of-coolant pressure conditions.

The first radionuclide retention barrier in the SC-HTGR consists of the fuel kernel that retains a substantial fraction (>95%) of the radiologically important, short-lived fission gases such as Kr-88 and I-131.

The secondary barrier to the radionuclides release is the three ceramic coating layers surrounding the fissionable fuel kernel to form a fuel particle. As shown in Figure 5, these coating layers include the inner pyrocarbon (IPyC), silicon carbide (SiC), and outer pyrocarbon (OPyC), which together with the buffer layer constitute the TRISO coating. The coating system constitutes a miniature pressure vessel that has been engineered to provide containment of the radionuclides and gases generated by fission of the nuclear material in the kernel. Thousands of these TRISO-coated particles are bonded in a carbonaceous material into cylindrical fuel compacts for the prismatic SC-HTGR. These fuel particles can withstand extremely high temperature without losing their ability to retain radionuclides under all accident conditions. Fuel temperatures can remain well above 1600 °C for several hundred hours without loss of particle coating integrity [i]. This high temperature radionuclide retention capability is the key element of the SC-HTGR safety characteristics, providing its ability to tolerate a broad range of upset and accident conditions that result in elevated fuel temperature.

The third, fourth and fifth barriers (core graphite, reactor pressure boundary, and the reactor building) play a smaller role in the overall radionuclides retention capability of the SC-HTGR. However these barriers have other important operational and accident prevention and mitigation functions such as passive core heat removal and maintaining core geometry.

The peak fuel maximum temperature during normal operation is well over 400 °C below the peak local fuel temperature during accident condition when local fuel degradation could occur. This represents a significant safety margin that essentially eliminated fuel damage during normal and accident conditions. In addition due to the large size of the core and the passive heat removal capability of the system, only a small percentage of the fueled core volume can physically experience these elevated temperature ranges for an appreciable amount of time. Therefore, for all design bases accidents scenarios that involve core temperature rise, no fuel damage can occur resulting in excessive damage to plant systems and components. For this reason, once the cause of an accident is investigated and repaired the plant can return to normal power operation.

This accident tolerance and safety margin of SC-HTGR translates to a low investment risk. This means the investment in plant is not lost as a result of a design bases accident.

Furthermore, the radionuclide retention capabilities of the SC-HTGR limit accident source terms to such that the required emergency planning zone (EPZ) is limited to the site boundary (approximately 400 meters). The small EPZ allows for close-in location of the SC-HTGR plant with the energy users to limit line losses. Furthermore, the small EPZ assures that the process heat users outside the plant boundary are not affected by the plant during normal operation or accident mitigation conditions.

2.7 Electrical, I&C and Human Interfaces

The Control and Protection System (CPS) is the main SC-HTGR instrumentation system that monitors, protects, and controls reactor power operation, startup, shutdown, and refueling operations within pre-established safe boundaries. See Figure 8. The CPS consists of the following four (4) subsystems:

- Reactor Protection System (RPS)
- Investment Protection System (IPS)
- Plant Instrument and Control System (PICS)

- Plant Monitoring System (PMS)

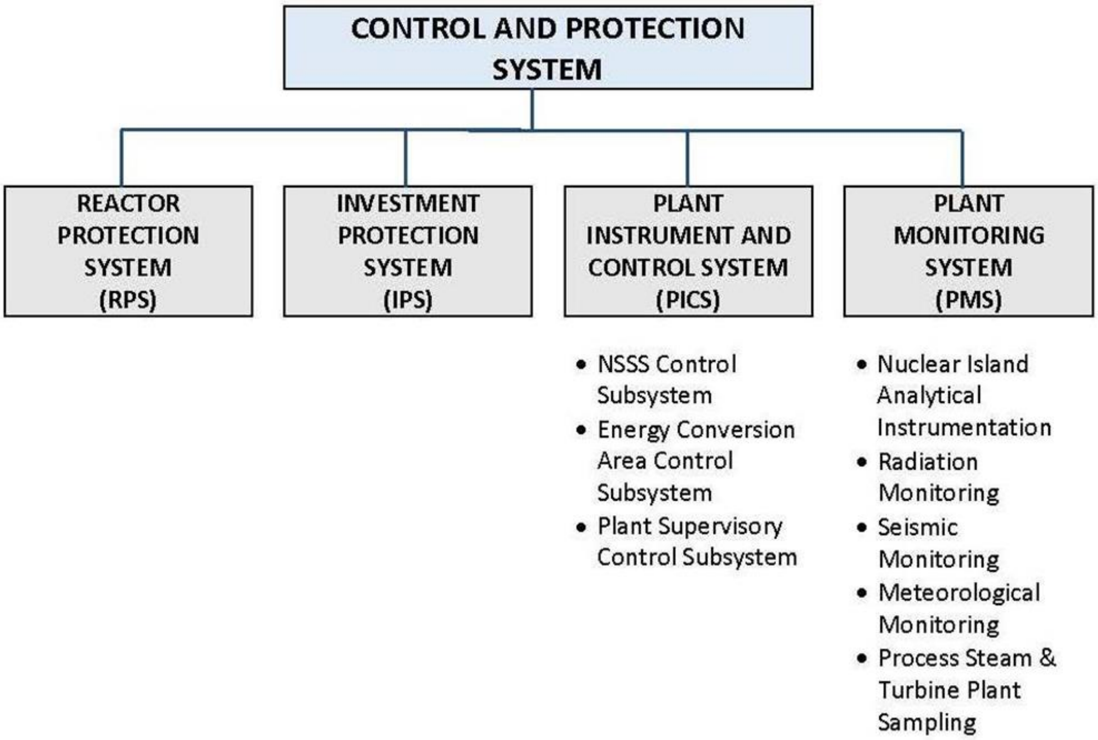

Figure 8 : Control and Protection System

2.8 Unique Technical Design Features

Sustainability and Fuel Utilization

There are three primary considerations regarding fuel cycle sustainability for the SC-HTGR. The LEU once-through fuel cycle is the dominant cycle in the current uranium market, and it is expected to remain so for the foreseeable future. Therefore, the first sustainability consideration is the quantity of spent fuel generated per quantity of energy produced, which reflects the amount of repository space and/or waste processing capability required. The second consideration is the uranium utilization of the stand-alone reactor in today's fuel market, which reflects the basic utilization of mined uranium resources. The third consideration is the feedstock utilization (uranium or thorium) of the reactor concept when fully integrated into the infrastructure of a mature closed fuel cycle. That consideration reflects the ultimate feedstock utilization of the long-term system. (It is noted that the mature closed fuel cycle infrastructure faces significant sustainability challenges beyond heavy metal feedstock utilization. Those environmental, technical, and business challenges are beyond the scope of this discussion.)

For the foreseeable future, the once through, open fuel cycle is clearly the most cost effective. Therefore, SC-HTGR initially employs this cycle. The driving issue is the uranium market. But this is a fuel cycle infrastructure question, not a reactor question. As the market shifts in the latter part of this century, SC-HTGR plants could shift to an advanced fuel cycle.

The SC-HTGR reference core design for the LEU once-through fuel cycle strategy has been selected to support the desired operational characteristics discussed in the preceding sections, and to minimize fuel reload size based on anticipated fuel cycle market conditions. Minimization of reload size has two benefits. Replacement of fewer fuel blocks will shorten the duration of periodic refueling outages, thus increasing plant availability. More importantly, smaller reload sizes will also produce smaller quantities of used fuel which must be handled and stored on site and eventually disposed of off-site. With high fuel burnup and high thermal efficiency, the SC-HTGR does well for this consideration. Given the current difficulties associated with dispositioning spent fuel, fuel minimization will likely turn out to be very valuable to fleet deployment of the SC-HTGR for the foreseeable future.

Regarding feedstock utilization of the SC-HTGR in the current fuel cycle environment, the utilization is comparable to current reactors. While the high burnup and high thermal efficiency of the SC-HTGR benefit fuel utilization, the 15% enrichment used in the current once-through LEU fuel cycle increases natural uranium feedstock requirements. The required natural uranium feed for the reference cycle can be estimated based on data presented in Reference [ii], which indicates that about 2,500 kg of enriched uranium is required to support 18 month reloads. This represents an annual need for 15.5 w/o enriched uranium of 1666 kg/year, or about 6.8 MTU/GWe-yr. The amount of natural uranium required to support this, based on an assumed 0.25% enrichment tails assay, is 61 MT/yr or 224 MTU/GWe-yr.

Although the SC-HTGR reference core and fuel design use the once-through uranium fuel cycle, the SC-HTGR is able to utilize a variety of fuel cycles including higher conversion recycle systems. These include use of uranium/thorium or plutonium/thorium as a fissile/fertile fuel mix, use of plutonium fuel, and deep burn concepts for plutonium and actinide burning [iii]. Each of these fuel cycles has a different resource utilization profile that can be leveraged to meet a variety of operational goals. These would require the formal qualification of new particle fuel designs. However, several previous HTGRs have already successfully demonstrated uranium-thorium fuel systems, and plutonium particle fuel has also been irradiated to very high burnups in past HTGR test reactors. Extensive work was also done on recycling of HTGR U/Th fuel in the 1970s (e.g., Reference [iv]). While the SC-HTGR operating in such an environment would not be expected to provide a high breeding ratio comparable to a modern fast spectrum reactor, it would provide much more flexible performance than current LWRs. As stated above, the SC-HTGR can utilize cycles to convert thorium or depleted uranium to fissile material using various fissile drivers, it can use pure plutonium fuels for various missions, and it can burn other spent fuel wastes. Utilization of mined uranium or thorium feedstocks would be significantly improved with such cycles.

A key benefit of the SC-HTGR is that the current reactor design is compatible with these alternate fuel cycles. Therefore, an SC-HTGR plant built during the early fleet deployment in the 2030s will be able to switch to one of these alternate closed fuel cycles later in the plant's life should ongoing expansion of nuclear power increase pressure on uranium resources necessitating the increased use of recycled fissile material and the use of alternate feedstocks such as thorium.

Finally, any discussion of sustainability and resource utilization as it applies to a particular reactor and fuel cycle choice would be incomplete without acknowledging the significant impacts of the complete fuel cycle infrastructure beyond the reactor. Overall sustainability and resource utilization must consider the efficiencies and ramifications of all of the facilities supporting the fuel cycle and the resource needs and environmental impacts of each. In addition, the readiness and path to deployment of the supporting infrastructure must also be considered. For example, the first few plants employing a new fuel cycle strategy will not be sufficient to warrant deployment of new fuel cycle facilities, therefore a certain minimum number of plants are needed to develop a commercial impetus to deploy the industrial fuel cycle facilities.

In summary, the SC-HTGR has been designed to operate economically and efficiently using the once through, uranium based fuel cycle. It has the capabilities to capitalize on advanced fuel cycle strategies should supporting facilities be developed and deployed, though such industrial facilities are not currently in existence.

Thermal Characteristics

The thermal-hydraulic performance of the SC-HTGR reactor core is linked directly to the nuclear core design to ensure that the resulting power distribution results in acceptable fuel temperatures throughout the core for all operating modes over the life of the reactor. Specifically, the power distribution and the coolant flow distribution must be consistent within prescribed limits.

The primary factor controlling the coolant flow distribution through the reactor core is core bypass flow. Most of the coolant flows through the coolant holes drilled in the fuel blocks where it is most effective in removing the heat generated in the fuel and carrying it out of the core to the steam generators. But a significant fraction of the total coolant flow goes through various other passages, thus bypassing the core coolant holes. Some of this bypass flow is intentional, in order to provide cooling for control rods and other structures within the core. The remainder of the bypass flow is the unavoidable flow through the gaps between fuel blocks, reflector blocks, and other core structures. This flow through gaps between blocks does provide some core cooling, but it is not as effective as the flow through the coolant holes.

The core bypass flow will vary significantly during the lifetime of the reactor internals due to dimensional changes in the graphite components due to irradiation effects. When all fuel and reflector elements are unirradiated, the core bypass flow will be about 10 percent, while core bypass will be between 25 and 30 percent near the end of a fuel cycle late in the reactor lifetime, when most fuel and reflector elements are fully irradiated. Under most operating conditions, the bypass flow will be somewhere in the middle of this range (i.e., 10 to 30 percent).

Core thermal performance calculations are performed over the full range of bypass flow. Low bypass flow cases are examined to confirm that there is adequate cooling of the reflector elements adjacent to the active core. These analyses confirm that 5 percent bypass flow is adequate to maintain desired reflector temperatures during normal operation. Thus the expected minimum bypass flow of 8-10 percent is more than adequate.

High bypass flow cases are examined to confirm that local fuel temperatures are acceptable over the whole fuel cycle. Analyses performed for VHTR concepts (ANTARES and NGNP) confirm that peak fuel temperatures can be maintained in the target range of 1250°C to 1300°C. The lower SC-HTGR operating temperatures provide increased margin to the target fuel temperature limits. Detailed SC-HTGR core design will leverage this extra margin in order to provide enhanced fuel performance over extended operating cycles.

Electricity generation performance

The nominal performance of the SC-HTGR system, that is the performance of the standard system for a typical site using traditional wet cooling where temperatures are not extreme, has been evaluated in Reference [v] . This evaluation takes into account preliminary efficiency estimates for the helium circulators, feedwater pumps, turbine, and generator, as well as electrical loads of the circulating water pumps, cooling tower fans, and other plant electrical loads. The net electrical output from each 625 MWth reactor module is 272 MWe for a net efficiency of 43.5%.

In addition to nominal plant performance, the performance of the SC-HTGR was evaluated for locations with a hot, arid environment. In these locations, use of dry cooling was assumed to be required. The dry cooling system was configured to use a conventional water-cooled condenser coupled to non-evaporative cooling towers. Results of this evaluation are provided in Table 3 .

While the use of dry cooling in a hot arid environment imposes a performance penalty on any thermal power plant, the penalty is not as severe for the SC-HTGR as other lower temperature concepts, such as LWRs, due to its higher steam supply temperature. This reduces the loss in generation resulting from an incremental increase in condenser temperature and it reduces the quantity of waste heat that must be handled by the dry cooling system. Thanks to the high temperature of the SC-HTGR steam supply system, switching from conventional wet cooling to dry cooling only results in a loss of 12% of the net electric generation output (for the hot arid case). This compares to a drop of almost 20% of the plant output for a light water reactor, or other low temperature steam system, under similar conditions. Moreover, the resulting efficiency of the SC-HTGR with dry cooling is still better than the net efficiency of a light water reactor even with wet cooling at a non-arid site.

Table 3 : SC-HTGR Performance Comparison

Type of site	Standard Reference Site	Hot Arid Site
Cooling tower type	Wet	Dry
Wet bulb temperature	16°C	NA
Dry bulb temperature	36°C	45°C
Condenser temperature	34°C	67°C
Reactor power (MWth)	625	625
Gross electricity generation (MWe)	293	264
Gross cycle efficiency	46.9%	42.3%
Total house load (MWe)	21	26
Net electricity output (MWe)	272	239
Net efficiency	43.5%	38.2%

Process heat and cogeneration performance

Since the high temperature process heat market is large, a cogeneration plant is an important near-term application of the SC-HTGR. As such, understanding the trade-offs of various design concepts on the performance of a cogeneration application will help further SC-HTGR commercialization. Table 4 presents the results of an internal study which illustrates the relative impacts of cogeneration on system performance for three reactor design concepts.

Table 4: Cogeneration Impact on Electricity Production

	SC-HTGR	Typical LWR	Lower Temperature Modular Reactor
Main steam temperature	696°C	290°C	230°C
Process heat steam temperature	560°C	200°C	200°C
Power production in full electric mode (normalized)	100%	100%	100%
Power production in cogeneration mode	53%	28%	13%
Fraction of electrical output lost due to cogeneration	47%	72%	87%

Two key points can be drawn from an examination of these results:

- LWRs and lower temperature modular reactors cannot supply process heat above 300°C and thus will not meet significant portions of the process heat market.
- At 200°C process steam supply temp, LWRs and low temperature modular reactors lose somewhere between 70% and 90% of electricity cogeneration capacity, while SC-HTGR loses only half as much.

3. *Technology Maturity/Readiness*

SUMMARY FOR BOOKLET

The SC-HTGR design relies on mature technology in order to maximize technological maturity, minimize project risk and to serve near-term markets as soon as possible. All major components are based on technology already demonstrated in previous steam cycle HTGRs or in other industrial applications. They are at high technology readiness levels that allow the design, procurement, and fabrication of the full size equipment. Key remaining development activities are limited to the ongoing TRISO coated particle fuel qualification and nuclear grade graphite qualification work being performed by Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL).

3.1. Deployed Reactors

The development of HTGR technology began over 50 years ago in the UK, the United States, and Germany. Seven experimental and demonstration reactors have been built worldwide, including US commercial-scale demonstrations of specific HTGR concepts for electric power generation at the Peach Bottom Atomic Power Station, Unit 1 (rated at 115 MWth), located in Delta, Pennsylvania, that was operated from June of 1967 to its final shutdown in October of 1974, and the Fort St. Vrain plant (rated at 842 MWth), located in northern Colorado, that operated from 1976 through 1989.

Figure 9 : HTGR Operational Experience

Each of these past HTGR projects provided valuable operating experience which has guided the development of the current SC-HTGR design. Even though each of these reactors operated for only a relatively short period of time, each of them demonstrated successful application of numerous facets of HTGR technology, and they also provided important lessons in how to further improve the technology. Each of these projects involved a unique concept demonstration reactor with specific programmatic objectives and constraints.

The commercial scale demonstration reactors are particularly valuable, since they are similar to the SC-HTGR in overall scale and operating conditions. The Peach Bottom 1 reactor provided an early successful demonstration of a block-type HTGR core using different early particle fuel designs. It provided experience with actual power generation using HTGR operating conditions. The reactor operated for only a few years, since it had completed its planned demonstration mission and was soon overshadowed by the Fort St. Vrain (FSV) reactor project.

The FSV concept was much larger than Peach Bottom, with similar capacity to the SC-HTGR. It demonstrated extremely good performance of the prismatic block fuel element concept which is the basic building block of all subsequent US prismatic block core designs. Remote fuel handling of these elements was also very successful. The FSV design predated the current modular HTGR design strategy, so instead of using a steel reactor vessel, it had a pre-stressed concrete reactor vessel (PCRV). The ultimate objective was to build very large HTGRs using PCRV technology, and the FSV plant was a demonstrator of the required technologies for such concepts. However, in the mid-1980s, this technology was replaced by the strategy to pursue smaller modular HTGRs with completely passive heat removal as the policy and economic benefits of that safety approach were recognized. Ultimately, FSV operation was terminated for economic reasons primarily resulting from two main factors. First, the use of unique water-lubricated main circulator bearings resulted in occasional water ingress into the primary system which lowered overall availability significantly. Second, the core used a fuel cycle based on high enriched uranium (HEU). This necessitated elaborate security procedures related to all fuel cycle activities, driving up costs substantially. If FSV had been part of a larger fleet, it would have been worthwhile to resolve these issues, but for a fleet of only one plant, it was not pursued. The SC-HTGR incorporates specific features to avoid these issues. Instead of water-lubricated circulator bearings, the SC-HTGR circulators have active magnetic bearings which are based on a large body of industrial experience with very high reliability. Also, the SC-HTGR fuel cycle is based on LEU, so that the extreme cost burden associated with HEU fuel is avoided. The SC-HTGR takes full advantage of the FSV experience, leveraging the successful experience with such things as TRISO fuel in prismatic blocks, fuel handling, helium chemistry control and cleanup, and helical coil steam generator performance while avoiding the negative issues that affected FSV.

3.2. Reactors under Licensing Review

The US Department of Energy (DOE), the NRC, the HTGR vendor, and end user communities have been working on mutually identified key licensing issues associated with HTGR technology since the beginning of the Next Generation Nuclear Plant (NGNP) program in 2007. These licensing discussions build upon years of licensing interactions between the NRC and DOE for its MHTGR program in the late 1980s and 1990s that resulted in a preliminary safety evaluation of the modular HTGR technology. The SC-HTGR licensing strategy has sufficient clarity for a successful and efficient licensing process for the first commercial scale plant i.e. demonstration plant and subsequent design certification for the NOAK plant. The technology specific pre-licensing discussion with the NRC puts the SC-HTGR licensing timeline years ahead of any other advanced reactor technology.

Framatome proposes a combined (hybrid) Part 50 and Part 52 licensing strategy for the first SC-HTGR plant. This strategy consists of initiating licensing of the first module of the first plant using the traditional two-step 10 CFR Part 50 process by obtaining a construction permit (CP) for the plant with one module based on a preliminary safety analysis report (PSAR). This will allow initial construction of the plant to commence and subsequent installation of the first of four NSSS modules. As a license condition the first module may have strategically placed instrumentation for data collection during simulated accident testing for validation of the plant design bases safety analysis assumptions.

The SC-HTGR design will be licensed by the host country. The first reactor is anticipated to be licensed in the U.S.A. therefore; the US NRC will be the first reviewing regulator. The design is expected to closely adhere to IAEA safety design requirements and guideline such that licensing of the SC-HTGR can be accomplished by any regulatory wishes to build the SC-HTGR.

3.3. Expected Reliability and Availability

There are two different concepts important to SC-HTGR reliability. The first addresses the basic overall reliability of the system and the likelihood that the SC-HTGR demonstration plant can be built and will function as envisioned during the design process. The second addresses how a mature SC-HTGR plant (or any other heat source) with finite availability can be operated as part of the energy delivery system of an industrial end user to provide the essentially 100 percent reliability required to support continuous operation of some chemical processes.

The reliable functioning of the demonstration SC-HTGR plant has been, and will continue to be, assured through conscious design choices. The designs of these systems have been selected to maximize the use of existing proven and reliable technology. All major reactor systems are based on established technology successfully demonstrated in earlier gas-cooled reactors or in other industrial applications. In those cases where past concepts encountered difficulties, the resulting lessons learned have been factored into the current design to take full advantage of relevant experiences and to avoid those difficulties going forward.

The SC-HTGR is designed to meet a minimum availability requirement of 90 percent. On one hand, this is achieved by following the project’s systems engineering approach which allocates individual reliability requirements for plant systems and components and then assesses resulting performance of the plant as the design progresses. In terms of the actual design process, the required reliability is achieved by selecting proven technology solutions and providing appropriate design margins consistent with the allocated requirements. Additionally, refueling studies have confirmed that the SC-HTGR can meet refueling timeline necessary to stay within the planned outage allocation of approximately 21 days. Anticipated unplanned outage allocations will be continually monitored during the detailed design process and confirmed by progressively more detailed probabilistic reliability analysis.

Overall reliability of an industrial energy delivery system using SC-HTGR as a key component was evaluated for several potential energy plant configurations. The results of the study demonstrated that the extreme availability and reliability requirements of a process heat plant can be met with HTGRs as the primary heat source. Similar to current industrial practice, the optimal configuration will be a hybrid system which includes low operating cost units (such as HTGRs) as the primary heat sources for baseload operation supplemented by low capital cost units (such as natural gas-fired boilers) in standby mode as backup to achieve the required reliability.

3.4. Reactors in the Design Stage

The SC-HTGR is the most credible advanced reactor option available for commercial deployment in the early 2030s. The design relies on near-term technology to the maximum extent possible in order to minimize project risk and to allow near-term markets to be served as soon as possible. Its systems, structures, and components are at high technology readiness levels that allow the design, procurement, and fabrication of the full size equipment. Key remaining development activities are limited to the ongoing TRISO fuel and nuclear grade graphite qualification work. Interim results from these programs are excellent, and the remaining work will be completed in time to support the licensing of the full size demonstration plant.

Steam cycle modular HTGR technology is in a unique position in that it is directly supported by the successful operation of previous HTGR concepts of comparable size and operating conditions. All components are derived from components successfully applied in earlier HTGR demonstration reactors or in other relevant industrial facilities. While most advanced reactor concepts are based solely on scoping studies and evaluations or laboratory-scale reactor experiments, the steam cycle HTGR builds on substantial past commercial scale reactor experience. Even though previous operating HTGRs were not modular reactors employing fully passive heat removal under all conditions, they provide a solid foundation of successful experience in most facets of HTGR technology. The SC-HTGR fully leverages the successful operating experience and lessons learned from these past concepts.

There are no new materials needs for various SC-HTGR components and the technology readiness of major structures, systems, and components is high and well within existing technical capabilities.

It is important to note that technology readiness levels (TRL) of the HTGR major components are high; meaning existing manufacturing capabilities are available and no additional technology development is required.

4. *Safety Concept*

SUMMARY FOR BOOKLET

The primary safety objective of the SC-HTGR design is to limit the dose from accidental releases so that the US Environmental Protection Agency Protective Action Guides are met at an exclusion area boundary only a few hundred meters from the reactor. To achieve this safety objective, the design uses the high temperature capabilities of TRISO-coated fuel particles, graphite moderator, and helium coolant, along with the passive heat removal capability of a low power-density core and an un-insulated steel reactor vessel.

The primary radionuclide retention barrier in the SC-HTGR consists of the three ceramic coating layers surrounding the fuel kernel that forms a coated fuel particle. The coating system constitutes a micro-scale pressure vessel around each kernel that has been engineered to withstand extremely high temperatures without losing its ability to retain fission products even under accident conditions.

The high temperature capabilities of the massive graphite reactor core structural components complement the fuel's high temperature capability. The high heat capacity and low power density of the core result in very slow and predictable temperature transients even without cooling. Helium, the reactor coolant and heat transport medium, is chemically inert and neutronically transparent. Additionally, helium will not change phase during normal operation or accidents.

4.1. Safety Philosophy and Implementation

The primary safety objective of the SC-HTGR design is to limit the dose from accidental releases so that the US Environmental Protection Agency Protective Action Guides are met at an exclusion area boundary only a few hundred meters from the reactor. To achieve this safety objective, the design uses the high temperature capabilities of TRISO-coated fuel particles, graphite moderator, and helium coolant, along with the passive heat removal capability of a low power-density core and an un-insulated steel reactor vessel.

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The SC-HTGR has three heat removal systems. The two main cooling loops transfer heat to the secondary circuit during normal operation. When maintenance is being performed on the main cooling loops, a separate shutdown cooling system is available. This system uses a separate and independent circulator and heat exchanger located at the base of the reactor vessel. These systems also provide cooling during refueling and normal shutdown conditions as well as most Anticipated Events and Design Bases Events.

If the above two active systems are unavailable, the SC-HTGR is designed to passively remove decay heat from the core regardless of whether or not the primary coolant is present. The Reactor Cavity Cooling System (RCCS) is a redundant natural circulation water-cooled system that maintains acceptable concrete temperatures in the reactor cavity during normal operation and Anticipated Events, and maintains acceptable fuel, vessel, and concrete temperatures during Design Basis Accidents. This heat removal path remains effective even if all primary coolant has been lost. Heat from the core is conducted radially through the graphite reflectors to the core barrel and eventually to the reactor vessel. Heat is transferred from the vessel to the RCCS by thermal radiation and natural convection. The concrete walls surrounding the reactor vessel are covered by the RCCS panels, which provide natural circulation cooling during both normal operation and accidents, eliminating the need for the system to change modes or configuration in the event of an accident. Each independent loop of the safety-related RCCS consists of heat collecting panels in the cavity surrounding the reactor vessel connected by a natural circulation loop to a water storage tank. See Figure 10. This loop uses natural circulation for all operating and accident conditions. A separate, non-safety-related active loop cools the tank during normal operation. The water in the tank provides the required thermal capacity for a minimum of 7 days of continued cooling during accidents when the active system may not be available.

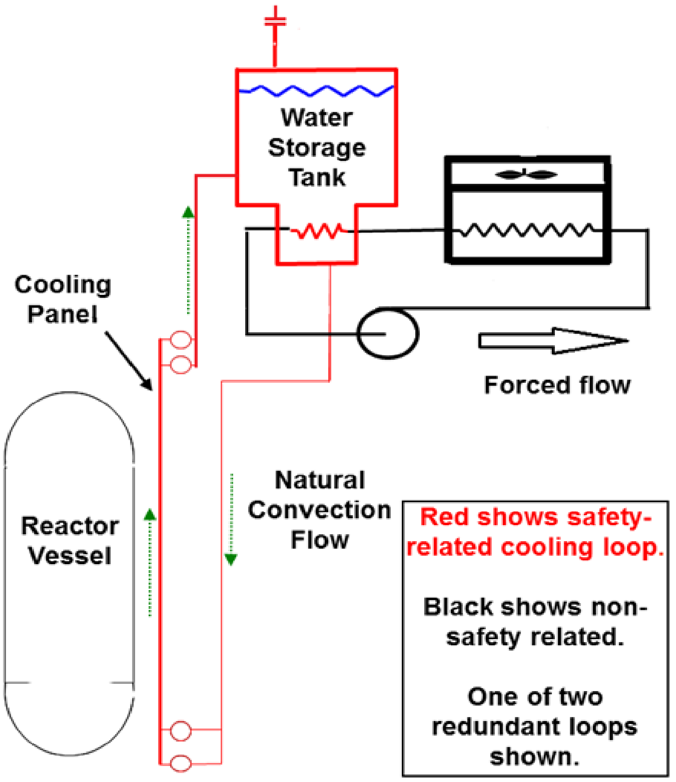

Figure 10 : Simplified RCCS Diagram

The radionuclides containment function in the SC-HTGR is performed primarily by the TRISO fuel coatings. The graphite core structures, primary coolant boundary, and reactor building provide supplemental containment capability. The SC-HTGR reactor building uses a vented confinement system. The building provides supplemental fission product retention in the event of an accident. However, a pressure retaining building such as a light water reactor containment building is not necessary or technically appropriate due to the excellent fission product retention performance of the fuel even under extreme accident conditions.

Engineered Safety System Configuration and Approach - No powered safety-related systems and no operator actions are required to respond to any of the accident scenarios that have been postulated for the various modular HTGR concepts, including the SC-HTGR, throughout the modular HTGR licensing history.

Reactor Cooling Philosophy - The SC-HTGR has three heat removal systems. The two main cooling loops transfer heat to the secondary circuit during normal operation. When maintenance is being performed on the main cooling loops, a separate shutdown cooling system is available. This system uses a separate and independent circulator and heat exchanger located at the base of the reactor vessel. These systems also provide cooling during refueling and normal shutdown conditions as well as most Anticipated Events and DBEs.

If the above two active systems are unavailable, passive heat removal can be used. Heat from the core is conducted radially through the graphite reflectors to the core barrel and eventually to the reactor vessel. Heat is transferred from the vessel to the Reactor Cavity Cooling System (RCCS) by thermal radiation and natural convection. This heat removal path remains effective even if all primary coolant has been lost.

Radionuclides Containment Function - The radionuclides containment function in the SC-HTGR is performed primarily by the TRISO fuel coatings. The graphite core structures, primary coolant boundary, and reactor building provide supplemental retention and containment capability. The SC-HTGR reactor building uses venting to the atmosphere during a primary system depressurization accident. The reactor building provides supplemental fission product retention in the event of such an accident. However, a pressure retaining reactor building such as a light water reactor containment building is not necessary or technically appropriate due to the excellent fission product retention performance of the fuel even under extreme accident conditions.

4.2. Transient/Accident Behaviour

As described above, the SC-HTGR utilizes three primary heat removal systems, two for normal operations and one for emergency cooldown. Limiting design basis accidents are defined by events that result in maximum core and vessel temperatures mitigated only by safety related components. The most challenging heat removal event for high temperature gas reactors is a depressurized loss of forced cooling event, typically called a depressurized conduction cooldown (DCC). In this event, the plant suffers a complete loss of primary coolant, electrical power and all active cooling systems. Therefore, the SC-HTGR main coolant loop with steam generator heat removal and the shutdown cooling system are unavailable for core heat removal. All core and vessel heat removal for the DCC event is accomplished by the safety related, passive RCCS.

The RCCS is the sole safety related heat removal system in the SC-HTGR design. During a DCC, no changes to the RCCS normal operational system configuration are required. After reactor trip via the safety related control elements, core heatup occurs. Due to the very large thermal mass of the SC-HTGR, core and vessel heatup are very slow evolutions allowing sufficient time for operator diagnosis, monitoring and response. Core decay heat is removed from the fuel assemblies through the vessel internals and vessel wall, across the vessel cavity and to the RCCS panels via conductive and radiative heat transfer. Heatup of the RCCS fluid drives a natural circulation flowpath in the system which conveys the core decay heat to the ambient environment heat sink. The overall core temperature transient response is a gradual heatup followed by a cooldown. Preliminary scoping analysis have demonstrated that, even under these challenging accident conditions, the predicted core temperatures are maintained within the accepted TRISO fuel performance window and the TRISO fuel maintains fission product retention. Additionally, these preliminary analyses have demonstrated that the vessel internals and walls are maintained within the ASME Section III Division 5 material temperature criteria (refer to Table 5).[vi]

Table 5: Preliminary SC-HTGR DCC Analysis Scoping Results

Component	Conservative Peak Temperature	Scoping Acceptance Criterion
Fuel	1635°C	1650°C
Core Barrel	784°C	800°C
Reactor Vessel	482°C*	538°C
*Duration RPV above 371°C Duration RPV above 427°C	446 hrs 233 hrs	750 hrs 250 hrs

All SC-HTGR systems, structures and components (SSC) important to safety are designed to withstand the effects of natural phenomena such as earthquakes, tornados, hurricanes, floods, tsunami and seiches without the loss of capability to perform their design safety function. In addition, structures important to safety will perform their design safety functions under consideration of aircraft impacts per US NRC final rule RIN 3150-AI19.

5. *Fuel and Fuel Cycle*

SUMMARY FOR BOOKLET (optional)

The SC-HTGR has been designed to operate economically and efficiently using the once through, uranium based fuel cycle. It has the capabilities to capitalize on advanced fuel cycle strategies should supporting facilities be developed and deployed, though such industrial facilities are not currently in existence.

The core cycle length for the SC-HTGR is between 420 and 540 effective full-power days. This has been confirmed for the initial core, using an initial core loading of 10.36 w/o U-235 enriched particles with a packing fraction of 0.289 for all fuel elements in the core, and for reloads utilizing half-core replacement with fuel blocks having a 15.5 w/o U-235 enrichment and a packing fraction of 0.279.

5.1. Fuel Cycle Options

The SC-HTGR utilizes a particle-based fuel system in which fissionable material is contained within small individual fuel particles, which are formed with a carbonaceous binder into fuel compacts. In a TRISO particle, uranium oxy-carbide (UCO) kernel of fissionable material is surrounded by layers of various materials designed to work together to encapsulate the fuel and fission products over the lifetime of the fuel. TRISO fuel can withstand temperatures in excess of 1600°C (2912°F) without damage. These fuel compacts are themselves loaded into prismatic graphite blocks to form a basic fuel element as shown in Figure 11.

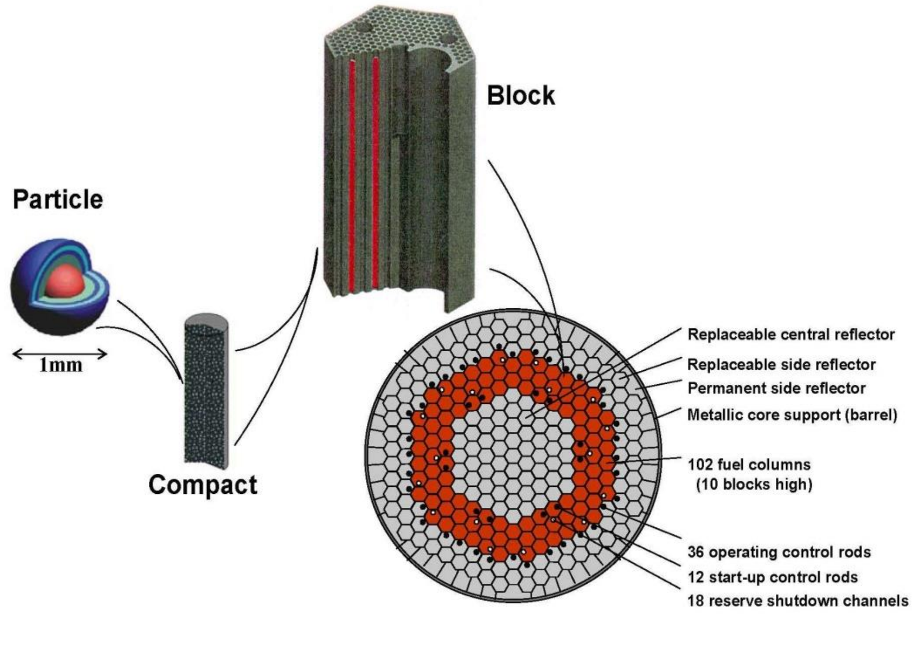

Figure 11: Ceramic Fuel Particles in Graphite Prismatic Block in Annular Core

The basic fuel element is a hexagonal graphite block of 360 mm external flat to flat width and 800 mm height. The core structure consists of an annular arrangement of prismatic fuel and reflector blocks, both replaceable by means of a fuel handling machine. The fuel blocks are configured into a 102 column annular core surrounded by graphite reflector elements. The inner or central reflector also contains graphite reflector elements, refer to Figure 12. Hence, the basic core structure is entirely ceramic. This configuration maximizes the reactor's passive heat removal capability. The active core is 10 blocks high. Thirty (30) columns have a dedicated channel for the introduction of an absorber material, 12 for control rods and 18 for Reserve Shutdown System (RSS) control material. The other 72 columns contain only fuel, with no control rod or RSS channel.

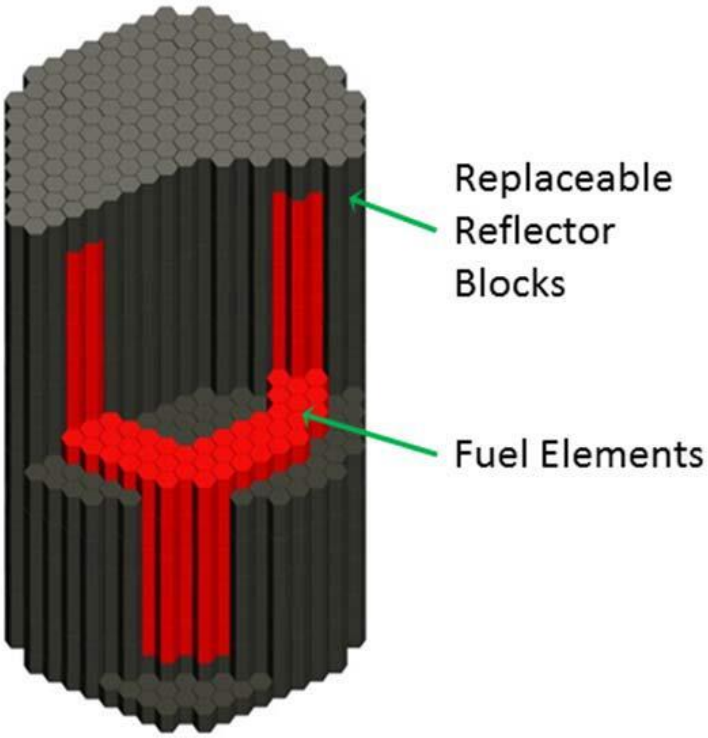

Figure 12: SC-HTGR Core Structure

The core cycle length for the SC-HTGR is between 420 and 540 effective full-power days. This has been confirmed for the initial core, using an initial core loading of 10.36 w/o U-235 enriched particles with a packing fraction of 0.289 for all fuel elements in the core, and for reloads utilizing half-core replacement with fuel blocks having a 15.5 w/o U-235 enrichment and a packing fraction of 0.279.

The large negative temperature coefficient of the modular SC-HTGR, along with its large thermal margins, provide for an inherent shutdown capability to deal with failures to scram the reactor. Gravity-driven and diverse reactivity control systems provide further confidence of the ability to shut down the reactor. Control of local fuel power peaking and limiting of resulting peak fuel temperatures at critical locations within the fuel block will be accomplished through loading discrete burnable absorbers, variation of fuel packing fraction, and variation of fuel particle enrichment.

5.2. Resource Use Optimization

The SC-HTGR core design allows the optimization of the core power distribution in three dimensions and can also be used to support effective fuel utilization, proliferation resistance and waste reduction. The high thermal efficiency and high fuel burnup of the SC-HTGR support sustainability for current once-through fuel cycles by minimizing spent fuel volume. Because the thermal efficiency of HTGRs is roughly 1.5 times higher than for LWRs, the quantity of fission products generated per unit of electricity produced will be correspondingly lower by a factor of 1.5. Therefore, storage and disposal requirements, which largely depend on fission product decay heat, will be lessened by about 50% for HTGRs as compared to LWRs. The high burnup achieved by HTGR fuel means that the transuranic production per unit of electricity produced will be improved and the isotopic composition of the plutonium in the spent fuel will be degraded by a significant concentration of Pu-238. The LEU once through fuel cycle requires about 6.8 MTHM/GWe-yr that equates to a natural uranium feedstock utilization of about 224 MT/GWe-yr. The SC-HTGR core design is also compatible with various more advanced fuel cycles employing fertile/fissile material conversion and recycle including Th/U, Th/Pu, Pu, and actinide fuel forms.

5.3. Unique Fuel/Fuel Cycle Design Features (if any)

The TRISO coated particle fuel with UCO kernel is the ultimate accident tolerant fuel forms. The fuel qualification currently being completed shows excellent radionuclide retention during the credible post-accident scenarios of depressurized conduction cooldown and pressurized conduction cooldown. Continues coating and modern CVD (chemical vapor deposition) techniques has been shown to produce high quality fuel can be manufactured consistently.

6. *Safeguards and Physical Security*

SUMMARY FOR BOOKLET (optional)

The SC-HTGR design will fully cooperate with the all regulatory requirements defined by the applicable regulatory authority (e.g. French, EURATOM, USNRC, IAEA) having jurisdiction over the control of nuclear materials. Among the primary design goals for the SC-HTGR systems is proliferation resistance and physical protection which focus on controlling and securing nuclear material and nuclear facilities.

Additionally the SC-HTGR plant design will have comprehensive securities features that, at a minimum, meet the requirements of the national regulating authority.

6.1. Safeguards

The SC-HTGR fuel cycle is proliferation resistant by design. New fuel enrichments are less than 20% U-235 which meets typical regulatory requirements for low enriched uranium. The International Atomic Energy Agency (IAEA) acknowledges that LEU is of less immediate use to potential "proliferators" than U enriched to 20% or more as re-enriching to higher levels is first required to make an efficient nuclear device. The SC-HTGR TRISO fuel is not as amenable to extraction of the LEU as are some other types of nuclear fuels thus making SC-HTGR fuel a less desirable candidate for diversion. Once the fuel is irradiated, like other used nuclear fuel, the external radiation hazard is substantial; heavy shielding would be required to avoid a lethal dose.

There are a number of barriers that make it difficult to produce a nuclear explosive (nuclear device) related to isotopic composition of the material, isotopic separation/processing required, radiation hazard and signature, and detectability and difficulty of movement of the mass / bulk required. The SC-HTGR utilizes a number of these barriers to ensure proliferation resistance. For example:

- The reference fuel cycle uses low enriched uranium that has less strategic value and is of less immediate use to potential proliferators than U enriched to 20% or more. LEU from new SC-HTGR fuel would require re-enrichment to higher levels to make it into weapons-useable material.
- In new SC-HTGR fuel, small kernels of fissile material are encased in a carbide coating along with other buffering layers making it more difficult to recover the contained uranium than from some other oxide fuel types. Carbide fuels are more difficult and time-consuming to dissolve and reprocess into weapons-usable material.
- In used fuel, the discharge exposures are much higher than in some counterpart fuels, resulting in Pu isotopic compositions (high Pu -238 and Pu-240 content) that make use of the material relatively unattractive for use in an illegal nuclear device.
- High temperature gas reactors by nature are excellent consumers of the plutonium that is generated in an LEU cycle compared to that generated in a typical light water reactor cycle. The SC-HTGR generates about a half of the typical light water reactor plutonium amount which from a proliferation perspective is an advantage because less undesirable material is produced.

- Like other use nuclear fuel, the external radiation hazard is substantial with the used SC-HTGR fuel and any attempts to divert it without use of a large shielded vessel would likely lead to a lethal dose to the individuals involved.
- All fuel elements are uniquely identified for accountability and are tracked by the fuel handling system.

The design of the SC-HTGR will meet all regulatory requirements for nuclear material safety and safeguards established by the competent regulatory authority having jurisdiction at the plant location. The design emphasizes passive barriers to the potential theft of nuclear materials with a minimization of operator actions to respond and mitigate security and safeguards events.

6.2. Security

Security of the HTGR facility is provided both by the inherent invulnerability of the system to malicious acts and by the optimization of the facility critical component arrangement to prevent unintentional access. The fundamental safety characteristics of the system make it resistant to inappropriate operator actions of omission or commission. This also minimizes the vulnerability of the system to deliberate malicious acts (such as deactivating cooling systems or removing the primary coolant). In addition, the minimal reliance of the system on safety cooling or protection systems minimizes the vulnerability to potential sabotage involving those systems.

6.3. Unique Safeguards and/or Security Features (if any)

Limited access to the reactor underground silo and all passive decay and residual heat removal features of the SC-HTGR reduces vulnerability of the reactor to any malicious internal or external acts. The size and weight of the fuel blocks in addition to digital accountability of individual blocks eliminates the potential for theft or diversion.

7. *Project Delivery and Economics*

SUMMARY FOR BOOKLET (optional)

- Project Preparation and Negotiation
- Construction and Commissioning
- Operation and Maintenance

7.1. Project Preparation and Negotiation

Framatome is currently in discussions with potential government agencies, investors and early adopters for funding opportunities to build the first commercial scale plant to demonstrate design completion, licensability, cost, and schedule.

7.2. Construction and Commissioning

There has been several high temperature gas reactor cost estimates produced by various independent design teams both the prismatic and block type HTGRs in the same design category (i.e. core outlet temperature of ~750°C). These cost estimates were validated and commingled by Idaho National Laboratory (INL) to build up a benchmark figure for modular HTGR reactors of various module sizes. The overnight capital cost trend for three types of modular HTGRs is shown in Figure 13.

The blue, red, and green lines trace overnight capital costs for modular HTGRs that use a 200 MWt/module pebble bed reactor, a 350 MWth/ module prismatic reactor, or a 600 MWth/ module prismatic reactor respectively. The overnight capital cost estimates for an eight-module pebble bed plant (w/200 MWth per module), a four module prismatic plant (w/350 MWth per module), and a four-module SC-HTGR plant (w/625 MWth per module) indicate good agreement with the expected trend lines. Two observations can be made from this figure: a) economy of scale - the overnight cost of a 600 MWth per modular plant is lower than that for a 200 MWth per module plant, and b) pebble bed modular HTGR technology is 30% more expensive than prismatic HTGR technology.

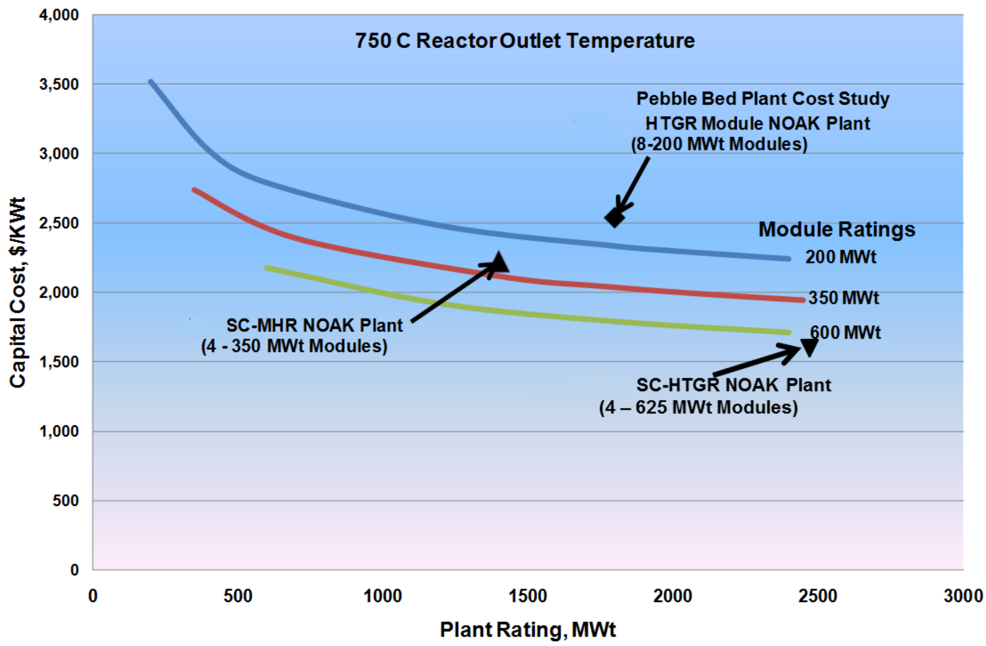

Figure 13: HTGR NOAK Plant Capital Cost as a function of Module and Plant Ratings

As discussed above, the SC-HTGR power level can be scaled to account for specific customer demand. For example, specific scaling processes and parameters as well as conceptualized design optimizations were utilized to scale costs for a 165 MWth SC-HTGR single module plant. The NOAK plant capital cost roll-up was determined to be approximately $3,600 $/KWth for a one module 165 MWth steam only HTGR plant. The conformance of the scaled capital cost with the trend lines in Figure 13 (which uses several independent cost estimates) indicate that the utilized scaling process and parameters is reasonable.

Schedule

The most efficient path to commercialization of the HTGR technology is through the design and licensing of the reference FOAK demonstration plant.

Concurrent with the licensing activities, the design process follows a systems engineering approach to design progression. This includes the Conceptual Design (2-years), Preliminary Design (2 years), Final/Detail Design (3 years), procurement activities, and construction overlapped with licensing activities. A summary schedule is presented in Figure 14.

The SC-HTGR design concept was developed with a low-risk philosophy in part to allow timely deployment of the initial demonstration unit. Taking advantage of the technology maturity of the SC-HTGR, a schedule has been established for development and deployment of the FOAK plant. This schedule indicates that initial operation of the first module is expected to commence approximately 13 years following initiation of Conceptual Design. Completion and operation of the remainder of the four module plant is expected to follow in four years. This schedule assumes that there is a source of adequate funding available to support all required activities. Insufficient funding, at any point in the schedule will delay the commercial operation date.

Supporting this schedule is a mature infrastructure able to provide the materials, particularly fuel, graphite, and pressure boundary components necessary for the first plant.

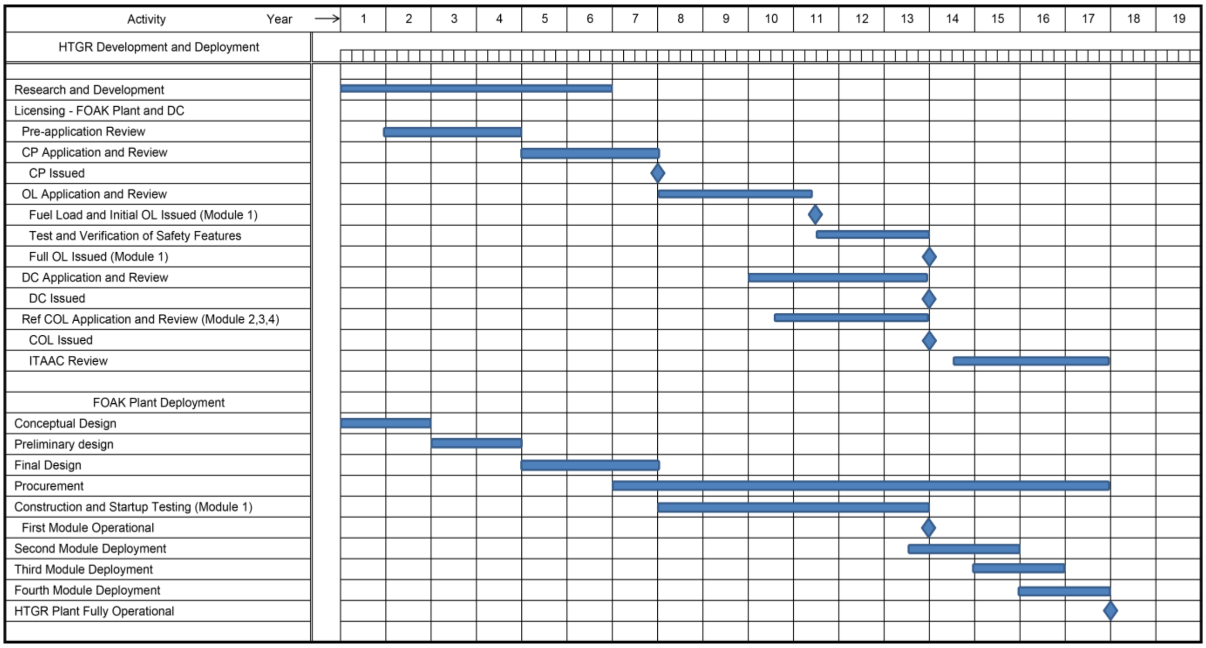

Figure 14: Summary Project Schedule

7.3. Operation and Maintenance

The design of the reference SC-HTGR concept is currently in the early Conceptual Design Phase. Further design activity is required to complete the remaining Conceptual Design work, to perform the Preliminary Design work required to support the licensing and order long lead materials, and to complete the Final Design work necessary for actual construction of the demonstration plant. The Conceptual and Preliminary Design development are considered one-time costs. The Detailed Design cost is for the FOAK plant. Other costs include FOAK site-specific Detail Design cost and the engineering costs during construction of the first plant.

The commercial demonstration will consist of the initial single reactor module operation to confirm that all licensing requirements and performance requirements have been satisfied. The demonstration project is then expanded to include the remaining modules of a full four module plant.

The operations costs of the reference FOAK plant include the fuel, operation, engineering, security, and maintenance staffing costs. The revenue generated during the “shake-down” will defray the operating expenses. The extra cost for the development project is the cost associated with the specific demonstration tests that must be run which will briefly suspend revenue generating operations.

This is a multi-year project with the lowest financial, technical, and regulatory risks among the advanced Generation IV reactor concepts. The outcome of this development venture will be a commercial demonstration plant with four SC-HTGR modules (625 MWth / module). Table 6 includes the cost estimate associated with each category.

Table 6: Reference FOAK Plant Design, Development, Construction, and Operation Cost[3]

SC HTGR Cost Breakdown ($x-1000)	1st Module	FOAK Plant (Modules 1-4)	One Time Costs
Development (Remaining R&D)			**$245,000**
Equip. & Infrastructure Development			**$175,000**
Engineering			**$270,000**
Conceptual Design			$97,000
Preliminary Design			$173,000
Final Design	**$311,000**	**(2)**	
Engineering During Construction	**$223,000**	**(2)**	
Licensing			
CP, OL, COL			**$140,000**
DC			**$70,000**
License Cost (per year)	**$11,000(1)**	**$5,000**	
Hardware and Construction (total)	**$1,459,000**	**$5,545,000**	
Power Conversion Plant	**$281,000**	**$1,069,000**	
Process Heat Plant	**$65,000**	**$247,000**	
Nuclear Heat Plant	**$582,000**	**$2,211,000**	
Reactor Systems (vessels, CRDs, etc.)	$388,000	$1,475,000	
Primary HTS Capital Cost (Circ. Etc.)	$53,000	$201,000	
Secondary HTS Capital Cost (SGs, etc.)	$141,000	$535,000	
Overall Site BOP	**$531,000**	**$2,018,000**	
Reactor building (below ground)	$77,000	$291,000	
Power conversion building	$16,000	$59,000	
Other buildings & Plant Systems	$439,000	$1,668,000	
Fuel (initial core)			
1020 Blocks	$168,000	$672,000	
Land and Infrastructure	**$182,000**	**(2)**	
Owner's Indirect Cost	**$638,000**	**(2)**	
O&M per year (no fuel)	**$25,000**	**$100,000**	
Annualized fuel costs (1/2 core every 18 months)	**$56,000**	**$224,000**	

(1) Per year for 3 year testing phase only
(2) Included in the 1st module cost
(3) In 2015 dollars

i. NGNP Fuel Qualification White Paper, Idaho National Laboratory, INL/EXT-10-17686, July 2010.

ii. AREVA Report 12-9051191-001, "NGNP with Hydrogen Production Preconceptual Design Studies Report", June 2007.

iii. Lommers, L., "Advanced Fuel Cycles and Actinide Burning in HTRs and NGNP", MIT Symposium on NGNP Goals and Challenges, February 23-24, 2005.

iv. Brooks, L.H., Lotts, A.L., Wymer, R.G., "Progress in the Thorium-Uranium-233 Reprocessing-Refabrication Technology, ANS-CONF-740501, Topical Meeting on Gas-Cooled Reactors, May 7-10, 1974, Gatlinburg, TN.

v. Lommers, L. J.,et. al., "SC-HTGR Performance Impact for Arid Sites", Proceedings of the HTR 2014, Weihai, China, Paper HTR2014-21345, October 2014.

vi. Lommers, L.J., et al., "Passive Heat Removal Impact on AREVA HTR Design," Proceedings of the HTR 2012, Tokyo, Japan, Paper HTR2012-8-010, November 2012.