Attachment 1

Demonstration Reactor Point Design Details: AREVA Steam Cycle – High Temperature Gas-Cooled Reactor

AREVA Inc.

Technical Data Record

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Summary Report – SC-HTGR Demonstration Reactor

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LIST OF ACRONYMS

AGR	DOE Advanced Gas Reactor TRISO fuel program
AVR	German experimental pebble bed reactor (Arbeitsgemeinschaft Versuchsreaktor)
CP	Construction Permit
DBE	Design Basis Event
DCA	Design Certification Application
DC	Design Certification
DOE	US Department of Energy
EAB	Exclusion Area Boundary
EFPD	Effective Full Power Days
EPA	US Environmental Protection Agency
EPZ	Emergency Planning Zone
FOAK	First of a Kind
GHG	Greenhouse Gas
HTGR	High Temperature Gas-Cooled Reactor
HTTR	High Temperature Engineering Test Reactor
INL	Idaho National Laboratory
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MOX	Mixed Oxide
MWe	Megawatts Electric
MWth	Megawatts Thermal
NGNP	Next Generation Nuclear Plant
NOAK	Nth of a Kind
NRC	US Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
O&M	Operation and Maintenance
OL	Operating License
PSAR	Preliminary Safety Analysis Report
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
RCCS	Reactor Cavity Cooling System
SC-HTGR	Steam Cycle - High Temperature Gas-Cooled Reactor
THTR	Thorium High Temperature Reactor
TRISO	Tri-Structural Isotropic
TRL	Technology Readiness Level
UCO	Uranium Oxycarbide
VHTR	Very High Temperature Reactor

EXECUTIVE SUMMARY

The Steam Cycle – High Temperature Gas-cooled Reactor (SC-HTGR) is a near-term advanced reactor concept that is being developed to provide high temperature steam for process heat applications. It also provides high efficiency electricity generation for small markets and markets requiring incremental capacity addition. This will extend the benefits of nuclear power to the broader energy economy.

The SC-HTGR is a modular, helium-cooled, graphite-moderated, high temperature nuclear heat source. Each reactor module has an annular prismatic block core with a power level of 625 MWth (272 MWe net module output) and a core outlet temperature of 750°C. The reactor uses low enriched uranium (LEU) oxycarbide (UCO) fuel which is encapsulated in TRISO coated fuel particles contained in graphite fuel elements. This provides high burnup capability and excellent fission product retention.

The main Heat Transport System uses heat from the reactor to produce superheated steam at 566°C and 16.7 MPa. Each reactor module is coupled to two helical coil steam generators in parallel. The system uses electrically driven circulators for maximum reliability. A Shutdown Cooling System is also available for heat removal during maintenance. And the natural circulation Reactor Cavity Cooling System provides cooling of the reactor cavity under all operating and accident conditions.

Each SC-HTGR plant contains one or more standard reactor modules. The use of standardized reactor modules best leverages the substantial investments in design, licensing, and fabrication capability in order to minimize deployment cost. The specific plant configuration for each site depends on the total energy demand and the type of energy required. The energy demand determines the number of standard reactor modules, and the type of energy determines whether the balance of plant is configured for process steam supply, electricity generation, or cogeneration.

In the all-electric mode, the plant uses a conventional Rankine cycle with a net efficiency of 43.5 percent.

The SC-HTGR is exceptional in its capability to serve process heat users. High temperature steam meets the needs of a broad segment of the process heat market. The use of a modular reactor concept allows the plant capacity to be tailored to individual applications. And the safety characteristics provide low investment risk which is required by chemical plant owners.

Together, industrial process heat and transportation fuels account for about half of the total US energy economy. In coming decades, large scale supplies of non-fossil energy will be required to support process industries and synthetic transportation fuel production due to increasing environmental constraints, energy price stability concerns, and the need to preserve chemical feedstocks. Increasing energy demand in all sectors will further exacerbate this situation. These high temperature demands cannot be replaced by renewable sources such as wind or solar. The only economical option within technical reach today that can provide a secure source of greenhouse gas-free energy with stable long-term prices is the HTGR.

A conservative estimate shows that a U.S. market approaching 600 SC-HTGR modules could exist for process heat users in the next four decades. Such a deployment is achievable and would eliminate 480 million metric tons/year of CO_2.

The graphite-moderated SC-HTGR concept also benefits fuel cycle sustainability, since the reactor design is compatible with alternate fuel cycles using thorium, MOX, plutonium, and spent fuel actinides. In past HTGR development programs, TRISO fuel was successfully demonstrated using a variety of fissile and fertile materials including LEU, HEU, thorium, and plutonium.

Modular HTGRs offer unparalleled safety performance. The helium reactor coolant is inert, and it cannot change phase or react with other reactor materials under any circumstances. The ceramic core structural elements are graphite, which is robust at very high temperature and does not melt. The reactor has multiple shutdown systems and negative temperature coefficient of reactivity, so the reactor will shut itself down even if the active shutdown systems fail to respond to an accident.

The SC-HTGR configuration ensures acceptable fuel and component temperatures for all Design Basis Events. This accident performance is achieved without the need for active cooling systems, AC electrical power, operator actions, or even reactor coolant. The TRISO coated particles retain virtually all fission products, even at very high temperatures beyond those experienced during normal operation and accidents. These safety characteristics result in enhanced public safety and increased siting flexibility. As a result of the extremely low accident doses, no evacuation is required beyond the EAB (e.g., 400 m from the reactor).

The safety characteristics also minimize investment risk for both the plant operator and for any adjacent process heat users. They facilitate restart of the SC-HTGR plant following any Design Basis Accident, and they ensure that a reactor accident will not jeopardize adjacent industrial facilities.

The SC-HTGR design relies on mature technology in order to 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 and nuclear grade graphite qualification work being performed by INL and ORNL. Interim results from these programs are excellent, and the remaining work will be completed in time to support the full size demonstration plant.

Thus full scale demonstration of the SC-HTGR is the next logical step for this technology. This is a necessary precursor to full commercial deployment of the technology beginning around 2035. The objective of the proposed demonstration reactor project is to design, license, build, and operate a full size first-of-a-kind (FOAK) SC-HTGR. This will provide data needed to support US Nuclear Regulatory Commission (NRC) Design Certification necessary for commercial deployment, and it will provide the confidence expected in the commercial marketplace.

Beyond the near-term high temperature steam market, the SC-HTGR also provides a necessary step toward more advanced VHTR technologies to serve specific process heat markets requiring even higher temperatures. The SC-HTGR project will provide a solid foundation for further development by addressing common HTGR project risks including licensing, fuel qualification, safety case demonstration, siting including collocation with industrial facilities, and process heat interface definition. Then, while SC-HTGR fleet deployment proceeds, subsequent VHTR development can focus directly on remaining VHTR risks. This provides the lowest risk, most timely path forward to address both HTGR and VHTR markets.

Deployment of the SC-HTGR demonstrator before 2035 is an achievable goal. The ability to deploy the full scale FOAK plant without an intermediate smaller scale reactor eliminates substantial cost and shortens the overall commercialization schedule significantly. Relying on mature technologies minimizes technology risk compared to more advanced reactor concepts, and the exceptional safety characteristics of the modular HTGR minimize the licensing risk in comparison to other non-LWR advanced reactor concepts. This is the lowest risk path forward for any advanced reactor concept.

A government investment in the development and demonstration of this technology would provide large national benefits. The required investment for the demonstration reactor project (about $4B) is beyond the ability of industry, but it is small compared to the ultimate benefit to the national economy. This relatively small national investment would be leveraged many times over, first of all in the actual deployment of the SC-HTGR plant fleet, and eventually in the resulting economic activity enabled by this advanced energy source. Estimates indicate that the initial investment would be leveraged into approximately $1 trillion in domestic economic activity in the ensuing decades, it would enable domestic process industries to remain viable, and it would reduce GHG emissions from the process heat and associated electricity cogeneration sector by more than 480 million tons per year.

1.0 INTRODUCTION

This report provides a summary description of the Steam Cycle – High Temperature Gas-Cooled Reactor (SC-HTGR) point design. The SC-HTGR is one of the candidate demonstration reactor concepts proposed for consideration in the Advanced Test / Demonstration Reactor Planning Study being conducted by the US Department of Energy (DOE). In this study, the SC-HTGR and other candidate reactor concepts will be evaluated against a broad set of advanced reactor criteria. Within the study framework, Idaho National Laboratory (INL) is leading the advanced reactor working group addressing HTGR technology, and AREVA is assisting INL in defining HTGR advanced reactor concepts for both the test and demonstration reactor roles.

The SC-HTGR is a modular, helium-cooled, graphite-moderated advanced reactor. It has a prismatic block annular core with TRISO coated particle fuel. Each reactor module produces 625 MWth, capable of producing 272 MWe, with a reactor outlet helium temperature of 750°C which is used to produce high temperature superheated steam at 566°C. The SC-HTGR concept is a logical progression from the initial concept development work performed under the DOE Next Generation Nuclear Plant (NGNP) program.

The SC-HTGR is being developed to support electricity production and a variety of industrial process heat markets. The high temperature steam conditions are compatible with a broad segment of the process heat applications. Equally important, the exceptional safety characteristics of the SC-HTGR allow collocation of the nuclear steam source with chemical processing plants and other process heat users. Investment risk is minimized for both the SC-HTGR and the adjacent heat user, since no events result in significant damage to the SC-HTGR plant nor do they require evacuation of the chemical facility adjacent to the nuclear site boundary. The modular configuration of the SC-HTGR allows the overall plant size to be adjusted for the requirements of each application. It also supports incremental capacity addition for high efficiency electricity generation markets. In such applications, the net generating efficiency is 43.5%. Therefore, the SC-HTGR satisfies a market need for power reactors to be ‘smaller and safer’, while maintaining comparable economics with Generation III LWRs.

The objective of the proposed demonstration reactor project is to design, license, build, and operate a full size first-of-a-kind (FOAK) SC-HTGR. The SC-HTGR concept is based on established HTGR technology. It combines mature technology from past HTGR operating experience and more recent modular HTGR development work incorporating passive safety features. Thus, full scale demonstration is the next logical step for this technology. This is a necessary precursor to full commercial deployment of the technology beginning in 2032. Operation of the demonstration plant will provide data needed to support US Nuclear Regulatory Commission (NRC) Design Certification for fleet deployment, and it will provide the confidence and project certainty necessary for the commercial marketplace.

AREVA has developed this report in accordance with the requirements of INL/MIS-15-35444 [1] to support ongoing evaluations being conducted by INL and a panel of other national laboratory and university members. The information provided in this report is based on past AREVA work on the ANTARES concept, work performed for the NGNP by various program participants, NGNP Industry Alliance activities, and current AREVA work on the SC-HTGR design.

The remainder of this report provides a summary description of the SC-HTGR advanced reactor concept, and it addresses specific topics relevant to the advanced reactor study evaluation process and criteria. The information presented in this summary report is discussed in detail in Reference [2].

2.0 OBJECTIVES FOR NEXT GENERATION OF REACTORS

Two main sources were used to guide the development of the objectives described in the following sub-sections. Potential DOE perspectives are captured through consideration of a recently provided draft of DOE strategic objectives from the DOE Advanced Test and Demonstration Reactor study group [3]. Industry perspectives, including those of potential owner/operators and end users, are taken from the NGNP Industrial Alliance Business Plan. These sources are supplemented with reactor vendor perspectives, as informed by frequent contact with potential owner-operators of current and future reactors.

The objectives for the next generation of advanced reactors are:

Extend Benefits of Nuclear Power beyond Electricity Market - Transitioning of the process heat market from heavy reliance on fossil fuels to a more balanced portfolio of sources, including nuclear power, is necessary to achieve the desired reduction in GHGs to meet climate change goals, provide long term energy cost stability, and secure a reliable supply of energy and process feedstocks. Opening the process heat market to nuclear power will require an advanced reactor concept that demonstrates very robust and inherent safety characteristics.

Provide a Replacement of Fossil-Fired Electricity Generation - Adding new, advanced nuclear reactors to the electricity generating mix will reduce carbon sources and diversify the fuel supply with a stably-priced fuel source, thereby addressing environmental concerns and helping to mitigate future price volatility in the electric power market. To be effective in replacing existing fossil units, a reactor system must be sized to match existing capacity and be within an existing site footprint, and be able to load follow. For sites in more developed locations, the reactor safety profile must not disturb daily activities of the local population.

Provide Alternatives to Fossil Fuels in 2030-2050 Timeframe - In order to have a positive near-term impact, an advanced reactor design concept must be able to be deployed commercially beginning in the early 2030s. This will foster a potential build-out of additional reactor units over the following 20 years such that the benefits of the advanced reactor system can be realized in a meaningful way in the overall energy economy.

Exhibit Enhanced Safety and Reduced Investment Risk - To support public acceptance, and address vulnerabilities such as identified at Fukushima, proposed advanced reactors must introduce a fundamentally different accident response strategy and associated consequence profile. They should maximize reliance on natural processes and intrinsic safety characteristics, and minimize reliance on complex engineered safeguards systems, to build a robust system that practically eliminates significant core damage accidents. Adopting such a design philosophy will also address investor confidence by fostering the ability to re-start the reactor following any Design Basis Event.

Provide Incremental Capacity Addition - The ability to add small to moderate increments of power alleviates one of the major obstacles for new plant deployment, that is, the need to dedicate large sums of capital to add large blocks of power, not all of which may be necessary or desirable. The ability to add moderate-sized increments of power also makes advanced reactors more comparable with many existing process heat sources, thus simplifying the conversion of industrial facilities from reliance on fossil-fueled heat sources to use of nuclear heat.

Provide Long Term Fuel Cycle Flexibility - Advanced reactor concepts should support various fuel cycle alternatives to better configure the nuclear industry for the future. The reactor concept should support mitigation of the current spent fuel buildup by providing a mechanism to reduce existing spent fuel inventories. The concept should also be able to extend existing fissile material supplies and meet emerging fuel cycle challenges through a potential to use alternate fertile material supplies, such as a thorium fuel cycle.

Support Technology Development for More Advanced Concepts - The next advanced reactor should be able to support, at least in part, development and deployment of a later generation of technologies through demonstration of the technical and economic viability of nuclear power for roles beyond electricity generation. It should support development of alternative licensing strategies and protocols beyond those used to license the current fleet of LWRs.

3.0 MOTIVATION FOR SELECTING THE SC-HTGR CONCEPT

The SC-HTGR is an advanced reactor concept ideally suited for near term development and deployment. This reactor concept meets the majority of the near term objectives described in Section 2.0 in a manner that presents the least technical and project risk to achieving successful commercial operation in the early 2030s. This minimized risk approach to demonstrating an advanced reactor technology is critical to follow-on deployment in that it provides the greatest assurance of project success thereby facilitating marketplace consideration of other advanced designs. Initial success is critical; otherwise it will be very difficult for others to follow. Given this constraint, the SC-HTGR is the most viable option for an advanced reactor demonstration plant supporting deployment in the early 2030s.

It Has Broadest Impact on Energy Economy - The SC-HTGR concept can provide a source of both process heat and electricity for industry, thus providing a broad impact on the energy economy. Its intrinsic safety characteristics facilitate collocation with industrial installations and its ability to provide high temperature process heat allows it to address industrial sectors responsible for more than 20 percent of energy usage in North America. The national benefits obtained by displacing fossil fuels in these markets in coming decades will far outweigh the comparatively modest near-term cost of deploying the technology.

At 625 MWth per reactor module, the SC-HTGR is in the same size range as many fossil-fired boilers used in existing power plants. With a supplied steam temperature of 566°C, the SC-HTGR is compatible with process steam needs for a significant segment of industrial users and provides them with an alternative source of energy without the long term environmental or price and supply volatility issues associated with fossil fuels in coming decades. The SC-HTGR high temperature steam supply system not only offers the flexibility to serve a variety of process heat and electric applications, it also offers the flexibility to efficiently serve a wide variety of site conditions including sites requiring collocation with a process application and arid sites requiring dry cooling.

It Provides Enhanced Safety - The SC-HTGR is designed with unparalleled, "walk away" safety performance. In fact, the performance is such that there is no credible event during which the reactor sustains damage that would prevent restarting the plant. The Emergency Planning Zone for the reactor is limited to areas within the site boundary. SC-HTGRs can be located adjacent to operating industrial facilities and in other non-rural settings without the potential risk that operations of the reactor will negatively impact its neighbors. In short, SC-HTGR is designed so that electric power is not needed in order to prevent fuel damage and release of radionuclides.

This level of safety provides an acceptable risk profile for potential investors, both in the reactor and the adjacent process heat facility. The ability of the SC-HTGR to restart after all Design Basis Events removes the risk that an accident may require write-off of the plant or pose significant investment risks to adjacent facilities.

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.

It Maximizes Use of Existing Technology - The SC-HTGR was conceived to bring advanced high temperature reactor technology to the marketplace in a timely fashion with the least technology and investment risk. The chosen configuration minimizes risk through the use of established, mature technologies. The heart of the design, the prismatic block reactor core, is based on the successfully operated core designs in Fort St. Vrain and the High Temperature Engineering Test Reactor (HTTR). The particle fuel has been designed incorporating key lessons learned through operation of several earlier HTGR plants. This fuel is currently undergoing extensive testing under the INL AGR TRISO fuel development program, which is yielding exceptional results. All other key components are based on designs demonstrated in previous reactor systems or in other industrial applications. Section 8.0 provides additional discussion of the mature technical basis for the concept.

This low risk approach makes the SC-HTGR the Generation IV reactor with the most realistic opportunity to support operation of a first demonstration reactor in 2030 with commercial deployment anticipated by 2035. In fact, it is the leading advanced reactor technology that can support widespread deployment in this timeframe.

With all key technologies demonstrated, what remains is to design, license, and build an actual FOAK modular HTGR plant, i.e., complete the NGNP program as originally envisioned.

It Is Deployable in the 2030 Timeframe - 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 key components, a schedule has been established for development and deployment of the FOAK plant that supports initial operation approximately 13 years following the formal launch of full Conceptual Design. This 2029 FOAK operation capability will create confidence in a buildout of many modules in the 2030's. This schedule assumes that there is a source of adequate funding available to support all required activities. Plans for development and deployment of the SC-HTGR are discussed in Section 7.0.

Supporting this schedule is an established infrastructure able to provide the materials, particularly fuel, graphite, and pressure boundary components necessary for the first plant. There is no need to develop a full complement of new fuel cycle facilities to support operation of the first plant. The existing US pilot scale facilities and stockpiles will suffice to fuel the demonstration reactor. Expansion of this supply can be completed in concert with deployment of subsequent plants.

It Is Sized for Optimal Cost Performance - The 625 MWth, 272 MWe, power level of the SC-HTGR has been selected to support optimal cost performance while preserving the intrinsic safety attributes of this modular Generation IV reactor concept. Maximizing reactor module size, within modular HTGR design constraints, including passive heat removal, provides economies of scale not available to smaller HTGR concepts. For example, studies conducted during the course of the NGNP project demonstrated that a 600 MWth modular HTGR had an approximately 30-40% lower cost of energy compared to a 200 MWth HTGR.

The design condition that determines the maximum power achievable in a modular HTGR is the ability to passively remove decay heat from the core under all accident conditions without temperatures exceeding design allowable values for the fuel and other major components. For the SC-HTGR these design values were chosen such that not only is acceptable safety performance maintained, but the major components remain at temperatures within their normal allowable design envelope. This facilitates re-start of the reactor following any credible event without significant repair or major component replacement.

It Provides a Foundation for Future VHTR Development - Near-term deployment of the SC-HGTR will immediately impact the broader energy market and maximize the near-term benefits while providing the time necessary to complete technology development in key areas supporting VHTR development, and for markets potentially benefiting from this higher temperature process heat to mature. Initial operations of SC-HTGR will also provide operating experience to inform VHTR design.

Many of the technology choices implemented in the SC-HTGR design will also benefit advanced VHTR designs. Development of the SC-HTGR will also resolve some of the policy issues which also affect the VHTR. Deployment of the SC-HTGR in advance of the VHTR allows partitioning of development risks, with one set addressed and resolved, operational experience accumulated, and regulatory confidence gained prior to addressing the technically more challenging issues related to the very high temperature conditions of the VHTR.

It Supports Advanced Fuel Cycle Concepts - Though not its primary mission, the SC-HTGR supports a variety of advanced fuel cycle options consistent with goals of utilizing alternate fissile and fertile materials, and minimizing spent fuel wastes. Most of the HTGRs that have operated in the past were designed to employ a thorium fuel cycle and demonstrated its use at scales beyond those considered for the SC-HTGR. Several design programs, including the international GT-MHR program performed by OKBM, have explored the use of plutonium-fueled design variants to dispose of excess plutonium 239. The HTGR is able to handle a broad array of additional potential fuel cycles. This flexibility is a direct result of the unique combination of fuel, moderator, and coolant employed in the HTGR. The fuel cycle flexibility of the HTGR comes without the need to make significant changes to the reactor structure other than the fuel itself. Thus, an appropriately designed HTGR could operate with an LEU cycle, a MOX cycle, and an actinide burning cycle over different periods of its lifetime.

4.0 SC-HTGR DESIGN DESCRIPTION

The 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 the experience of past 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 MHTGR and the HTR-MODUL.

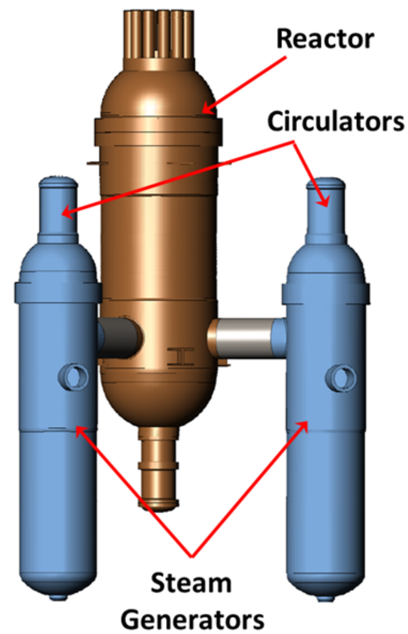

Figure 4-1 : Nuclear Process Steam Supply System

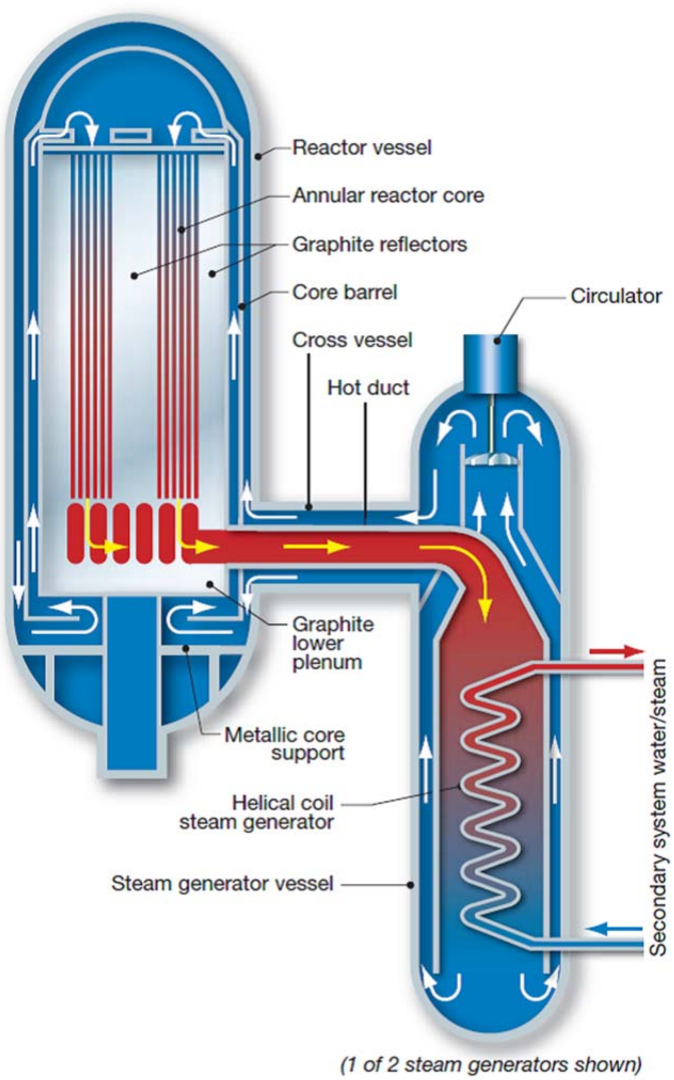

Figure 4-2 : Primary Circuit Layout

4.1 SC-HTGR System Arrangement

The SC-HTGR reactor is a two-loop modular steam supply system. Each module consists of one reactor coupled to two steam generators. The steam generators are configured in parallel, each with a dedicated main circulator, as shown in Figure 4-1.

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. 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 surface is bathed in cool reactor inlet gas, so conventional LWR vessel material can be used. This is shown in Figure 4-2.

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).

Electric motor-powered main circulators provide the primary coolant flow. The variable speed circulators use submerged motors with active magnetic bearings for simple operation and high reliability.

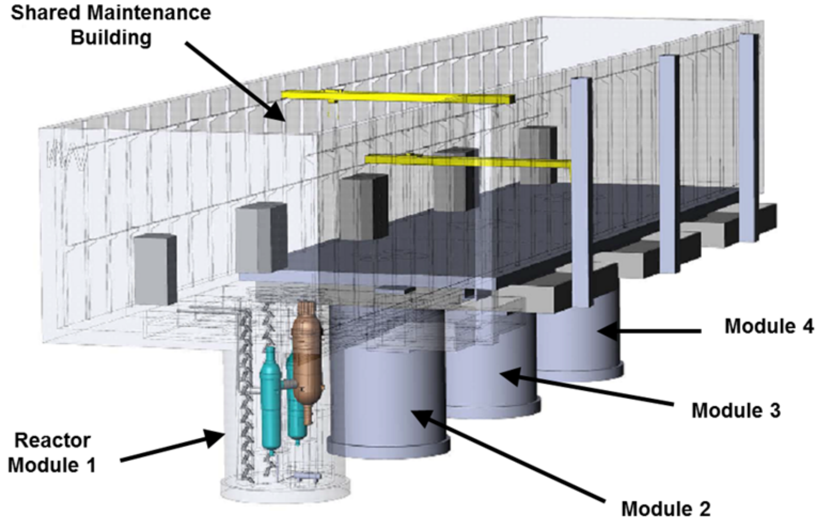

Figure 4-3 : Standard Reactor Building Configuration

Each reactor module is located in a separate reactor building. The standard configuration uses a fully embedded below grade reactor building design as shown in Figure 4-3. 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. 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.

Multiple reactor modules can be grouped together on a single plant site. 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, supporting systems and maintenance systems, but safety systems, including the RCCS and Reactor Protection System, are independent.

4.2 SC-HTGR Reactor Description

The SC-HTGR is designed around proven helium-cooled and graphite moderated reactor technology, the heart of which is the 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 4-4, 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.

The fuel blocks are configured into a 102 column annular core surrounded by graphite reflector elements as shown in Figure 4-5. 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 reactor inlet and outlet temperatures are 325°C

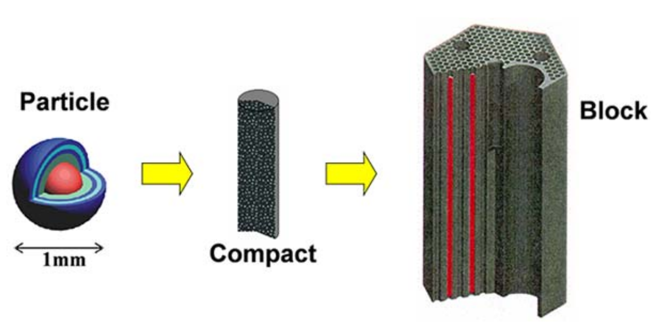

Figure 4-4 : TRISO Fuel Particle, Compact and Block

and 750°C, respectively. These temperatures were selected primarily to support the desired steam outlet conditions for the target markets.

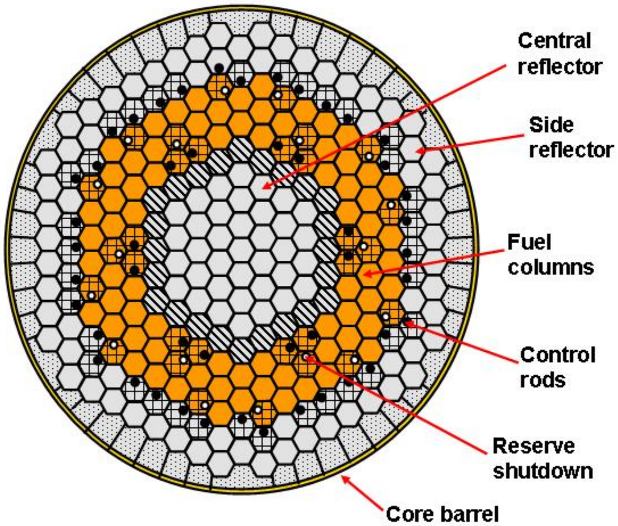

Figure 4-5 : Annular Core Layout

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.

4.3 Heat Removal Systems

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.

The RCCS, Figure 4-6, 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. Each 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. This loop uses natural convection 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 continued cooling during accidents when the active system may not be available.

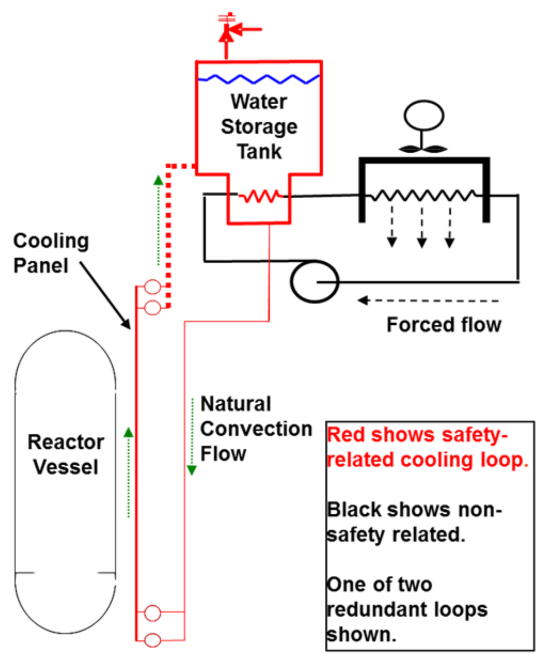

Figure 4-6 : RCCS Flow Path

4.4 SC-HTGR Normal Operating Performance

The achievable cycle length for the SC-HTGR is between 420 and 540 effective full-power days (EFPD). This has been confirmed for operation of the initial core, assuming 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 [4].

An assessment of the neutronic performance of the NGNP core was performed and is documented in Reference [4].This study can be used to judge the expected performance of the SC-HTGR due to the similarities in core design. Results of the study indicate an expected fast flux of 2.367E+13 n/cm^2-s (E>0.1 MeV) and thermal flux of 1.570 n/cm^2-s (E<= 0.1 MeV) at the interface between the inner row of core blocks and the first row of reflector blocks.

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. Results of scoping studies indicate that these strategies are effective and, since these are measures typically taken by core designers to optimize core performance, as more detailed core design analyses are conducted it is anticipated that a mix of these options will be used to achieve precise control of core power distribution in three dimensions. This will support effective fuel utilization and reduction of spent fuel wastes produced. It will also support proliferation resistance through minimization of the production of vulnerable isotopic characteristics in the spent fuel elements.

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. For the LEU once through fuel cycle, the SC-HTGR has a core heavy metal loading requirement of about 6.8 MTHM/GWe-yr. With the reference 15.5% enrichment, this equates to a natural uranium feedstock utilization of about 224 MT/GWe-yr. The SC-HTGR 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. These cycles will provide significantly improved utilization of uranium (and thorium) resources as long-term expansion of nuclear power increases uranium demand and drives the establishment of the required fuel cycle infrastructure.

The thermal-hydraulic performance of the SC-HTGR reactor core is linked directly to the nuclear core design to ensure that the power distribution results in acceptable fuel temperatures for the whole core for all operating modes over the life of the core. Specific consideration is given to beginning-of-life conditions where core bypass flow is lowest and end-of-life, when bypass flow is greatest.

The nominal electricity generation performance of the SC-HTGR system has been evaluated [5], taking into account preliminary efficiency estimates for the helium circulators, feedwater pumps, turbine, generator 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 has already been evaluated for hot arid locations where dry cooling was assumed to be required. Results of this evaluation indicate that a net electrical generation output of 239 MWe is achievable, for a corresponding efficiency of 38.2%. Results of these studies are shown on Table 4-1.

Table 4-1 : SC-HTGR Electrical Performance Summary

Type of site	Nominal	Hot Arid Site
Heat rejection mode	Wet Cooling	Dry Cooling
Wet bulb temperature	16°C	NA
Dry bulb temperature	36°C	45°C
Reactor power	625 MWt	625 MWt
Total house load	21 MWe	26 MWe
Net electricity generation	272 MWe	239 MWe
Condenser heat load rejected	340 MWt	369 MWt
Net efficiency	43.5%	38.2%

4.5 SC-HTGR Operational Configuration

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. The steam cycle is also 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 4-7 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 the potential flexibility of the system. The secondary and tertiary system of the plant can be easily customized for each end-

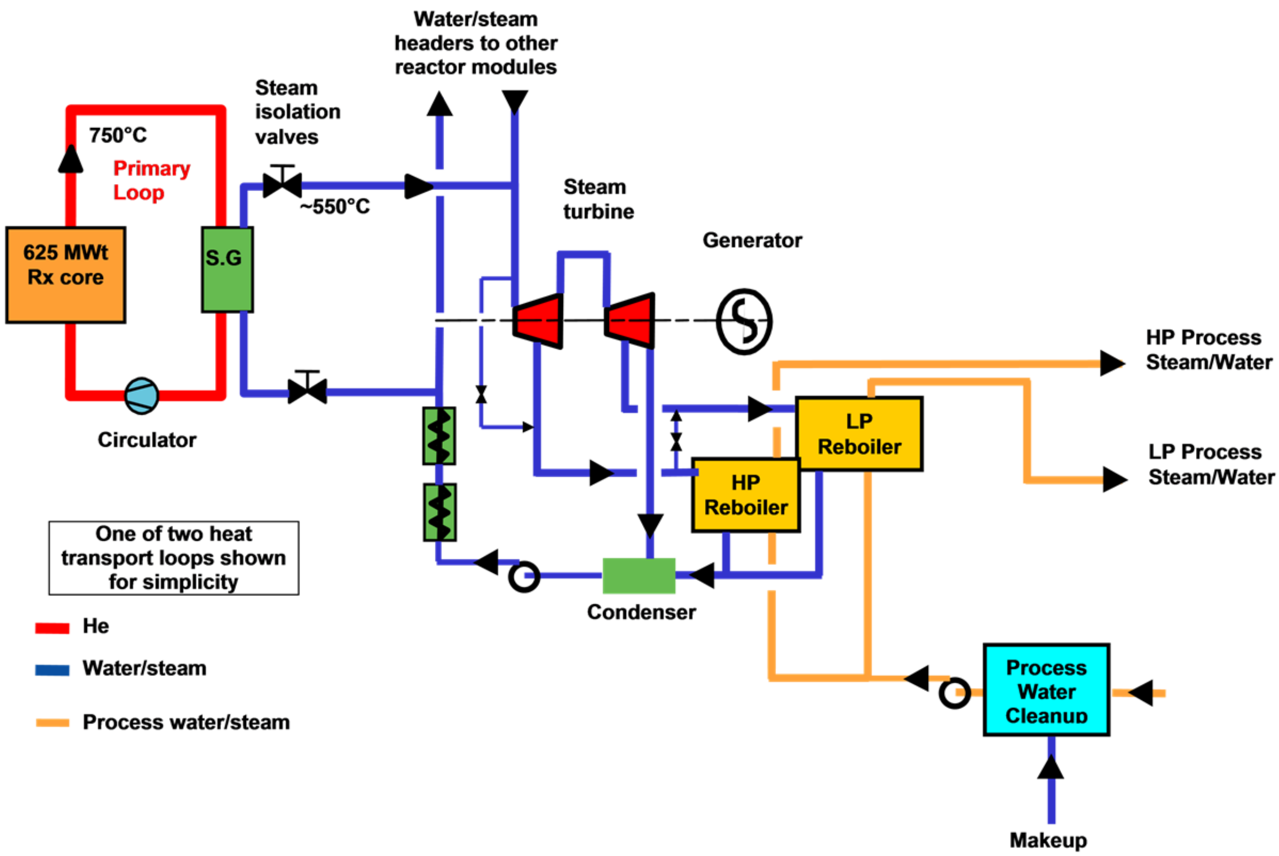

Figure 4-7 : Typical Cogeneration Plant Configuration

user energy application without affecting the reactor module configuration or safety case.

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 real-time load and market conditions vary, all while keeping reactor power constant. This provides the maximum utilization of the HTGR nuclear heat source.

4.6 SC-HTGR Physical Security and Proliferation Resistance

The inherent safeguards characteristics of the SC-HTGR prismatic block reactor are robust.

- The reactor is based on a low-enriched uranium (LEU) fuel cycle.
- Absence of on-line refueling in SC-HTGR precludes diversion of partially irradiated elements (preventing attempt to get isotopic characteristics favorable to proliferation).
- Access to the fuel materials is limited since the fuel cannot be removed from the reactor in mid-cycle without shutting down the reactor and opening the pressure boundary.
- Resulting isotopics of spent fuel are unattractive for diversion.

- The individual fuel elements are not easily diverted or transported due to their size and weight.
- Each element has a low fissile material inventory.
- All fuel elements are uniquely identified for accountability and are tracked by the fuel handling system.

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 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.

4.7 SC-HTGR Reliability

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. Section 8.0 addresses the technical readiness of the key SC-HTGR systems. 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.

A sound systems engineering approach provides a key tool to ensure reliable functioning of the demonstration plant. This approach assesses overall system performance throughout the design process and manages the allocation of margins and performance requirements, bringing a whole-plant focus to design decisions for each system.

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. For example, the SC-HTGR circulators use active magnetic bearings which have been shown to be reliable in numerous industrial applications in place of the problematic water-lubricated bearings used at Fort St. Vrain.

The largest single contributor to the planned outage allocation is the refueling time. 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 [6]. 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.

4.8 Key Plant Parameters Summary

The following table presents key parameters associated with this baseline design for one module.

Table 4-2 : Key SC-HTGR Plant Parameters

Overall SC-HTGR		**Reactor Cavity Cooling System**	
Nominal Power level	625 MWth	Type	Passive Water Based
Reactor Building Type	Vented & Filtered	Configuration	Water Tube Panel in Reactor Cavity Connected to Water Storage Tank by Natural Circulation Loop
Energy Delivery Configuration	Conventional Steam Cycle	Number of Loops	2
Refueling Cycle	½ core every 18 mo.	Normal operating heat load	1.4 MWth
Vessel System		Heat load during accident	2.5 MWth
Reactor Vessel	SA-508/533 Partially insulated	Water Storage Tank Capacity	7 days (per loop)
Cross Vessels (one per loop)	Metallic Vessel w/center hot duct Partially insulated	**Loop Configuration**	
SG Vessels (one per loop)	Metallic Vessel Fully insulated	Number of Main Loops	Two Parallel Loops
Reactor Core		**Steam Generator Unit**	
Core inlet temperature	325°C	Steam Generator Type	Once-through helical coil
Core outlet temperature	750°C	Heat Transfer Medium	He to Water/Steam
Fuel Form	Hexagonal Graphite Blocks	SG Heat Transfer (each)	315 MWth
Configuration	Annular core, 102 column, 10 blocks /col	Gas Side Inlet Temperature	750°C
Moderator	Graphite	Gas Side Outlet Temperature	320°C
Reflector (inner and outer)	Graphite Blocks	Steam-Water Side Inlet Temp.	281.5°C
Fuel		Steam-Water Side Outlet Temp.	566°C
Fuel Design	TRISO Coated Particles	Main Steam Pressure	16.7 MPa
Fuel Kernel	UCO	Main Steam Flow (per loop)	140.7 kg/s
Fuel Enrichment	<20%	**Power Conversion System** (for 100% electrical generation)	
Fuel Compact	Cylindrical, with Particle Fuel in a Graphite Matrix	Configuration	Multi Stage Steam Turbine
Heat Transport System		House load	21 MWe
Primary Fluid	Helium	Net module generation	272 MWe
Primary Pressure	6 MPa	Net plant efficiency	43.5%
Mass Flow (both loops)	282 kg/s	Cooling Tower	Mechanical Draft Evaporative Cooling
Primary Circulator Power (each)	4 MWe	**Process Heat System** (for 100% process heat utilization)	
		Energy Output	630 MWth

5.0 SC-HTGR SAFETY BASIS

The SC-HTGR design ensures safety under all credible events by relying on the fundamental design of the system. The design includes proven accident tolerant and radionuclide retaining fuel form, solid moderator with high thermal capacity such nuclear grade graphite, an inert helium coolant, a true passive decay heat removal system, and the choice of engineered plant operating envelope. The unique combination of fundamental design choices provides systematic redundancy and phenomenological independence in providing true defense-in-depth in reactor safety. This allows for close-in installation of the plant near industrial facilities that will use the output of the plant without undue burden of nuclear investment risk.

5.1 SC-HTGR Safety Design Approach

The SC-HTGR level of safety is attained without the need for elaborate safety systems, electrical power for system actuation, or operator actions. The potential damage to the plant systems or release of radionuclides from the core is limited after Design Basis Accidents resulting in quick recovery and restart. This is unprecedented among current nuclear power plant designs and advanced designs.

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

- Inert coolant – The single phase helium does not change phase or interact with reactor materials under any circumstances and it is neutronically transparent.
- Ceramic core – The ceramic core nuclear grade graphite provides a solid moderator, heat sink, and core structure that can withstand high temperatures beyond normal and accident conditions without loss of expected performance. There are no exothermic chemical drivers for core damage such as with Zr-H_2O systems.
- Robust fuel – The TRISO coated particle fuel has proven characteristics to retain the fission products and maintain structural integrity during normal and accident conditions
- Passive cooling – In an accident scenario the decay heat can be dissipated through a robust, passive system without power, component mode change, or any actuation signal. Passive operation of the RCCS is continuously monitored during all plant operating modes.
- Negative temperature coefficient – The core neutronic design is constrained to ensure a negative temperature coefficient of reactivity. This will shut down the fission reaction as core temperature rises above the normal operating range in case both the control rods and the backup absorber elements fail to actuate.
- Not dependent on electrical power – The SC-HTGR does not require AC electrical power to provide cooling or to activate systems to ensure safety. (It is anticipated that DC power will be needed to provide monitoring of key system parameters during accidents to support restart.)

5.1.1 Radionuclide Retention Barriers

The SC-HTGR has five diverse and independent barriers to radionuclide release to the environment that form its functional containment system and provide physical defense-in-depth. These barriers are as follows:

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

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 [7].

The secondary barrier to radionuclide release consists of the three ceramic coating layers surrounding the fissionable fuel kernel to form a fuel particle. As shown in Figure 4-4, 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. These fuel particles can withstand extremely high temperature without losing their ability to retain radionuclides under all accident conditions. They can withstand temperatures well above 1600 °C for several hundred hours without loss of particle coating integrity [8]. This high temperature radionuclide retention capability is the key element of the SC-HTGR safety design approach, 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.

5.1.2 SC-HTGR Safety Margin

The SC-HTGR margin to safety limits is provided by plant operating limits backed by inherent and passive safety features of the design. It uses the high temperature tolerant characteristics of TRISO-coated fuel particles, ceramic graphite moderator, and inert helium coolant, along with passive heat removal capability. The low power density core with a relatively large height-to-diameter ratio within an uninsulated steel reactor vessel assures sufficient core residual heat removal under loss-of-forced cooling or loss-of-coolant conditions.

The peak fuel temperature during normal operation is more than 400 °C below the peak fuel temperature which could lead to local fuel degradation during accident conditions. This represents a significant safety margin that essentially eliminates fuel damage during normal and accident conditions. In addition, due to the large physical size of the core and the passive heat removal capability of the system, only a very small percentage of the fuel experiences the peak temperatures during an accident, and those peak accident temperatures do not reach the level which would cause significant degradation. Therefore, for all design basis accident scenarios that involve core temperature rise, no fuel damage can occur which would result 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.

The core thermal inertia is another dimension of the SC-HTGR safety margin. Due to the large thermal inertia of the SC-HTGR core components, in a loss of cooling event, the temperature rise is extremely gradual. In the limiting core heat-up event, it takes almost a day for normal operating temperatures to be exceeded and about four days for the peak temperatures to be reached. Since most events would be terminated long before this, the timescale provides substantial additional margin. It takes days to reach the peak fuel temperatures, and the peak fuel temperatures do not cause significant degradation in any event.

The 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 heat transport 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.

The SC-HTGR functional safety approach is to: a) retain radionuclides as close to the fuel particle as possible during Design Bases Events, Anticipated Events, and normal operations, b) require no operator action 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.

5.2 SC-HTGR Safety Performance

The safety performance exhibits the expected response of the reactor system to the credible accident scenarios for that system. The SC-HTGR builds directly on previous HTGR design concepts such as the MHTGR and the HTR-MODUL, both of which have been evaluated in detail by the appropriate national regulatory authorities. Therefore, clear conclusions regarding the safety performance of the SC-HTGR concept are possible even though the concept is still in the Conceptual Design phase.

5.2.1 SC-HTGR Safety Evaluation Basis

The SC-HTGR is conceptually very similar to the German HTR-MODUL and particularly to the General Atomics/US DOE MHTGR. It is based on the same basic steam cycle modular HTGR technology. In particular, the technology of the SC-HTGR and the MHTGR are fully consistent, since both have prismatic block annular cores.

Both the MHTGR and the HTR-MODUL had progressed through Conceptual Design to the Preliminary Design phase. Detailed Safety Assessments have been performed for both concepts. Both concepts were reviewed in detail by the relevant regulatory authorities. The HTR-MODUL had completed much of the licensing process in Germany. In the United States, the MHTGR project submitted a Preliminary Safety Information Document (PSID) to the US Nuclear Regulatory Commission (NRC). The NRC performed a review of the PSID, resulting in an in-depth dialogue between the NRC and the MHTGR project and the eventual issuance of an NRC Preliminary Safety Evaluation Report. This provides a strong basis for assessing the expected safety performance of the SC-MHTGR even though the concept itself is at an early stage of development. The only exception is the passive cooling behavior of the SC-HTGR, which is geometry dependent and therefore not transferrable from HTR-MODUL or MHTGR. This has been assessed for the SC-HTGR and is acceptable, as described in the following Section.

5.2.2 SC-HTGR Safety Evaluation

Based on previous experience with various steam cycle HTGR concepts and particularly with the MHTGR, five types of events are considered:

- Reactivity events
- Depressurization events
- Loss of forced cooling events
- Air ingress events
- Water ingress events

The response of the SC-HTGR for relevant safety analysis event families is consistent with the behavior of other steam cycle modular HTGRs using similar system configurations and operating parameters.

Safety limits are satisfied without the need for electrical power or reactor coolant, while relying only on passive cooling systems (which require no change in operating mode or alignment for any cooling system component), and without the need for operator actions. Results for the analysis of fuel temperature for a Depressurized Conduction Cooldown event are provided in Figure 5-1 as an example. This graph also illustrates the long time scale associated with typical HTGR events.

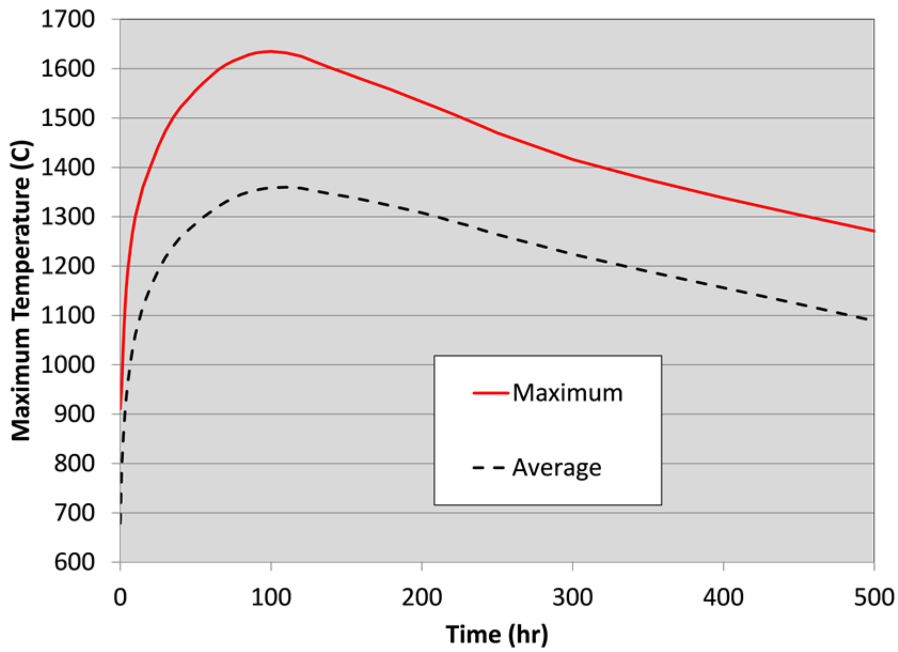

Figure 5-1 : SC-HTGR DCC Results for Conservative Fuel Case

Virtually all radionuclides are retained in the reactor core for all events. Therefore, the required dose limits are satisfied immediately adjacent to the plant at the EAB (a few hundred meters). This includes the EPA Protective Action Guides. Therefore, offsite accident response or evacuation is not required.

As part of its review of the MHTGR PSID, the NRC also considered scenarios beyond the range of credible events. This was done to confirm that there were no cliff edge effects due to hypothetical serious accidents beyond the normal design basis. Beyond Design Basis Events were considered, including the complete failure of the cross vessel. The resulting dialogue confirmed that even for such extreme events, the basic safety characteristics of the MHTGR concept were maintained. The resulting graphite oxidation due to unhindered air ingress was still limited to a small fraction of the core, and the resulting safety consequences were judged to be acceptable.

Thus, the fundamental safety characteristics of the steam cycle HTGR are robust, with negligible offsite impact for all foreseeable events.

6.0 SC-HTGR LICENSING

The 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 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 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.

6.1 Licensing Strategy Background

The SC-HTGR demonstration plant will be licensed under commercial nuclear plant licensing rules. NRC's existing regulations for licensing of commercial nuclear power plants have evolved over the last fifty years in a way that is focused on the current LWR-based power plant and inherently advocate a LWR-based reactor safety philosophy.

The SC-HTGR achieves a higher level of reactor safety in a fundamentally different way from current LWRs. Therefore, current LWR regulations established by the NRC do not readily apply to any advanced non-LWR technologies. DOE, with support from the HTGR design community, has reviewed and identified the necessary changes and deviation to the NRC regulations including the current 10 CFR 50 Appendix A – General Design Criteria [9]. At this writing the NRC is reviewing the proposed changes and will establish a path forward for licensing of the reactors that do not use LWR technologies, such as SC-HTGR [10].

6.2 Current Licensing Status

DOE and its NGNP licensing team through a series of "white papers" have developed a roadmap identifying and proposing resolutions for the most significant modular HTGR technology licensing issues. Figure 6-1 identifies the themes of prospective white papers, along with their relationship to foundational regulatory issues that underlie their purpose. NGNP white papers are presented in References [8], [11], [12], [13], [14], and [15].

The NRC reviewed these white papers and responded with a series of official requests for additional information (RAI). The results of these early and generic SC-HTGR pre-application discussions with the NRC and the ACRS are documented in Reference [16]. Although no specific regulatory decision was possible due to the lack of a specific design or license application, the NRC concluded that based on their reviews and associated technical discussions there are no "show stoppers" associated with licensing of a nuclear power plant that uses the modular HTGR technology.

6.3 Licensing of Demonstration Plant and Subsequent NOAK Commercial Plants

AREVA is proposing a combined (hybrid) Part 50 and Part 52 licensing strategy for the SC-HTGR demonstration plant. This strategy consists of initiating licensing of the demonstration 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.

The first of the four module demonstration plant will begin operation under a "test and demonstration" plant operating license provision (in accordance with the Atomic Energy Act of 1954 Section 104c). During the first two to three years of testing and data collection a complete set of pre-negotiated and NRC pre-approved accident simulation tests will be conducted to collect actual plant data and validate the associated SC-HTGR safety analysis. Upon successful completion of this so called shake-down period the test and demonstration license for the demonstration plant module 1 will be converted to a standard "commercial nuclear" plant operating license (i.e. an AEA Section 103 license) under 10 CFR Part 50.

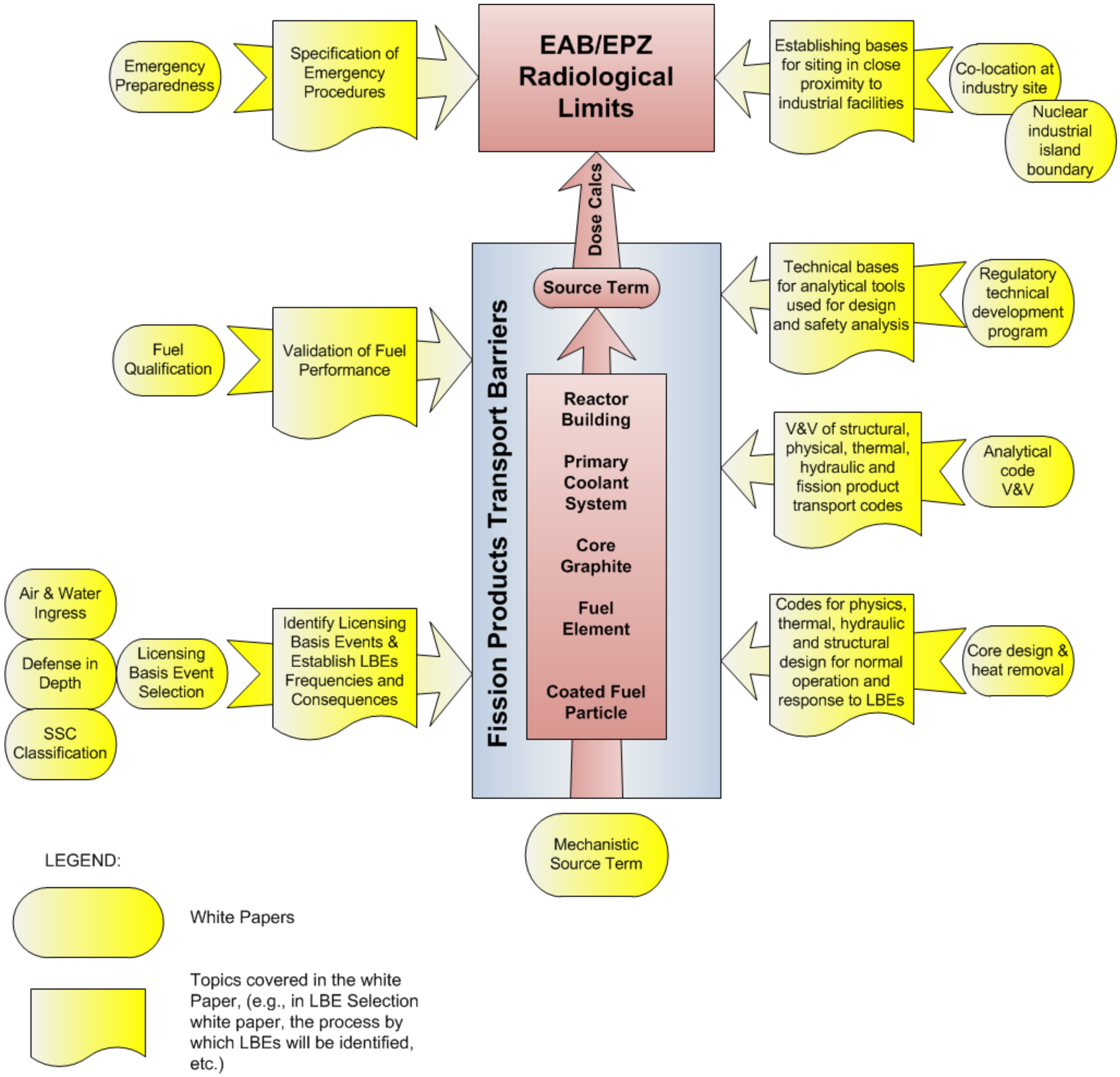

Figure 6-1 : Topical Relationships of NGNP Pre-Licensing White Papers

Concurrent with plant module 1 initial operations and testing a module design certification application (DCA) will be prepared and submitted for the NRC review utilizing the 10 CFR Part 52 and based actual plant data collected for module 1. After completion of the NRC review and approval of SC-HTGR DCA for licensing of subsequent NOAK plants under 10 CFR Part 52.

This licensing path is the most efficient, quickest way to obtain a design certification with the highest level of project certainty. It is considered an achievable path primarily due to the large safety margin available in the SC-HTGR design that would allow safety testing without damage to the plant or the fuel.

7.0 SC-HTGR DEVELOPMENT AND DEPLOYMENT PLANS

The SC-HTGR development strategy takes full advantage of a large body of successful and ongoing R&D conducted in the U.S. and internationally. This includes operation of several small scale technology demonstration facilities as well as large scale commercial design projects.

7.1 Overall Development Strategy and Cost

The roadmap to SC-HTGR commercialization is comprised of the following overlapping elements that, once completed, will provide a commercially viable energy supply system based on HTGR technology [17].

Technology Development – Development activities include the nuclear fuel, graphite reflector and structural materials, high temperature materials, and contemporary analytical methods. In the US, the extant development activities are currently being funded by the Department of Energy (DOE) and led by Idaho National Laboratory (INL). There are two categories of technology development: a) continuation of DOE R&D to qualify TRISO particle fuel, characterize nuclear grade graphite, and develop codes and methods for HTGR accident analysis, and b) supplier R&D activities that support development of SC-HTGR major components' supply chain infrastructure, e.g., circulator, steam generator, reactor pressure vessel, control rod drives, and shutdown cooling system heat exchanger.

Design Development – 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.

Licensing and Regulatory Requirements – The SC-HTGR licensing plan continues the current pre-application iterative process of collaboratively working with the U.S. Nuclear Regulatory Commission (NRC) to establish the regulatory framework and requirements for modular HTGRs. The cost categories includes a one-time cost of licensing the reference FOAK plant first module under 10 CFR Part 50 (includes methodology approvals, Construction Permit, and Operating License) and the associated testing and data collection during the two to three years of the first module's operation. This cost category also includes a subsequent one-time cost of preparing and obtaining the SC-HTGR module design certification under 10 CFR Part 52 based on the operation and test results from the first module of the reference FOAK plant.

Construct and Deploy the First-of-a-Kind Demonstration 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.

Operations – 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 7-1 includes the cost estimate associated with each category.

Table 7-1 : Summary of FOAK plant Costs

Cost Category	Cost Item	Cost
Technology Development	Remaining R&D Equipment and Infrastructure R&D	$316M * $175M *
Design Development	Engineering FOAK Plant Final Design FOAK Plant Engr. during Construction	$270M* $311M $223M
Licensing and Regulatory	Module 1 Licensing Design Certification (standard module) Plant Licensing Cost (module 1 test period) Plant Licensing Cost (4-module plant)	$140M* $70M* $11M per year (3yr) $5M per year
Construction Costs	Module 1 FOAK Plant Fuel - Module 1 initial core Fuel - FOAK plant initial cores	$1,459M (module 1) $5,545M (4 modules) $168M (module 1) $672M (4 modules)
Operation Costs	Module 1 (during test period) FOAK Plant Annualized Fuel Costs (18month - ½ core)	$25M per year (3yr) $100M per year $56M/yr (per module)
Other Costs	Land and Infrastructure Owner's Indirect Cost	$182M $638M

* Onetime Costs

7.2 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 discussed in Section 6, 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 discussed in Section 6.0. A summary schedule is presented in Figure 7-1 at the end of this Section.

7.3 R&D Required and Status

Modern era HTGR R&D activities associated with advanced HTGR technology development have been underway in the U.S. since the early 2000s. The key activities are the fuel qualification and nuclear grade graphite characterization work at Idaho National Laboratory with support from Oak Ridge National Laboratory along with codes and methods development and thermal effects test facilities at Oregon State University and the University of Wisconsin, Texas A&M University, and Argonne National Laboratory. Interim results of fuel and graphite testing are very promising. It is estimated the fuel, graphite, codes and methods development R&D could be completed before 2022. Timely completion of these technology development activities is essential to the success of HTGR commercialization.

7.4 Alternatives to Full-Scale Demonstrator

The development and deployment plans for commercialization of the SC-HTGR concept are based on the conclusion that the most logical and cost efficient development path is to design, license, and construct a full scale FOAK demonstration plant. The overriding reason for this recommendation is the high readiness level of the HTGR technology and its key components. This is based on years of experience with the fuel, the technology demonstration both in the U.S. and abroad, and the technology readiness level of key plant systems, structures and components. The HTGR technology has been shown to work and there is little benefit to demonstrating it again on a small scale.

Nevertheless there are three other approaches that could be pursued although ultimate project cost would increase:

- Technology demonstrator (basic HTGR technology demonstrator; smaller and simplified design compared to the target NOAK plant) followed by full-size FOAK demonstrator
- Small scale commercial demonstrator (similar design to target NOAK plant but smaller scale) followed by full-size FOAK demonstrator
- Small scale commercial demonstrator followed by NOAK plants (without FOAK demonstrator)

All three alternate approaches lead to substantially higher project commercialization cost as a result of repetition of licensing and design activities. They would all extend the commercialization schedule, thus failing to support the 2030 commercialization timeframe. In addition the cost of scaled technology or the commercial demonstrated plants would have to be considered sunk and would not be recouped through revenue generation. In the third case above (no FOAK demonstrator) the lack of a full scale FOAK demonstrator introduces an additional risk and potentially fatal deterrent for early adopters.

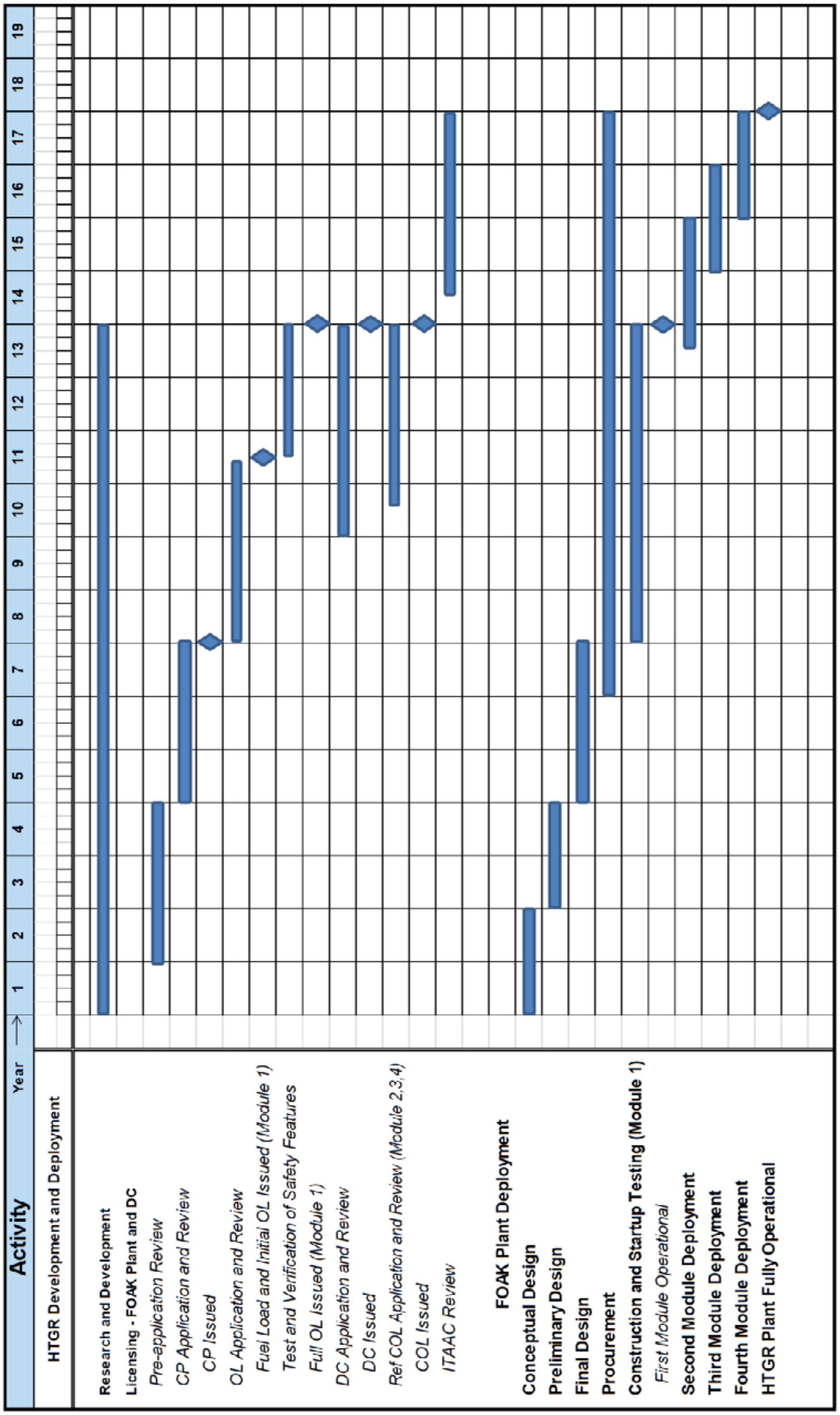

Figure 7-1 : Summary Project Schedule

8.0 TECHNOLOGY READINESS OF THE SC-HTGR

The SC-HTGR design offers the lowest risk path to successful operation of a commercial scale demonstration reactor within the required timeframe. The SC-HTGR technology risks have been minimized to help achieve this goal. As such, the concept makes the maximum use of existing mature technologies. The majority of the technologies employed are either essentially off the shelf technology, as is the case for the Rankine steam cycle generating equipment, or based on successful operation of similar systems, such as the previously operated steam cycle HTGRs.

For these reasons, the SC-HTGR has very low technical risk and a high overall technology readiness level. Therefore, SC-HTGR is ready for full scale, commercial deployment once the detailed design and licensing activities have been completed. Furthermore, no significant additional R&D, beyond that already well underway, is required.

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 demonstrations of specific HTGR concepts for electric power generation at the Peach Bottom Atomic Power Station, Unit 1 (rated at 115 MWth), that was operated from 1967 to 1974, and the Fort St. Vrain plant (rated at 842 MWth), that operated from 1976 through 1989. Past and present HTGRs are illustrated in Figure 8-1.

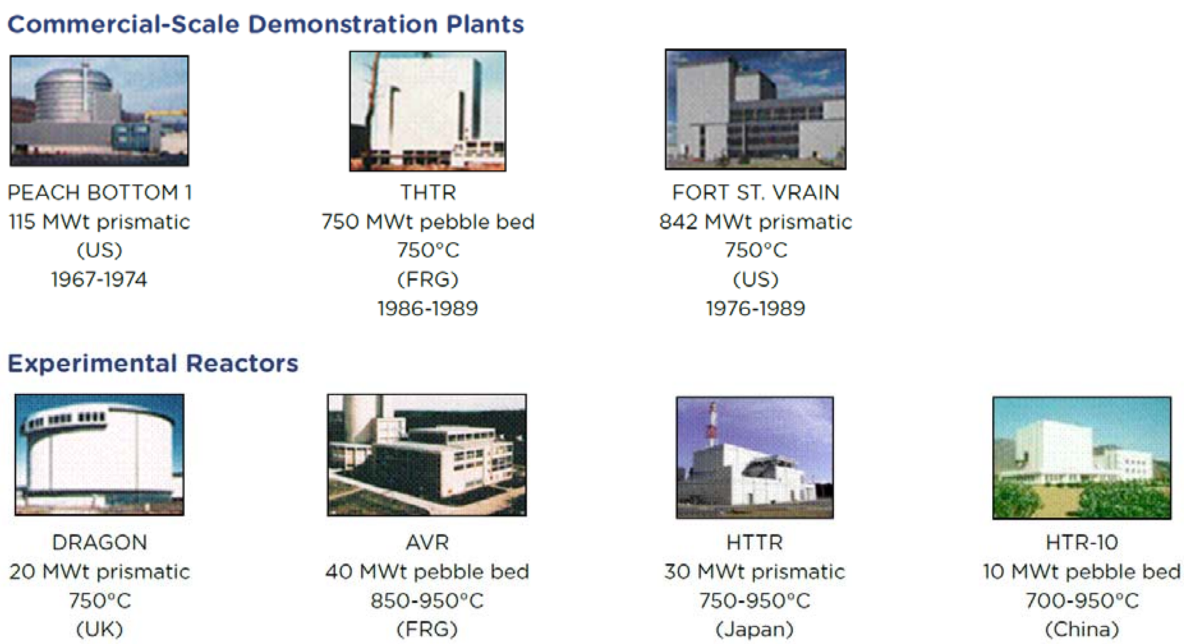

Figure 8-1 : HTGR Operational Experience

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.

Technology Readiness Levels were evaluated in detail for the AREVA steam cycle NGNP conceptual design concept in Reference [18]. Due to the similarity of that design to the SC-HTGR, the results of that report are generally applicable to both designs, with some modification. The reported TRLs are summarized in Table 8-1. The AREVA NGNP design considered alternate material options for some core components that included both metallic and composite materials. The SC-HTGR reference design incorporates metallic components in these cases. In the referenced report, the majority of the TRLs applicable to the SC-HTGR concept are fairly high, at least 6 or better. Items with a TRL below 6 are either graphite components or the RCCS system. These are considered to be at a TRL of 7 and 6, respectively, for the reasons noted in the Table notes.

Table 8-1 : TRLs for Key SC-HTGR Systems, Structures, and Components

System, Structure or Component	TRL	System, Structure or Component	TRL
Reactor Internals	7(A)	Helium Circulator	6
Upper Core Restraint	7	Housing	8
Permanent Side Reflector	7 (A)	Impeller	8
Permanent Bottom Reflector	7 (A)	Electric Motor	7
Core Outlet Plenum	7 (A)	Bearings	8
Lower Floor Blocks	7 (A)	Rotor	6
Metallic Core Supports	7	Inverter	8
Core Barrel	7	Diffuser	8
Top Plenum Shroud Structure	7	Hot Duct	6
Core	7 (A)	Liner	6
Fuel Blocks	7 (A)	Support Tube	7
Replaceable Reflector Blocks	7 (A)	Insulation	7
Reactor Cavity Cooling System	6 (B)	Intermediate Foil	7
Cavity Cooler Panels	6	Ceramic Spacer	6
Coolant Piping	7	Metallic Spacer	6
Water Storage Tank	7	Steam Generator	6
Water-to-Water Heat Exchanger	7	Steam Generator Hot Header	6
Water Pump	7	Evap. & Super Heater Tube Bundle	7
Water-to-Air Heat Exchanger	7	Re-Heater Tube Bundle	7
Air Blower	7	Steam Generator Hot Duct	7
Control Rod Drives	6	Steam Generator Support Plate	7
Reserve Shutdown System	7	Steam Reboiler System	8
Control Rods	8	HP Reboiler	8
Guide Tubes	7	LP Reboiler	8
Cable	7	Nuclear Instrumentation	7
Drum Drive	6	Ex-Vessel Neutron Detectors	7
Control Rod Position Indicator	6	Source Range Detectors	7
Control Rod Force Sensor	6	In-Core Flux Mapping Units	7
Vessel System	7	Primary Loop Instrumentation	6
RPV Upper Closure Head	7	Flow Rate Sensor	6
RPV Main Vessel	7	Reactor Cold Leg Temp. Sensor	6
Sealing Device	7	Reactor Hot Leg Temp. Sensor	6
RPV Fasteners	8	Pressure Sensor	6
CV Main Vessel	7	Moisture Sensor	6
SG Vessel	7	Fuel Handling System	6
Circulator Shutoff Valve	6	Fueling Adaptor	6
Valve Mechanism	6	Fuel Elevator	6
Housing	6	Fuel Handling Machine	6
Valve Seat	6	Fuel Storage Server	6

Group A – Graphite Components - The graphite components were initially given a 4, but are mature and are considered to be at a TRL level of 7. Material properties testing is needed to provide design data supporting use of a replacement graphite grade for the previously used H451, which is no longer available. There is no doubt that the resulting properties will be adequate to support the design.

Group B – RCCS System - This system relies on well proven technology, but a performance test has been proposed to demonstrate integrated system behavior. Completion of initial testing results in a change in TRL from the initial rating of 5 to a TRL of 6.

The TRL of the fuel that will be used in the SC-HTGR was not rated in the reference report. The performance of the TRISO fuel is critical to the performance of modern, modular HTGRs. As such, a significant development program has been ongoing at INL to demonstrate this performance under a range of operational and accident conditions. This program has been progressing as anticipated and has yielded excellent results to date. Observed fuel performance is well within anticipated design requirements, leaving significant design margin to accommodate unforeseen issues [19]. Successful completion of this program will provide the required confirmation well in advance of anticipated commercial operation of the SC-HTGR.

The SC-HTGR provides a low technical risk solution to support deployment of a commercially viable advanced reactor by the early 2030s. The effective TRLs of all major components and systems have been assessed and all are judged to be at least 6 and many are higher. While it is necessary to continue ongoing development efforts to provide needed engineering data to support detailed design activities, no unanswered questions remain as to the fundamental viability of the SC-HTGR concept.

9.0 EVOLUTION OF HTGR TECHNOLOGY BEYOND SC-HTGR

Development of the SC-HTGR also provides a path forward for the development of more advanced Very High Temperature Reactors (VHTRs).

High temperature steam is limited to a maximum practical temperature of 550-600°C. There are other chemical processes such as ethylene cracking that require higher temperatures like those from a VHTR.

Three main challenges must be addressed to provide very high temperature nuclear heat to the diverse array of higher-temperature processes:

- Direct delivery of high temperature heat requires more advanced heat transport technology
- High temperature chemical processes require modification to use a new heat source
- The VHTR-chemical process interface equipment must be customized for each application

The most efficient path forward is to first deploy steam cycle HTGR systems for broad use and then to shift the focus to VHTR development for specific very high temperature applications. This approach provides the best overall risk management, and it provides a significant industrial base to support VHTR development. It also maximizes the benefit of HTGR technology, since the steam cycle HTGR serves the broadest segment of the energy economy, and it can be deployed on the shortest timeline with the least risk. As Table 9-1 illustrates, steam cycle deployment mitigates several risks that must also be addressed for VHTR development. This reduces the residual risks for a future VHTR progress to a manageable level.

The reactor technology needed for the VHTR energy supply system is already relatively mature. The SC-HTGR reactor core design could be readily adapted for VHTR temperatures using current HTGR technology. The TRISO fuel particles and the ceramic reactor core structures can accommodate VHTR operating temperatures. Ceramic control rods are expected to be introduced as a future SC-HTGR design option, and they would be used for most VHTR applications.

As steam cycle development activities are completed, it is anticipated that R&D activities would shift to VHTR development activities concentrated on high temperature heat transport, intermediate heat exchangers, and adaptation of selected high temperature chemical processes for the VHTR interface.

Table 9-1 : Key HTGR/VHTR Development Risks

Risk Area	Steam Cycle	Future VHTR
Fuel Qualification	X	(X)
HTR Siting	X	(X)
HTR Licensing	X	(X)
Process Interface Issues	X	(X)
Safety Case Validation	X	(X)
Very High Temperature Materials (metals, ceramics)		X
High Temperature Fuel		X
IHX Development		X
Very High Temperature Process Interface		X

Long-term R&D supporting these needs would presumably continue to move forward as a secondary priority during early deployment of the steam cycle HTGR concept. Insights gained during the detailed design and development of the steam cycle HTGR will help to identify VHTR design alternatives. This will help to focus the ongoing R&D activities and maximize their value. Similarly, completion of initial R&D supporting VHTR technology prior to the commencement of detailed VHTR design and development will inform the initial definition of the VHTR concept and allow the subsequent detailed design work to proceed as efficiently as possible.

10.0 ECONOMIC SCALABILITY

The purpose of the economic scalability assessment is to determine the economic impact of plant scaling strategies on the cost of the SC-HTGR commercial demonstration project and subsequent industrial deployment of the technology. Understanding the SC-HTGR technology scaling needs is vital in order to select the most efficient path for SC-HTGR to reach commercial demonstration plant by mid-2030s enabling fleet deployment.

10.1 Impact of Plant Size on Project Cost

SC-HTGR reference power level was selected based on three key factors a) retaining inherent safety characteristics of modular HTGR technology, b) market needs for process heat plant size, and c) minimizing the energy cost from resulting mature SC-HTGR plants.

AREVA and the NGNP Industry Alliance performed independent market studies of the demand for high temperature process heat and electricity. Given the size of market, the traditional economy of scale was the key factor in the selection of the reactor size. Market demand drove the size of the reference reactor module to the largest possible size, tempered by the second market requirement of inherent safety characteristics. These two factors lead to selection of a 625 MWth reactor module configured in a four module reference plant as an optimum module size and standard plant configuration for major industrial sites in the U.S. and the world.

The costs for delivering the full size demonstration plant fall in the following three categories: a) development, b) construction, and c) operating cost.

Development Cost - This cost category includes the one-time costs of the design, licensing, and component development. There are two aspects of this cost category that must be considered. First is the actual cost of SC-HTGR development independent of the size of the plant. Second is the overall project cost impact to reach commercial deployment. Only a small fraction (20 to 30 percent) of the overall development work is independent of size. Therefore, most of the development work (and cost) would have to be repeated for a second plant of significantly different size.

The high technology maturity of the SC-HTGR makes scaled demonstration of various systems or components unnecessary. Use of a scaled demonstration reactor would, in fact, increase the total demonstration program cost and extend the commercialization time frame from the 2030s to the mid- to late- 2040s.

Construction Cost - This cost category includes engineering during construction, material and labor costs and plant operating license costs. Naturally the construction cost of a scaled plant is lower than the cost of a full size plant due to sheer size, material, and labor required. However, for plants based on the same basic design, key plant component and facility costs do not scale linearly with plant capacity. The fuel unit costs are the same but the remaining major components, systems, and structures (e.g., reactor vessel, vessel internals, steam generator, circulator, reactor building, etc.) do not scale linearly in cost. Their size does not vary linearly with power level, and the component cost does not vary linearly with size. For example, the cost of a reactor vessel for a 100 MWth module is nearly the same as the cost of the 625 MWth modules, because only the raw material cost, which is a small fraction of the overall component cost, is lower.

Another factor that will increase the overall project cost, if a scaled demonstration plant is built first is the one-time nature of the scaled plant. The manufacturers and vendors must recover all their development costs from the scaled demonstration project since only one small scale plant will be sold.

Operating Cost - Assuming a scaled demonstration plant produces revenue, the O&M cost differential is directly tied to the plant staffing, infrastructure needs, maintenance, and the fuel costs. Only the fuel cost is lower as the size of the plant is lowered, i.e., lower number of required fuel blocks. The other three cost categories (staffing, infrastructure, maintenance) have a weak relationship with the size of the plant. Therefore, the larger size plant has a major O&M cost advantage.

10.2 Cost Advantages of a Full-Sized Demonstration Plant

The aggregate cost of commercialization for any advanced Generation IV technology is in the billions of dollars. The cost distribution falls in the following categories:

a. Basic technology development such as materials and fuel. For SC-HTGR there are no additional technology development needs (other than the nearly completed AGR and AGC programs), hence the high TRL levels for various systems and components.

b. Proof of concept to show that the concept technology works on a laboratory scale and later at progressively increasing size. The HTGR concept has already been shown to work through several partial and full scale plant designs that have operated with coated particle fuel in a variety of configurations.

Based on the above two elements the SC-HTGR design is ready for commercial scale demonstration. There is no benefit to building an intermediate scale demonstration plant. In fact significant time will be lost in reaching commercial deployment of the technology if a small scale demonstrator is used, since an additional full scale FOAK plant will have to be built following the scaled demonstrator. This will delay any real benefit to the energy market and environment by as much as 10 to 15 years.

The design cost of a full size FOAK plant following operation of the smaller demonstration plant would be only slightly less than it would have been without the preceding small demonstration plant.

Licensing cost for the full size FOAK plant following the licensing of a small scale demo plant will be slightly reduced, however the total project licensing cost is increased by a large fraction.

Construction cost savings for the FOAK plant following construction of a small scale demo plant is negligible due to the timespan between projects.

Hence, by proceeding directly with a full-size demonstration plant, the extra design, licensing, and construction cost of an unnecessary small scale demonstration plant is avoided without increasing project risk. In fact, overall project risk is decreased by simplifying the project and shortening the overall schedule.

10.3 Cost of Scaling From One Plant Size to Another

A full scale plant must be demonstrated both in operational performance and cost before customer acceptance and serial building can begin. This is true for all new reactor types including SMRs and advanced reactors. No commercial owner/operator wants to buy the first new advanced reactor due to the economic uncertainty of being the first adopter.

Scale Up - For SC-HTGR where initial costs associated with items (a) and (b) in Section 10.2 have already been spent, there is no benefit gained by designing, licensing and building a small scale demonstrator. AREVA estimates that approximately eighty percent of the cost of a scaled demonstrator project is sunk and cannot be recovered. Only about a twenty percent cost savings in area of design tools and licensing experience are transferable to the full scale demonstration project. Considering a ten year delay introduced in the total commercialization project schedule, any benefits to the energy markets are also deferred. And building a scaled demonstrator does not make economic sense on a standalone basis, because little cost recovery can be expected from the scaled demonstrator.

Scale Down - If a viable market for a smaller size plant (e.g. 200 MWth or 300 MWth) materializes after construction of a full size demonstration plant, developing a smaller scale plant might be considered. At that point, certain safety and licensing costs can be averted since the safety case of the 625 MWth plant envelopes the safety case of the smaller plants. However, the detail design costs and the component development costs of the smaller size plant are unavoidable. If market demand changes from the current large module to a smaller module, the total project cost impact for switching is lower than that going from a small module to a large module.

10.4 Other Scalability Considerations

Aside from cost and schedule there are several other important scalability issues that must be considered.

Safety - The inherent safety feature demonstration in a scaled-down reactor may not be convincing to the regulator for extrapolation to a full size reactor. In fact some of the passive features may not work well for small scale reactors, since the driving heads might not be as significant and the system would be in a less effective operating regime.

Operational Efficiency – Another factor affecting performance verification using a small scale demonstration reactor is the fact that efficiency enhancements typically incorporated in a larger plant are not justified in a smaller plant and the fact that parasitic heat losses are often somewhat worse in a smaller plant.

Market - The question of market is the question of what size is optimum for any given market. On the one hand, there are more process heat customers that can absorb 50 MWth than can absorb 600 MWth or even 4000 MWth. But on the other hand, it is easier to displace natural gas with the economy of scale of a 600 MWth plant than a 200 MWth plant that has 40% higher net energy cost.

Other Factors – Normally the optimal configuration and operating conditions for a larger plant and a smaller plant based on the same technology will be different. This has important ramifications for both licensing and commercial deployment. Therefore, the project must make the demonstration plant exactly the same as the commercial concept, even if the size is somewhat different. That ends up making a small scale reactor more expensive than it might otherwise be if properly optimized.

In summary, if the basis for the plant design is changed then everything changes. So for example, if a 100 MWth plant does not need an RCCS but the 600 MWth plant does, then the design cost, the safety analysis cost, the licensing cost, and the capital cost will all have a significantly different basis for the two concepts.

11.0 CONCLUSIONS

The SC-HTGR Demonstration Reactor will provide a full scale FOAK steam cycle HTGR demonstrating the commercial viability aspects of licensing, cost, schedule, supply chain, and operability of this technology by the early 2030s. The SC-HTGR concept demonstrates those attributes critical for success, including:

Safety – The inherent safety characteristics are robust and unique. Its walk away safety and minimal EPZ allows collocation with industrial process heat facilities.

Investment Risk – The fact that the SC-HTGR can be returned to service following any DBE, has negligible risk of plant write-off due to the accident, and presents no significant risk to surrounding facilities minimizes investment risk for both the reactor operator and the energy user.

Ability to Serve Process Heat Market – The size, delivered steam temperature, and safety profile are right to supply process heat to market sectors traditionally dependent on fossil fuels.

High Efficiency Electric Generation –The reference SC-HTGR has a net efficiency of 43.5% when configured to generate electricity. It can provide 38.2% net efficiency under hot arid dry conditions using dry cooling.

Supports VHTR Development – The SC-HTGR is a low risk stepping stone in a two phase approach that serves near-term markets and reduces risk for future VHTR project as very high temperature markets mature.

Supports Alternate Fuel Cycles – The SC-HTGR can operate with core designs based upon LEU, thorium, plutonium, and MOX fuel cycles. It can be utilized to burn actinides from spent LWR fuel.

High Technology Readiness Levels - The SC-HTGR is based on mature technologies and presents a low overall project risk than other advanced reactor concepts. All key SC-HTGR components are based on concepts demonstrated in previous reactors or industrial applications.

Supports 2035 Deployment Timeline - The SC-HTGR development timeline supports a 2030 demonstration reactor and 2035 commercial deployment. The concept is ready for full sized FOAK demonstration.

Considering these attributes, the SC-HTGR provides the lowest risk approach to meeting DOE's strategic objectives for an advanced reactor. It fully supports a primary mission to deploy a high temperature process heat source for industrial applications and electricity production and in doing so, it illustrates that nuclear energy has the potential to help reduce the carbon footprint of the US industrial sector. Its nuclear characteristics also allow it to be a part of an overall infrastructure supporting a secondary mission of extending natural resource utilization and reducing nuclear waste for future generations. Finally, near term deployment of the SC-HTGR can help support and pave the way for more advanced, but less mature, very high temperature reactor options designed to meet market needs that are just beginning to emerge.

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APPENDIX A: EVALUATION AGAINST DEMONSTRATION REACTOR METRICS

This appendix provides explicit ratings for the SC-HTGR against the Goals and Criteria defined in Reference [3] using the metrics provided. For each rating, brief comments are provided to explain the basis for the assigned rating.

Metric	Topic	Score	Comments
Goal D1 - Demonstration Reactor significantly advances the technology toward a potential FOAK plant			
D1.1.1	Safety characteristics	9 - Demo replicates the passive and inherent safety characteristics and has prototypic systems/ components	Since the SC-HTGR is a full-sized demonstration reactor, it will have all of the characteristics of a commercial plant and it will be able to demonstrate DBA behavior for all events without plant damage.
D1.2.1	Adequate instrumentation	9 - High fidelity instrumentation and data to validate performance and safety models	The first module of the SC-HTGR demonstration plant will have all necessary instrumentation to gather data to support code validation. All data will be directly applicable, that is, no scaling will be necessary, due to the reactor's full sized nature.
D1.3.1	Technology selections	9 - Prototypic	All technology selections will be fully prototypic for the commercial unit.
D1.4.1	Maintenance approaches	9 - Prototypic	Since the FOAK plant is identical to the commercial unit, all maintenance approaches will be prototypic.
D1.5.1	Fabrication of systems	9 - Prototypic	Due to its full-sized nature, all fabrication technologies will be prototypic.
Goal D2 - Demonstration Reactor operations help resolve technical barriers (e.g. predictability) to advanced reactor economics and reliability			
D2.1.1	Project cost	9 - < $4 B	The cost for the first demonstration module is less than $4B. The cost for the overall 4 module plant is between $4-8B.
D2.1.2	Schedule	5 – 10-15 years	The development and deployment for the first of a kind SC-HTGR is estimated to be 13 years.
D2.2.1	Annual operating costs	9 - < $0/MWh (revenue exceeds cost)	Annual operation costs for the SC-HTGR are expected to be less than recovered revenues.
D2.3.1	Availability Factor	9 - >90%	The single module availability factor for the SC-HTGR is expected to be greater than 90%.
Goal D3 - Demonstration Reactor has a robust Safety Design Basis for licensing			
D3.1.1	Key licensing issues	9 - Demonstration unit can address most of key licensing issues for follow-on commercial units	As a full-sized FOAK reactor, all of the key licensing issues of follow-on commercial reactors will be addressed by the SC-HTGR.
D3.1.2	EPZ Size	9 - EPZ <400 m	The EPZ for the SC-HTGR is set at the site boundary. Initial designs have used an assumption of a 425M site boundary, however, as individual site designs are completed, this distance will be optimized and achievement of a <400m site boundary is expected to be supportable if required.
Goal D4 - Demonstration Reactor supports demonstration of technology and system integration (enhancing immediate, intermediate and long term value of the project)			
D4.1.1	Demonstration of components	9 - Prototypic	Due to the full sized nature of the SC-HTGR, all component demonstrations will be representative of the follow-on commercial units.

Metric	Topic	Score	Comments
D4.2.1	Alternative core configurations	9 - More than 2	The SC-HTGR has the ability to alter its core configuration in three dimensions, and as such, has the ability to utilize many different alternatives.
D4.2.2	Alternative fuel types	9 - More than 2	The SC-HTGR can accommodate many different types of fissile material with many different particle designs
D4.3.1	R&D Time	9 - 0 – 5 years	The schedule identifies 7 years between the start of R&D and the start of construction. However it is design and licensing activities that drive the construction start date. Key R&D, particularly fuel related, is already underway and has made significant progress.
D4.3.2	R&D Cost	5 - $250-500M	Remaining R&D cost is approximately $316M.
D4.4.1	Fast flux conditions	1 - < $5x10^{14}$ n/cm^2-s fast (>0.1 MeV)	The commercial SC-HTGR demonstration reactor is not configured as a materials test reactor. It would be possible, however, to place samples within fuel or reflector blocks that would be exposed to normal operating fluxes.
D4.4.2	Thermal flux conditions	5 - 1 to $5x10^{14}$ n/cm^2-s thermal	See above.
D4.4.3	Irradiation volumes and length	9 - Volume > 10 liters Length > 2 meters	See above.
Goal D5 - Demonstrate reactor stage of advanced fuel cycle			
D5.1.1	Use of fuel natural resources	1 - >150 MT-U/GWe-yr Or 5 – 20-150MT-U/GWe-yr	For the reference LEU once-through fuel cycle, the SC-HTGR has uranium utilization of about 224 MTU/GWe-yr (score 1). If the SC-HTGR is used as part of an advanced fuel cycle system, fuel utilization would improve to the middle range (score 5). The precise value would depend on the specific cycle employed. The reactor is compatible with various fuel cycles. Plant operator would initially use the current once-through cycle and could shift to an advanced cycle if fuel market conditions change late in the plant life.
D5.2.1	Fuel fabrication approach	9 - Prototypic	Fuel fabrication for the SC-HTGR would be provided by a full-scale, prototype fuel fabrication facility.
D5.3.1	Fuel performance	9 - Prototypic	Due to its full scale nature, the SC-HTGR will have prototypic fuel performance.
D5.4.1	Spent fuel handling	9 - Prototypic	Due to its full scale nature, the SC-HTGR will have prototypic spent fuel handling and storage system.
Goal D6 - Demonstrate High Temperature Reactor Process Heat Applications			
D6.1.1	Energy conversion	9 - More than 3	The SC-HTGR is configurable to support many different energy conversion systems and industrial applications.
D6.2.1	Coolant outlet temperature	9 - >700°C	The SC-HTGR has a core exit temperature of 750°C.