StarCore Nuclear Generation IV HTGR

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Abstract

StarCore Nuclear (StarCore) is developing a High Temperature Gas Cooled Reactor using TRISO fuel, prismatic graphite blocks and a helium primary loop. The design is currently evolving, with the intent of completing the conceptual design and submitting it to the Canadian Nuclear Safety Commission (CNSC) as part of a Vendor Design Review within one year. The paper will focus on the status and plans for the design of the reactor plant.

1. Introduction

The StarCore High Temperature Gas Cooled Reactor (HTGR) plant is based on the TRISO fuel originally developed in the United Kingdom, the United States and Germany in the 1960's, and then used in a wide variety of plants in many countries. These plants have been based on graphite-moderated fuel microsphere designs developed to meet various operational requirements. The TRISO fuel has received a lot of recent attention in the Next Generation Nuclear Plant (NGNP) program [1] [2], the HTGR plant initiative in South Africa [3]; the reactor program at Tsinghua University (INET) in China [4]; the reactor program at the Japan Atomic Energy Research Institute (JAERI) [5], the International Atomic Energy Authority (IAEA) [6], and others.

This recent activity has resulted in improved TRISO fuel specifications and performance, and it is now generally regarded that TRISO is a fuel suitable for an HTGR that will be deployed to remote sites. The design has a very steep negative temperature coefficient that causes an automatic reduction in reactivity as temperature increases, which drives the plant into a low power state if there is a loss of coolant flow. In this regard the IAEA has defined the HTGR as "*an inherently safe nuclear reactor concept with an easily understood safety basis that permits substantially reduced emergency planning requirements and improved siting flexibility compared to other nuclear technologies*" [6].

StarCore has been developing the reactor and plant systems over the last several years and has selected the TRISO fuel and a prismatic graphite reactor core design, rated at 35 MWth. The fuel, core design and other features use the same technology as developed in the NGNP program [1] [2], on which the US Department of Energy has spent more than $500 million. This program continues as an R&D program at the Idaho National Laboratory (INL), who is currently completing qualification work on fuel, graphite and high temperature materials [2]. StarCore expects that the qualifications for its design will be proven for these three critical elements by the completion of that program. The operating reactors in Japan, HTTR [5], and China, HTR-10 [4], have many similarities with the StarCore design and have provided valuable insights into the design and operation of the plant.

AREVA is a major participant in the (NGNP) program [1], and the AREVA reactor was chosen by the NGNP Alliance over its rivals for further development [7]. The StarCore and AREVA designs have many similarities. Under contract with StarCore, AREVA will provide the reactor core, reactor vessel systems, and core components, along with reactor control systems and instrumentation for the StarCore reactor plants.

The StarCore reactor plant produces both electricity and thermal energy, and uses a three-stage energy transfer process (from helium to nitrogen and then from nitrogen to an air-breathing turbine) to generate electricity. The three-stage process is designed to prevent helium migration at the first stage heat exchanger by balancing pressure across this interface, to enable the use of a Brayton cycle and thus optimize thermal efficiency, and to allow the use of a readily available air-breathing turbine instead of a helium turbine or other closed loop design.

At the site, the reactor pressure vessel (RPV) will be installed underground in a concrete containment structure that includes a heat transfer path to the surrounding ground layer to provide a passive path for the management of the operating heat load and for reactor decay heat following shutdown. In addition, systems, structures and components which perform safety functions for the plant will be installed underground. The actual depth of the plant will be set based on safety and security requirements as well as on the site conditions.

The reactor is designed to operate in two normal states - load following and shutdown. The plant is designed to be fully automatic and operated locally by the advanced StarCore HyperVector Control System, with three satellite links to a remote real-time monitoring and intervention system located at StarCore Central Operations. The only on-site staff are those required for routine maintenance, materials and supplies.

The StarCore units are available in various configurations that will be tailored to the client's requirements. The base case reactor design produces 10 MWe and 15 MWth, where the thermal energy could be used for steam or district heating or other purposes. If less electrical power is required, then more energy in the form of shaft horsepower, steam or hot air can be provided. The standard reactor plant design consists of two reactors integrated into a single building, but for larger applications up to six units can be integrated into a single reactor plant in a three-legged star arrangement. This results in a maximum of 60 MWe and 90 MWth for a six-unit plant, with many possible variations trading off electrical and thermal energy.

Each reactor unit is self-contained, sharing only systems, structures and components that do not have safety functions. The balance of the facility is optimized to share systems, structures and components. Many configurations will be available to meet customer requirements, including, for example, elimination of one or both turbines to maximize thermal energy. The design life of the plant is 25 years, with the reactors being refueled at site every five years.

The following sections go into more detail on the Nuclear Engineering, Energy Transfer Systems, Balance of Plant, and Control Systems.

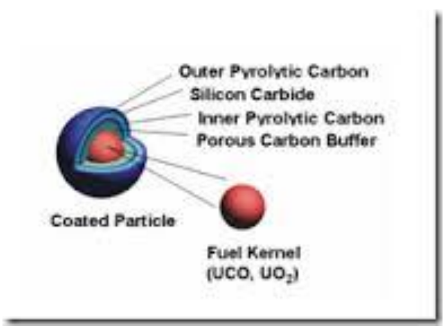
2. Nuclear Engineering

2.1 TRISO Fuel

In the TRISO fuelled reactor 0.92 mm TRISO microspheres are formed into fuel compacts for use in the reactor core. TRISO fuel is formed from small spherical granules of enriched uranium, which are then coated with a layer of porous carbon, a layer of extremely hard pyrolytic carbon, a layer of silicon carbide, and a further layer of pyrolytic carbon. The final microsphere is 0.92 mm in diameter and provides a containment structure for all the fission products that are formed. The internal pressure caused by the decay products and gaseous isotopes is around 5 MPa, and although the fuel structure is strong enough to retain this internal pressure, the counter-pressure of the primary coolant system will also cause a positive pressure gradient towards the inside of the TRISO microsphere thus providing an additional level of security.

These photos show the microspheres and the compacts into which they are made. (Artwork courtesy of INL and General Atomics)

TRISO Microsphere



Microspheres & Compacts

StarCore intends to base the TRISO fuel specification on the fuel that is currently being qualified by in-reactor testing at INL, and will set the level of enrichment as needed to meet the overall requirements of the system, but expects it to fall between 16-19%.

2.2 Reactor Core Design

There have been two main TRISO core designs used over the years - the spherical 60 mm "pebble" used in the pebble bed designs and the prismatic designs, which consist of hexagonal graphite blocks with fuel compacts inserted in them. StarCore has decided to use the prismatic core design. In the prismatic design the core is made up of hexagonal graphite blocks that are 360 mm across the flats and 793 mm long. Cylindrical fuel compacts (26 mm diameter and 39 mm long) are inserted into holes drilled in the graphite blocks, and burnable poison elements will also be inserted as needed. The helium flow will be through vertical holes drilled in the blocks.

Graphite Fuel Block

The final design of the reactor core has not been completed, but initial neutronics models and performance assessment have been carried out at INL. The dimensions of the core will be adjusted during the modeling of the neutronics and the thermal hydraulics to produce the optimal results. The main core characteristics of the current design are shown in the table below

Reactor Core and Fuel Properties	
Property	**Value**
Moderator	Graphite
Reactor Pressure Vessel Height	7.4 m
Reactor Pressure Vessel Diameter	2.6-3.0 m
Reactor Pressure Vessel Material	SA508/533
Reactor Cooling (Forced or Natural)	Forced
Coolant Type	Helium gas
Number of Control Rod Drive Mechanisms (CRDMs)	12 (6 in each of 2 systems)
Fuel Type	TRISO (coated particles of UCO)
Graphite Reflector: Radial / Top / Bottom	29 cm / 50 cm / 50 cm
Maximum Fuel Burnup: GWd/t / Percent	60 GWd/t / 6 %
Fuel Enrichment	16-19 wt% U-235/U
Fueled Core Diameter / Height	186 cm / 400 cm
Number of Fuel Blocks: (1 + 6 + 12) x 5	95
Fuel Cycle	60 months

The reactivity control mechanism is a reflector/absorber in the form of a cylinder running the length of the core, split into two semi-circular regions, with one being static and the other capable of rotating through 180 degrees to present either a reflective or absorptive surface to the main neutron flux. The closed (reflective) position of the cylinders is controlled by a stop, the position of which can be changed as required. It is intended that these cylinders will not be fully closed (100% reflective) when the reactor is first commissioned, and that the closed stop position will be changed as the core ages to allow the reactivity margin to be maintained over the life of the core.

There are two separate sets of six control cylinders, with each set using a different control mechanism design to provide operational redundancy. Each set can shut down the core even if the other set does not deploy. The reactivity control cylinders are controlled by means of helium powered mechanical motors, so that if the helium system loses integrity and the pressure falls the cylinders will automatically fail to the fully open (absorptive) position.

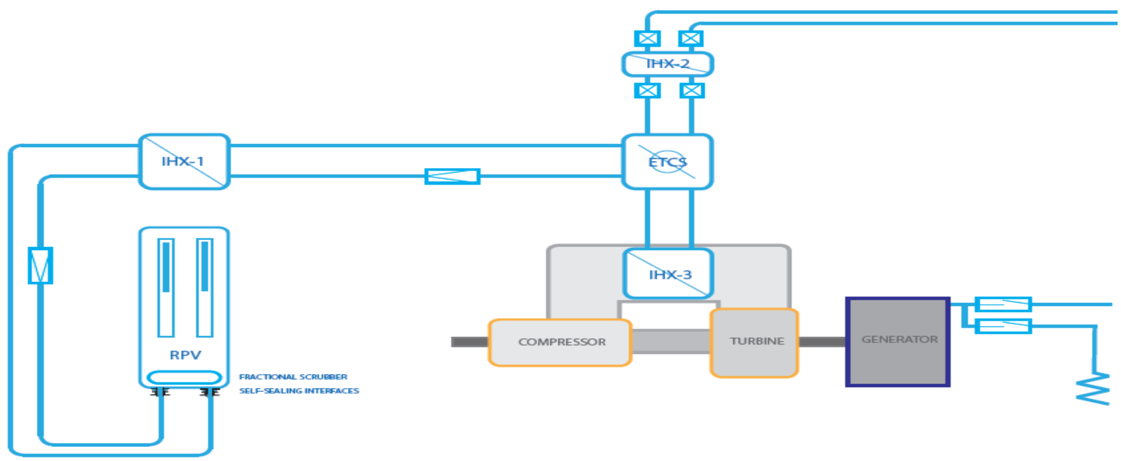
2.3 Reactor Safety

The TRISO fuel exhibits a very strong negative temperature coefficient. As the fuel temperature increases the neutron energy also increases; this effect reduces the neutron cross sections and lowers the number of fissions and thus the power level. The result of removing all reactivity controls and shutting off the primary and secondary cooling systems in the Chinese HTR-10 test reactor was a thermal output that peaked at around 225% as the temperature increased, and then dropped to an extremely low level after about 50 seconds [4]. After around 55 minutes the core cooled off enough for the output to rise again, and then it stabilized after several cycles to around 10% of the base thermal output level. This output will (obviously) automatically follow the thermal dissipation of the RPV; the greater the thermal dissipation the greater the core output. StarCore expects the thermal output when the core is stable to be around 600 kWth.

3. Energy Transfer Systems

The system schematic for the plant is presented below; it shows the energy transfer path as well as the main components.

Schematic of Reactor, ETS-1 and ETS-2



There are two main energy transfer stages, Energy Transfer System 1 (ETS-1) and ETS-2. ETS-1 uses helium pressurized at 7.4 MPa and transfers the thermal energy from the RPV to the ETS-2 through the intermediate heat exchanger, IHX-1. It also has a helium circulator. The output temperature of the RPV is (nominally) 850 C. The ETS-2 system will operate at a lower temperature due to energy loss in the ETS-1 and IHX systems; it uses nitrogen pressurized at 6.8 MPa to provide a nominal pressure balance across the IHX-1 to reduce any tendency for helium leaks in this critical area. The slight pressure gradient is established from ETS-1 to ETS-2 so that any gas migration will be in the direction of helium-to-nitrogen, and thus avoid any chemical contamination on the ETS-1.

The ETS-1 forms the secondary pressure boundary of the reactor and associated first stage energy (heat) transfer system, with the TRISO microsphere forming the first pressure boundary and the underground silo forming the third boundary. ETS-1 includes the RPV, reactivity control systems, helium transfer piping, IHX-1, and helium circulator.

3.1 Helium Circulator

The helium circulator is placed in the cold piping leg of ETS-1. It is planned that the circulator will use one of the available tested designs, either submerged in the primary coolant with active magnetic bearings, foil bearings or operated outside of the pressure boundary with a drive shaft penetrating it combined with a dry gas seal design.

3.2 Intermediate Heat Exchanger-1

The intermediate heat exchanger design has not been chosen at this time. As a part of the NGNP design, INL produced a study [8] of the various technologies available for a high-temperature helium-helium intermediate heat exchanger. This study considered a number of designs, including a plate machined heat exchanger, plate fin heat exchanger, and the plate stamped heat exchanger (all of which are compact heat exchanger designs). In addition, the standard shell and tube heat exchanger is a low-risk, robust, common industrial design. StarCore will be evaluating these competing designs as part of the design concept validation phase, with a compact heat exchanger the preferred design.

4. Balance of Plant

The two main energy transfer systems are summarized above in Section 3. This section discusses ETS-2, the power conversion unit, ancillary outputs and civil design.

4.1 Energy Transfer System 2

The ETS-2 nitrogen system transfers the energy to the energy transfer control system that directs the high temperature nitrogen to either the IHX-3 heat exchanger in the external combustion turbine, or the IHX-2 heat exchanger that can be used for load following.

4.2 Power Conversion Unit

The base case power conversion unit is an axial flow aero-derivative turbine converted from an external combustion design, with a heat exchanger (IHX-3) located in the internal gas path where the fuel burner cans would normally be located. Other turbo-machinery is also being considered, including a hybrid marine turbo-charger and a compressor-expander unit of the type used in heat process plants. No decisions have been taken at this time about single spool or two spool designs; two spool units are more efficient, flexible and provide greater load swing capabilities, but they must be protected from spool runaway in the event of sudden load dumps.

Various load following arrangements are being considered, including diverting the energy input from the power conversion turbine to a cogeneration super-heated steam output via IHX-2. The IHX-2 unit is rated at 5 MWt so it can provide an instantaneous plus 2 or minus 3 MWt load swing from the nominal output. This unit is kept at the nominal 2 MWt steam output. Also being considered are bypassing gas flow around the turbine, and incorporating a flywheel in the system.

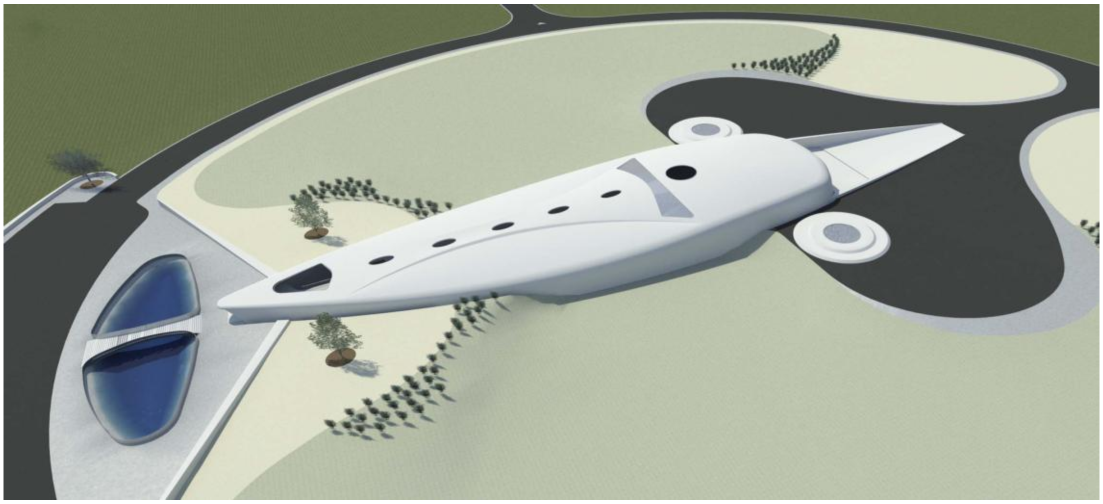
4.3 Ancillary Outputs

There are a number of ancillary outputs planned for the StarCore plants; these include super-heated steam (450 C nominal), high temperature air (400 C nominal) from the turbine exhausts) and shaft horsepower. These outputs will be tailored to the application and could be used for a variety of purposes including potable water production, space heating, the provision of compressed air and district heating.

4.4 Civil Design

The conceptual design of the plant is shown below. The main elements of the design are intended to provide passive safety, and to prevent any unauthorized access or intentional damage to the plant occurring without the need to provide overt security fences or onsite personnel.

Conceptual Design of Reactor Plant



The site is 250 m in diameter, and is graded to show that the property belongs to StarCore while allowing free access to the facility. The building has two floors at the personnel entrance on the right and a single two-story turbine room on the left. Accommodation is provided for full time occupation by four personnel on the second floor, although not needed for the operation of the plant, which is fully automatic. It is expected that there will be two full time personnel on the site. Two backup diesel generators of 500 kW each are provided, and there are two-story spaces for secondary output processes. The interior has a hardened internal citadel to keep unauthorized personnel out of the turbine and machinery rooms, and access to these spaces is by means of double-door personnel locks. There are emergency exits located on each floor, and the whole building and silos are constructed of high performance concrete with varying strengths between 30,000 and 70,000 psi. The building and silos are made from pre-fabricated concrete sections that are assembled on site after foundations are poured.

5. Control Systems

Most nuclear plant control systems today rely on operators to determine the correct course of action in complex circumstances. This is not practical for remote locations. StarCore's control technology will provide on-site automatic control with full-time monitoring and intervention capability from StarCore Central by satellite. Only maintenance and power distribution engineers will be on-site. Local control will be provided for start-up, monitoring and shutdown during plant qualification and local emergency conditions. The StarCore Control System is secure and is ideal for remote sites.

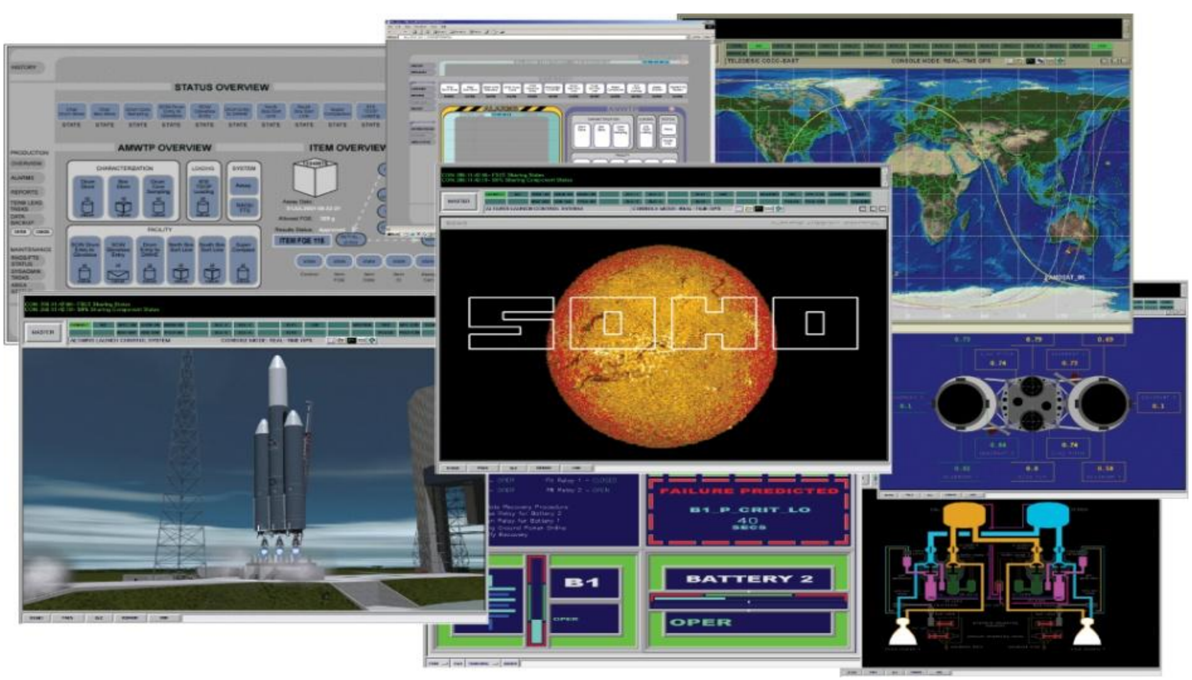
5.1 StarCore HyperVector Automated Control

StarCore will install an advanced, fully automated HyperVector Control System previously used in many safety-critical aerospace systems. There are many benefits that this control system technology brings, including: automatic failure prediction for every system or component in an arbitrarily complex application, alarms that uniquely identify any specific failures that have occurred or are predicted, controls that prevent wrong commands or actions ever being taken, and automatic responses to arbitrarily complex failures.

The system is named after the manifolds in state space that define the operational limits of the systems; these are represented by n-vectors, or HyperVectors, defined as (complex) data in the imaginary plane. The states are defined for every component in the plant, with each component having a state topology that reflects system operations. They also use the state loci and rate to calculate time to state boundary, and thus predict - in real time – time to failure of every component in the system.

Some of the systems on which HyperVector control has been deployed are shown in the figure below; the Solar Deep Space Observatory, SOHO; Titan II; Delta IV; Nuclear Waste Management and other systems can be seen.

Typical Systems Using Hyper Vector Control Systems



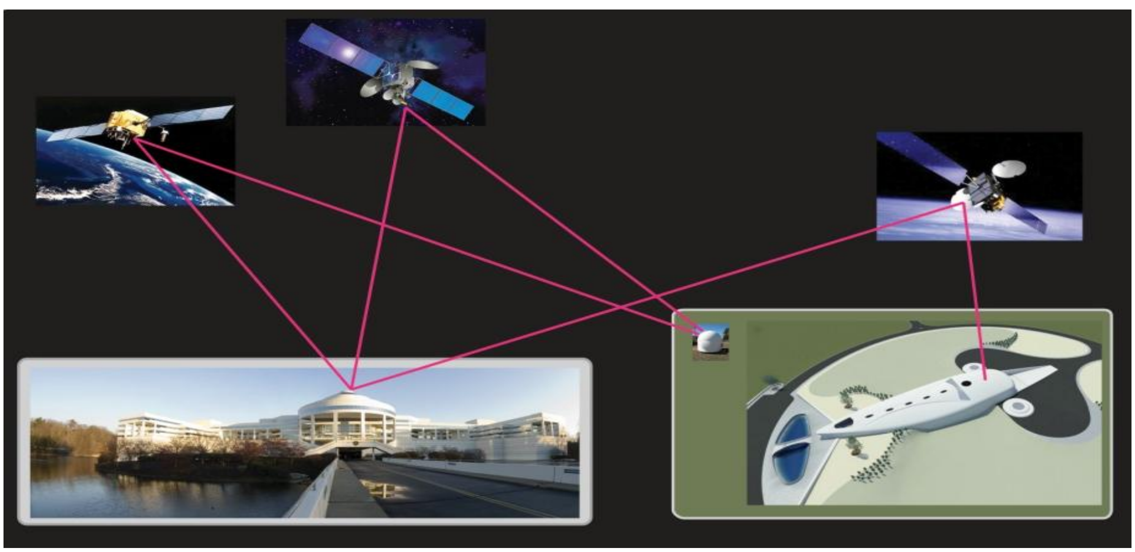
5.2 Safety and Security

The system is a model-driven, real-time, component-based, software architecture that features a triple-redundant backbone with real-time error monitoring and voting. It uses the Security Enhanced Linux operating system for all main processing and control, a two-bus separate system for operator user Interfaces, and has triple-redundant embedded field-programmable gate arrays for real time processing of critical safety functions. This design makes the system immune to virus and other malicious software. It also offers several important benefits, including the ability to bring additional functionality or plug-in modules without disturbing the certification or stability of the deployed systems. The complete cyber-security design is being developed and coordinated with the Canadian Standards Association (CSA) under CSA Standard N290.7. StarCore is a member of the CSA standards committees.

5.3 Architecture

The StarCore HyperVector I&C Control System is three-bus component-based design; it has a total of nine independent processors for each reactor/turbine unit. Three of these are installed in the silos themselves; these safety systems are logically and physically separated from the remainder of the system. There are three general purpose processors in the remote plant; and three more are installed in StarCore Central Control, connected by three, independent, satellite links, each with triple redundancy. The general arrangement of the satellite links is shown below. There is a main and backup full time 50 Mb/s link through two different geosynchronous (GEO) satellites that provide continuous coverage, and an emergency backup link through a low-earth (LEO) orbiting satellite. The GEO links use radomes at the StarCore site, while the LEO link uses an antenna embedded in the surface of the StarCore main building.

Satellite Links



The StarCore I&C technology also includes a “Keep Alive” signal, transmitted to a plant at pre-defined intervals. This sets a defined period at the end of which the plant will shut down if the next Keep Alive is not received. This feature clearly will not be appropriate for all plants but is available for remote installations that may present significant operational risks.

6. Conclusion

StarCore has made significant progress in developing a reactor plant that can be used at remote sites off-grid or at end-of-grid. Its power level has been designed to meet the requirements of these remote sites, whether they are mining sites, industrial sites or communities. The next steps in its development are the completion of the conceptual design and participation in a Vendor Design Review with the Canadian Nuclear Safety Commission.

7. References

1. INL, “NGNP project 2011 status and path forward “, *INL/EXT-11-23907, December 2011*
2. INL, “NGNP program 2013 status and path forward “, *INL/EXT-14-31035 Revision 0, March 2014*
3. Matzner, Dieter, “PBMR project status and the way ahead”, *2nd International Topical Meeting on High TEMPERATURE REACTOR TECHNOLOGY, Beijing, China, September 22-24, 2004*
4. Yuanhui, Xu, “The HTR-10 project and its further development”, *IAEA conference on high temperature reactors; 22-24 April 2002*
5. Takizuka, Takakzu, “ Reactor technology under the HTTR project”, *Progress in Nuclear Energy, Vol. 47, No. 1-4, pp 283-291, 2005*
6. IAEA, “Advances in high temperature gas cooled reactor fuel”, *IAEA TECDOC 1674, 2013*
7. “Areva modular reactor selected for NGNP development”, *World Nuclear News, 15 February 2012*
8. Mizia, R. E., “Next Generation Nuclear Plant Intermediate Heat Exchanger Acquisition Strategy”, *INL/EXT-08-14054 Revision 0, April 2008*