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AREVA Modular Steam Cycle – High Temperature Gas-Cooled Reactor Development Progress

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Abstract – *The AREVA Steam Cycle – High Temperature Gas-Cooled Reactor (SC-HTGR) is a modular graphite-moderated gas-cooled reactor currently being developed to support a wide variety of applications including industrial process heat, high efficiency electricity generation, and cogeneration. It produces high temperature superheated steam which makes it a good match for many markets currently dependent on fossil fuels for process heat. Moreover, the intrinsic safety characteristics of the SC-HTGR make it uniquely qualified for collocation with large industrial process heat users which is necessary for serving these markets. The NGNP Industry Alliance has selected the AREVA SC-HTGR as the basis for future development work to support commercial HTGR deployment.*

This paper provides a concise description of the SC-HTGR concept, followed by a summary of recent development activities. Since this concept was introduced, ongoing design activities have focused primarily on confirming key system capabilities and the suitability for potential future markets. These evaluations continue to confirm the suitability of the SC-HTGR for a variety of potential applications that are currently dependent on fossil fuels.

I. INTRODUCTION

The steam cycle – high temperature gas-cooled reactor (SC-HTGR) is a graphite-moderated helium-cooled reactor coupled directly to a steam generator to produce high temperature steam. It is being developed by AREVA to serve a wide variety of applications including industrial process heat, moderate electricity generation, and cogeneration. The concept was introduced at HTR 2010 in Prague, Czech Republic [1]. The SC-HTGR concept relies on established technologies to the maximum extent possible in order to facilitate near-term deployment with minimum technical risk.

In 2012, the SC-HTGR design concept was selected by the NGNP Industry Alliance for near-term commercialization of HTGR technology [2]. Current SC-HTGR development is focused on supporting this effort.

The remainder of this paper has two main parts. The first provides an updated description of the SC-HTGR design concept. This reflects incremental changes that have taken place in the past few years. The second part of the paper discusses recent development activities conducted in support of SC-HTGR development and commercialization.

II. MARKET FOCUS

The SC-HTGR concept is intended to serve near-term applications which require high temperature steam including both process heat and electricity generation. The concept relies to the maximum extent possible on existing, proven technology in order to minimize technical risk and project risk and to reach markets as quickly as possible.

These markets include a variety of current and future process heat applications. Currently such applications consume about two-thirds of global energy production, and this energy is almost entirely reliant on fossil fuels. This reliance on fossil fuels results in price volatility, supply uncertainty, and unwanted environmental impacts. The SC-HTGR provides an alternative with strong environmental benefits and fuel supply and price stability for these markets.

The SC-HTGR can also serve small and moderate electrical markets. The use of high temperature steam provides high generating efficiencies, and the steam conditions are similar to existing fossil power plants which will need replacement in coming years.

The modular size of the SC-HTGR offers significant market advantages. Similar to other small modular reactors (SMRs), it offers incremental capacity addition to more closely align cash flow with market needs. Serial production benefits both production efficiency and quality with resulting cost benefits. And modular facilities provide significant benefits in terms of reliability, maintenance scheduling, and sharing of non-critical resources.

Of course there is a tradeoff between the benefits of SMRs and the economy of scale associated with larger plants. For the SC-HTGR, this tradeoff is balanced by the high thermal efficiency of the SC-HTGR. In addition, the SC-HTGR's inherent safety characteristics eliminate the need for powered cooling systems and other large safety systems. This reduces both plant cost and operating and maintenance costs.

Engineering work during the initial project phases is focused on commercialization support. The current design activities generally address one of three main areas: concept feasibility, market applicability, and site suitability.

III. SC-HTGR DESCRIPTION

The SC-HTGR concept builds on the experience of past HTGR projects, as well as development and design advances that have taken place in recent years. The steam cycle heat transport system takes full advantage of the experience from past operating HTGRs and the further development work performed on early modular HTGR concepts such as the MHTGR and the HTR-Module. The prismatic block reactor is based on AREVA's previous ANTARES concept [3] which is sized to take maximum advantage of the passive heat removal capability of modular HTGRs.

III.A. SC-HTGR Reactor Module Description

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

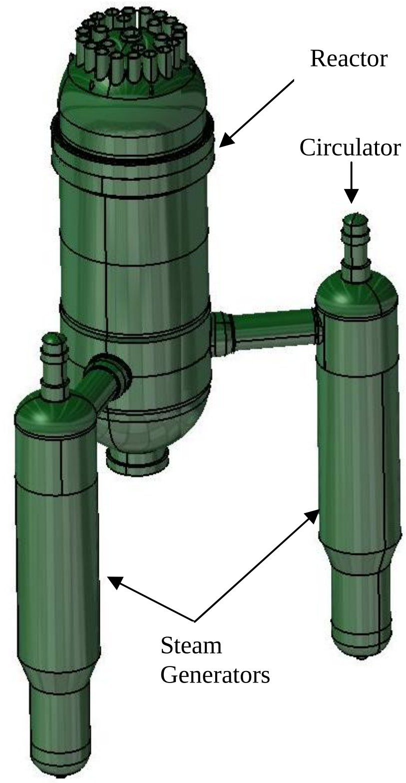

Fig. 1: SC-HTGR steam supply system.

The heart of the AREVA steam cycle concept is the prismatic block reactor. It is a 102 column annular core (Fig. 2). This geometry provides good radial conduction to maximize the benefits of passive decay heat removal.

The reactor uses TRISO coated particle fuel. At the center of each fuel particle is a kernel of uranium oxycarbide (UCO). The coated fuel particles are embedded in cylindrical compacts of graphite matrix material slightly over 1 cm in diameter. The compacts are loaded into graphite fuel blocks.

The nominal power distribution is controlled in the core design using a combination of particle packing fraction, burnable poison, and enrichment as appropriate for each specific fuel cycle. The enrichment is less than 20 percent.

Normal reactor control uses control rods in channels at the edge of the core. Each segmented control rod is supported on a cable from the control rod drive located in its control rod drive housing at the top of the reactor vessel. The control rods contain ceramic absorber material. The outer portion of each rod segment is made of Alloy 800H. A design alternative which replaces metallic portions of the control rod segments with ceramic composites or a ceramic-metallic hybrid construct may also be considered for increased investment protection, but this is unnecessary for the rods' safety function.

An alternate reserve shutdown system is also available. The reserve shutdown system drops absorber material into separate channels in the core interior when activated. Either the control rods or the reserve shutdown system can shut the reactor down. And, if neither system functions, negative temperature reactivity feedback will shut the reactor down with only a slight temperature increase.

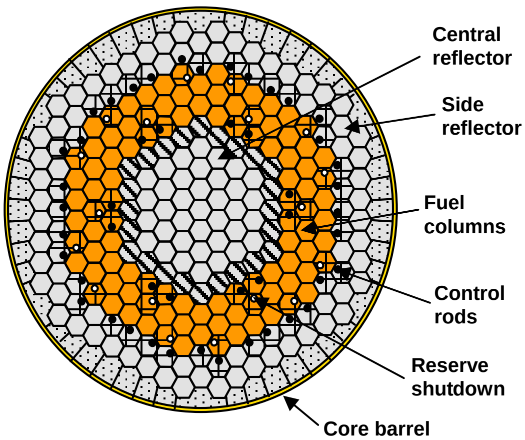

Fig. 2: SC-HTGR annular core arrangement.

A steel vessel system using conventional vessel material houses the entire primary circuit. The reactor vessel contains the reactor core, reactor internals, and control rods. Each steam generator is housed in a separate steam generator vessel. A separate cross vessel connects each steam generator to the reactor vessel. Each cross vessel contains a hot duct which 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 inner vessel surface is bathed in cool reactor inlet gas.

Each steam generator is a helical coil tubular heat exchanger. This steam generator is similar to those successfully employed in past gas-cooled reactors. The tubing is 2¼ Cr – 1 Mo in the economizer and Alloy 800H in the superheater.

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.

Each reactor module is located in a separate reactor building (Fig. 3). The standard configuration uses a fully embedded below grade reactor building design. This provides structural design advantages and superior protection from external hazards.

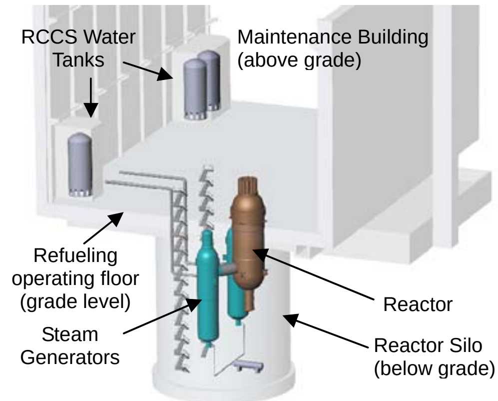

Fig. 3: Single SC-HTGR reactor module.

III.B. SC-HTGR Operating Parameters

The reactor inlet and outlet temperatures are 325°C and 750°C, respectively. These temperatures are slightly lower than the ANTARES temperatures, since the Rankine cycle does not need the same temperature as the combined cycle gas turbine used for ANTARES.

These lower temperatures provide several benefits. First, they allow the use of SA-508/533 for the vessels without separate cooling or special thermal protection.

In addition, the lower temperatures allow a higher reactor power level. The reactor design is based on the 600 MWt ANTARES. However, as demonstrated in previous studies [4], colder initial conditions allow a higher reactor power level to be used while maintaining acceptable peak accident fuel temperatures. For the steam cycle concept, the reactor power level was originally estimated to be 625 MWt. Subsequent analyses have confirmed that fuel and vessel accident temperatures are acceptable at this power level, as discussed later in this paper.

The major parameters of the SC-HTGR are summarized in Table 1.

The steam cycle concept is extremely flexible. A single basic design is capable of serving a wide variety of near-term markets. High pressure steam is a versatile heat transport medium.

The steam cycle is also well suited to cogeneration of electricity and process heat. The steam system can be configured in a variety of ways depending on the specific needs of the facility for high temperature steam, low temperature steam, and electricity. Figure 4 illustrates one possible cogeneration plant configuration in which high pressure extraction steam is used to supply tertiary process steam via a reboiler.

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

Table 1: SC-HTGR parameters.

Fuel Type	TRISO particle
Core Geometry	Prismatic block 102 column annular 10 block high
Reactor power	625 MWt
Reactor outlet temperature	750°C
Reactor inlet temperature	325°C
Primary coolant pressure	6 MPa
Primary coolant	He
Secondary coolant	Water/steam
Vessel material	SA508/533
Primary loops	2
Steam generator power	315 MWt (each)
Main circulator power	4 MWe (each)
Main steam temperature	566°C
Main steam pressure	16.7 MPa
Net electric output (all electric mode)	272 MWe

III.C. SC-HTGR Heat Removal

The AREVA concept has three heat removal systems. The two main cooling loops transfer heat to the secondary circuit during normal operation. They also can provide cooling during refueling and other shutdown conditions. When maintenance is being performed on the main cooling loops a separate shutdown cooling system is available. This system uses a separate circulator and heat exchanger located at the base of the reactor vessel.

If both active systems are unavailable, passive heat removal is used. Passive cooling in the SC-HTGR is similar to other modular HTGRs. Fuel and component temperatures are maintained at acceptable levels by the large thermal inertia of the graphite core and the radial conduction path outward to the surrounding reactor cavity. System temperatures are maintained within limits without forced cooling and without the helium coolant.

In an accident with a complete loss of primary coolant and active cooling systems, heat from the core initially moves from the annular active core into the central reflector and outer side reflector (see Figure 2). The heat capacity of these solid structures is sufficient to absorb the heat for several hours before significant heat is conducted to the outer structures. Eventually the heat is conducted and radiated out to the core barrel where it is transferred to the reactor pressure vessel, primarily by thermal radiation. From the reactor vessel, it is transferred by radiation into the reactor cavity where it is removed by the Reactor Cavity Cooling System (RCCS). This heat removal process does not require any moving components or activation of any standby systems.

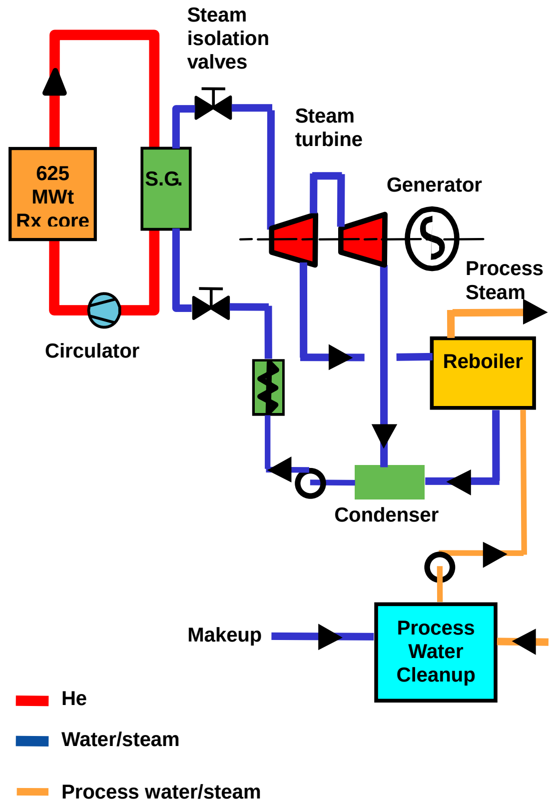

Fig. 4: SC-HTGR cogeneration system.

The RCCS is a natural convection water-cooled system (Figure 5). Each loop of the safety-related system consists of heat collecting panels in the cavity surrounding the reactor vessel connected by a natural circulation loop to a water storage tank. A separate non-safety active loop cools the water inventory in 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.

The water storage tank in each RCCS loop contains enough inventory for seven days. With both loops in operation, the system can go for many more days without additional water. If the RCCS water is depleted during a sustained accident, plant operations staff or relief staff can easily add water to one or more of the RCCS tanks. In any event, even if the RCCS water is exhausted, the peak fuel temperatures do not increase significantly. Vessel temperatures would increase, but functional performance of the vessel system would be maintained even for this beyond design basis condition.

The RCCS natural circulation loop functions the same during both normal operation and accident conditions. During normal operation, the RCCS maintains acceptable concrete temperatures in the reactor cavity. During accidents, the RCCS maintains acceptable fuel, vessel, and concrete temperatures.

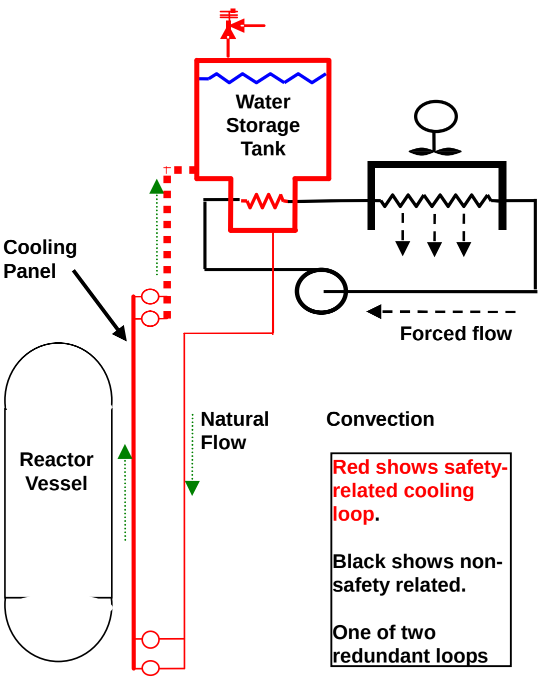

Fig. 5: Schematic of SC-HTGR Reactor Cavity Cooling System.

III.D. SC-HTGR Safety Characteristics

The SC-HTGR retains the excellent safety characteristics typical of modular HTGRs. The TRISO fuel particles retain virtually all fission products during both normal operation and accidents.

The use of inert coolant eliminates potential adverse interactions between the coolant and other reactor system components. The helium coolant is also effectively transparent to the neutrons in the reactor, simplifying the neutronics behavior and analysis during both operation and accidents. And the gaseous coolant cannot change phase during accidents, again simplifying plant behavior.

As mentioned previously, passive cooling can maintain acceptable system temperatures even with the loss of all active systems. The SC-HTGR RCCS provides passive cooling in the reactor cavity without the need for any electrical power and without the need for any active components or changes in operating modes during accidents. Moreover, the large thermal inertia of the systems provides stable operation and long response times for transients.

The negative reactivity temperature coefficient limits reactor power during accidents, even without the two active reactivity control systems. As a result, the peak fuel temperatures are not significantly higher following a loss of forced cooling even without a reactor trip.

These safety characteristics are a significant advantage for process heat applications where the reactor module may be sited in close proximity to the chemical plant or other process heat user.

III.E. SC-HTGR Plant Arrangement

The modular design of the system allows multiple reactor modules to be grouped together on a single plant sight. A typical plant layout might have four reactor modules as shown in Figure 6. However, the specific number of modules in an actual plant will depend on the nature of the application and the customer's needs.

Reactor modules share auxiliary and supporting systems during normal operation, but safety systems are independent. Common functions such as new fuel receipt and spent fuel storage would be provided in a common area. Maintenance facilities and other plant infrastructure would also be shared.

Each reactor module has independent control and protection systems. A common supervisory control system coordinates the interface between the reactor modules, process steam demand(s), and electricity generation. The supervisory control system allocates load demand between individual reactor modules and provides inputs to the independent module control systems accordingly. However, in the control hierarchy the individual control system for each reactor module ensures that operating constraints for its reactor module are satisfied regardless of the supervisory control demands.

The power conversion system portion of each plant will be customized for the application of interest. In a typical plant providing steam for process heat and/or cogeneration, steam from multiple reactor modules is supplied to a common header which supplies one or more turbines or process loads.

For process loads requiring very high reliability, current industry practice is to provide substantial redundancy. For the SC-HTGR plant this redundancy would be satisfied with a combination of multiple SC-HTGR modules based on the expected load together with natural gas or oil-fired boilers for backup steam supply (Figure 7). This approach is attractive since gas or oil-fired boilers have low installation cost [5].

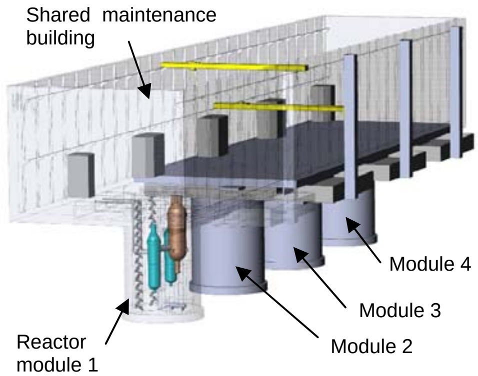

Fig. 6: Typical arrangement for four module plant.

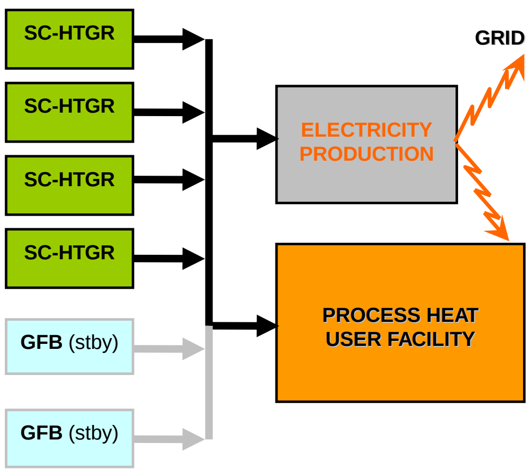

Fig. 7: Typical plant with SC-HTGR steam supply and natural gas-fired boilers (GFB) for backup.

While the energy delivery system for an SC-HTGR plant will normally be customized for the specific needs of each customer, the actual reactor modules are completely standardized. This is the key to successful commercialization of the SC-HTGR. The whole NSSS, including the reactor, the steam generators, the circulators, and the surrounding vessel system is identical for each module. The reactor modules are each housed in separate reactor buildings which are also identical. And primary supporting services such as fuel handling systems, reactor module control and protection systems, and primary auxiliary systems are the same for each reactor installation.

This standardization minimizes the amount of design work required for each installation and it allows serial production of reactor module components and facilities.

IV. DEVELOPMENT ACTIVITY

The main activities for this phase of the project are focused on commercialization efforts. Design activities are a secondary priority, with primary design activities being those complementary to the commercialization effort. The relevant design and analysis tasks are those which are focused on confirming commercialization capabilities and addressing specific market feasibility questions.

IV.A. Commercialization Development

The SC-HTGR concept was selected to minimize technical risk by relying on existing technology to the maximum extent possible. Nonetheless, significant challenges remain on the path to commercial deployment. First of all, remaining technology developments such as fuel qualification must be completed. Fortunately, excellent progress in these areas is being made in the US Department of Energy's AGR and AGC programs. The remaining deployment challenges are largely commercial and regulatory, not technological.

For any first-of-a-kind nuclear power plant, the amount of preliminary and detailed design work that is required is considerable. In addition, the required licensing for a new technology will require substantial work. And this work cannot be completed without significant design work. Hence a major investment is required.

Even for a technology such as the SC-HTGR which has a large potential market, the deployment timeframe must extend over many years. First, the design work and licensing must be completed. Then the initial demonstration plant must be built and operated for a period of time. Only then can subsequent plants finally be built in gradually increasing numbers. As a result, even though many plants would eventually be built, the lack of large near-term returns makes it difficult to dedicate the required resources to bring the project to completion. This is why all existing commercial nuclear reactor technologies have only been successful as a result of large initial governmental support.

The commercial challenges to HTGR deployment and potential success strategies are explored in a separate paper [6].

IV.B. Confirm Safety Performance for 625 MWt

Passive heat removal capability is central to the safety performance of modular HTGRs. This capability ensures that acceptable fuel temperatures are maintained under all circumstances. It also maintains required components within their design temperature limits during both normal operating conditions and design basis accidents.

The passive heat removal capability of the reactor is a direct function of the reactor geometry, power level, and operating temperatures. Therefore, for a given geometry and operating temperature, the operating power level is selected in order to ensure that all limits will be satisfied.

Two key decisions in the initial development of the SC-HTGR have a direct bearing on potential passive cooling performance. First, it was decided to use conventional LWR vessel material (e.g., SA-508/ SA-533) for the SC-HTGR reactor vessel. Second, the operating temperatures were chosen to be 750°C for the reactor inlet and 325°C for the reactor outlet. These temperatures work well with the selected Rankine cycle performance, and they also are compatible with the selected vessel material. Based on previous sensitivity results, the selection of these operating temperatures indicated that a peak power level of 625 MWt should be achievable, so this was selected as the initial operating power level.

Based on previous results, there was high confidence that these conditions would provide acceptable fuel temperatures once detailed safety analyses were completed. However, there were questions regarding whether or not the temperature limits for SA-508 could be satisfied at this high power level. Previous analyses of nominally 600 MWt modular HTGRs had used modified 9Cr-1Mo for the vessel. The modified 9Cr has higher temperature limits than the SA-508. For SA-508, the ASME code limits the service temperature to a maximum of 538°C with only 3000 hr above 371°C and a maximum of only 1000 hr above 427°C (number of excursions above 371°C is also limited). Concern was expressed in early reviews that these limits might be violated at the higher power level.

Therefore, a detailed study was initiated to examine SC-HTGR performance during a depressurized loss of forced convection (DLOFC) event. The study considered both nominal (i.e., best estimate or expected) performance as well as conservative or limiting performance [7]. A detailed uncertainty evaluation was also performed [8].

Two sets of results from those studies are provided here. Figures 8 and 9 show the peak and average fuel temperatures and the peak vessel temperature for a nominal event. Not surprisingly, both the fuel temperatures and the vessel temperatures are far below their limits in this case.

A second pair of figures shows the same temperatures for conservative evaluations. Figure 10 presents the fuel temperatures for a case that is specifically conservative for fuel temperatures. Similarly, Figure 11 presents the vessel temperatures for a case that is specifically conservative for vessel temperature.

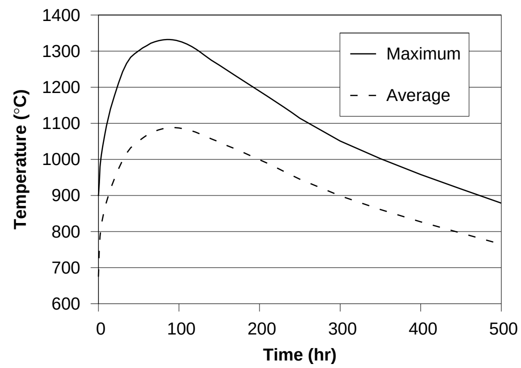

Fig. 8: Fuel temperature during nominal DLOFC event.

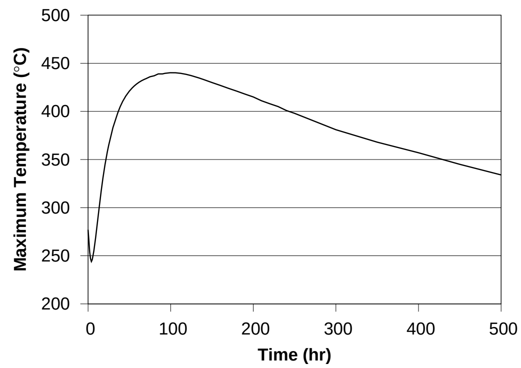

Fig. 9: Maximum reactor vessel temperature during nominal DLOFC event.

An in-depth discussion of the impact of uncertainty on DLOFC results is beyond the scope of this paper. Nonetheless, it is clear from these results that uncertainties must be properly accounted for, since they can have a large impact on DLOFC results. Therefore, both deterministic [7] and probabilistic [8] approaches were considered in order to provide a high level of confidence that both fuel and vessel temperatures would be acceptable at the 625 MWt power level.

The conclusion was clear that the results are acceptable even with conservative evaluation of the SA-508 vessel temperature. Table 2 summarizes the study results. The indicated temperatures are from separate cases which are each conservative for the indicated component. The acceptance criteria are those selected in [7]. (The duration limits shown for the reactor pressure vessel (RPV) are less than those mentioned above, since the design must allow for more than one event during the plant lifetime.)

All temperatures evaluated are conservatively within their design limits. This confirms that the SC-HTGR design conditions are appropriate for subsequent design work. Confidence is high that the results of detailed safety analyses during subsequent phases will provide acceptable results.

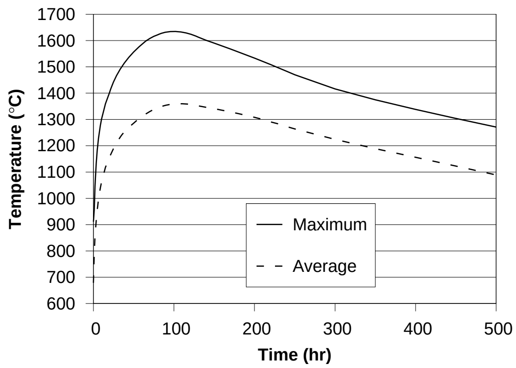

Fig. 10: Fuel temperature DLOFC results for conservative fuel case.

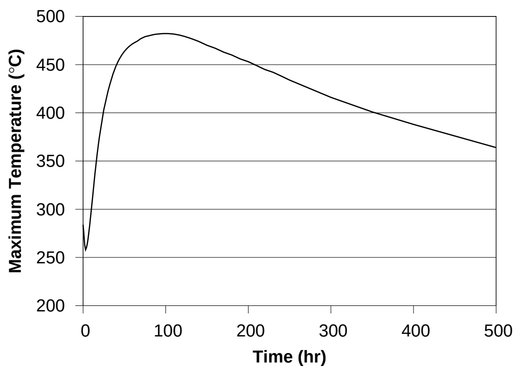

Fig. 11: RPV temperature DLOFC results for conservative RPV case.

Table 2: Summary of conservative DCC results.

Component	Conservative peak temperature	Scoping Criterion
Fuel	1635°C	1650°C
Core Barrel	784°C	800°C
RPV	482°C	538°C
Duration RPV above 371°C	446 hr	750 hr
Duration RPV above 427°C	233 hr	250 hr

IV.C. Performance in Arid Sites

Many developing areas experience rapid increase in energy demand also have limited supply of fresh water. Moreover, growing populations are putting increasing demand on both energy production and water supplies. Therefore, there is significant interest in the ability of power systems to use dry cooling instead of traditional evaporative wet cooling.

The use of dry cooling can have a significant effect on both power plant performance and power plant cost. Dry cooling typically results in a high condenser temperature which increases turbine backpressure and reduces electricity generation. Dry cooling also increases the size and cost of the heat rejection system which increases plant cost. And cooling tower fan power is also usually increased, further reducing net plant output.

Fortunately, the impact of these penalties is a function of the quantity of heat that the plant has to reject in the first place. This means that the impact should be less for a plant such as the SC-HTGR which produces high temperature steam and a relatively high thermal efficiency. A modest increase in condenser temperature has a smaller impact on the high temperature Rankine cycle than the same increase would have on a lower temperature system. Moreover, since a smaller fraction of heat has to be rejected, the heat rejection system is smaller to begin with, so a proportional increase in the size of that system has a smaller overall impact.

Since ongoing commercialization discussions for the SC-HTGR include markets with arid sites which could require dry cooling, a study to quantify the specific impact on SC-HTGR performance was undertaken [9]. This study confirms the benefits of the high temperature steam Rankine cycle. The main results of the SC-HTGR dry cooling study are summarized in Table 3.

The nominal performance of the SC-HTGR for a reference site with wet cooling is shown as Case 1. The gross generation of 293 MWe and a house load of 21 MWe, the net output is 272 MWe. This results in a net efficiency of 43.5% for the 625 MWt reactor module.

Case 2 examines an alternate plant designed specifically for service at a hot arid site using dry cooling. Because of the hotter environment and the use of dry cooling, the condenser temperature increases to 67°C. This reduces the gross generation to 264 MWe. In addition, the house load increases to 26 MWe, primarily due to increased fan power for the dry cooling towers. So the net output is 239 MWe, and the net generating efficiency is reduced to 38.2%.

Case 3 examines the performance of the same plant considered in Case 2 when operating at off-design conditions for an extremely hot day. This analysis assumes that the dry cooling plant design is optimized for a "typical" hot day at the selected arid site. Hence plant performance will be impacted slightly for the extreme day for the site, since the heat rejection temperature is higher and key plant equipment is operating slightly off from the design point.

For Case 3, the dry bulb temperature is increased to 55°. This raises the condenser temperature to 78°C. As a result, the gross electricity generation decreases to 254 MWe. The house load is essentially unchanged, since the same cooling tower fans are used in both Case 2 and Case 3. The resulting net output is 228 MWe for a net generating efficiency of 36.5%.

Table 3: SC-HTGR performance comparison.

	Case 1	Case 2	Case 3
Type of site and heat rejection mode	Nominal (Ref. plant)	Hot Arid Site	Extreme Day for Hot Arid Site
Cooling tower type	Wet	Dry	Dry
Wet bulb temperature	16°C	NA	NA
Dry bulb temperature	36°C	45°C	55°C
Condenser temperature	34°C	67°C	78°C
Reactor power (MWt)	625	625	625
Gross electricity generation (MWe)	293	264	254
Gross cycle efficiency	46.9%	42.3%	40.6%
Total house load (MWe)	21	26	26
Net electricity output (MWe)	272	239	228
Condenser heat load rejected (MWt)	340	369	380
Net efficiency	43.5%	38.2%	36.5%

So in going from wet cooling at a moderate site to a dry cooling configuration at a hot arid site, the SC-HTGR performance drops from 272 MWe net output to 239 MWe, a decrease of only 12%. This decrease is less severe than would be expected for a LWR. Of course, the relative economic performance of competing generating technologies is more complex than this simple comparison. But as noted previously, the relative impact of dry cooling on both plant output and dry cooling system cost should be less for a higher temperature system such as the SC-HTGR.

Finally, this study assumed operation in the all-electric generation mode. Operation in a process heat or cogeneration mode cannot be assessed without detailed considerations of the specific process application requirements and operational constraints as well as the relative value of each output stream. But it is safe to say that the relative benefit of the higher performance system would be significant in any case.

IV.D. Compatibility with Low-Lying Coastal Sites

The reference SC-HTGR configuration places the entire reactor module in a below grade reactor building. While this configuration offers several advantages, it also brings some challenges, especially for sites with high water tables or sites prone to flooding. This is a significant issue for SC-HTGR commercialization, since the target process heat and cogeneration markets include a large concentration of chemical plants and refineries on the United States Gulf Coast.

Many of these sites have high water tables which are almost at grade level. Moreover, they are potentially subject to significant flooding from storm surge during hurricanes, etc. These issues have impacts both during construction and operation as well as in external hazards assessments for plant safety analyses.

The potential impact of Gulf Coast site characteristics has been recognized for some time as a consideration for future plant configurations. The accident at the Fukushima Daiichi power plant following the March 2011 earthquake and tsunami in eastern Japan only serves to reinforce the need to consider flooding hazards in the design of the SC-HTGR for coastal applications.

A study was commissioned by the NGNP Industry Alliance in cooperation with the US Department of Energy under the Next Generation Nuclear Plant program to investigate the adaptability of the steam cycle HTGR concept to different types of sites.

An important part of this study was an evaluation of the adaptability of the SC-HTGR concept to a partially embedded configuration. This study evaluated the benefits of the fully embedded configuration versus the challenges imposed by a coastal site. The fully embedded configuration offers substantial benefits for most sites in terms of structural support of the NSSS components, the refueling equipment, and the RCCS water storage tanks. However, sites with a high water table pose significant construction challenges for such a structure. The difficulty of dewatering during construction, the need for temporary walls during excavation, and the potential challenge of building up lift all increase substantially with increasing building depth.

Two building configurations were evaluated during this study. The reference configuration was the existing concept with each reactor module housed in a fully embedded reactor silo and with the refueling floor located at grade level (Figure 12). The alternate configuration considered was a partially embedded structure as shown in Figure 13.

While the difference between the fully and partially embedded configurations may not appear to be that substantial, it is very significant in terms of both construction benefit and flooding hazards. In the revised configuration, roughly one third of the reactor building is above grade. This reduces the challenges of the excavation for the reactor silos significantly. For example, less dewatering and stabilization is required. In addition, the refueling operating floor is raised above the maximum anticipated storm surge, significantly reducing the external hazard threat due to flooding.

The study concluded that both fully and partially embedded structures are possible. The optimum structure for each installation can only be determined after detailed evaluation of the specific site conditions. Nonetheless, the partially embedded structure provides an attractive alternative for many coastal sites.

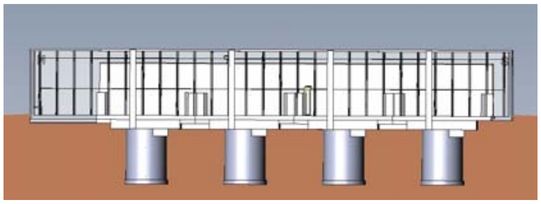

Fig. 12: Reference four module SC-HTGR with fully embedded reactor buildings.

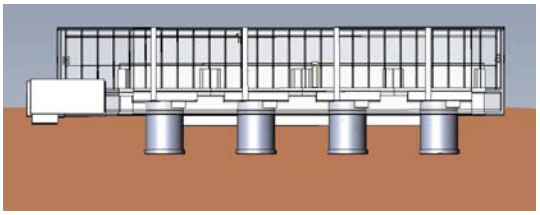

Fig. 13: Alternate four module SC-HTGR with partially embedded reactor buildings.

V. CONCLUSIONS

The SC-HTGR concept is being developed to provide high temperature steam to a variety of process heat, electricity, and cogeneration markets.

Preliminary evaluations continue to confirm the concept feasibility and suitability for these markets:

- The SC-HTGR concept minimizes technical risk by maximizing use of existing technology.
- The SC-HTGR power level of 625 MWt provides the best economy of scale for a modular HTGR.
- The ability of the SC-HTGR to meet passive cooling requirements at the 625 MWt power level has been confirmed.
- The use of high temperature steam maximizes thermal performance and provides good performance even in arid sites where dry cooling must be used.
- A partially embedded reactor building provides a feasible design option for coastal sites.

AREVA continues to pursue SC-HTGR development in support of the NGNP Industry Alliance effort to commercialize HTGR technology. Efforts to meet the commercialization challenges are ongoing. As commercial deployment expands, the SC-HTGR will provide key benefits as an alternative to fossil fuel dependence, with resulting economic benefits such as security of energy supply and price stability as well as important environmental benefits.

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