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# AREVA HTR Concept for Near-Term Deployment

L. J. Lommers, F. Shahrokhi[1], J. A. Mayer III[2], F. H. Southworth[1]
*AREVA Inc.*
*2101 Horn Rapids Road; Richland, WA 99354 USA*
*phone: +1-509-375-8130, lewis.lommers@areva.com*

[1]*AREVA Inc., Lynchburg, VA USA*

[2] *AREVA Inc., Marlborough, MA USA*

**Abstract –** *This paper introduces AREVA's High Temperature Reactor (HTR) steam cycle concept for near-term industrial deployment. Today, nuclear power primarily impacts only electricity generation. The process heat and transportation fuel sectors are completely dependent on fossil fuels. In order to impact this energy sector as rapidly as possible, AREVA has focused its HTR development effort on the steam cycle HTR concept. This reduces near-term development risk and minimizes the delay before a useful contribution to this sector of the energy economy can be realized. It also provides a stepping stone to longer term very high temperature concepts which might serve additional markets. A general description of the current AREVA steam cycle HTR concept is provided. This concept provides a flexible system capable of serving a variety of process heat and cogeneration markets in the near-term.*

## I. INTRODUCTION

This paper introduces AREVA's current High Temperature Reactor (HTR) concept for near-term industrial deployment. The background and motivation for the approach are presented as well as the main features of the design concept.

## II. BACKGROUND

Awareness of the important role of nuclear power in meeting future energy needs is increasing worldwide. However, nuclear power currently only supports electricity generation. The process heat and transportation fuel sectors are completely dependent on fossil fuels. Light water reactor (LWR) technology is not suited to meeting these needs for higher temperature applications.

In considering the potential of HTRs to supply high temperature process heat many different applications exist. A few of these include oil refining, chemical processing, heavy oil recovery, tar sands oil recovery, hydrogen production, etc. The potential applications cover a wide range of necessary temperature. Conventional HTRs would likely serve moderate temperature applications up to about 700°C, while other applications might require a Very High Temperature Reactor (VHTR).

Just as important, there is a wide variety in technical readiness between different applications. If the appropriate HTR nuclear heat source were ready today, some of these applications would be ready for immediate deployment, while others would still require years of development on the process application side.

### *II.A. Motivation for Near-Term Deployment*

The motivation for near-term deployment is based on the need to reduce our dependence on fossil fuels. LWRs and other renewables provide a significant fraction of electricity production, but electricity accounts for less than half of the total energy economy. Process heat and transportation fuels are almost completely dependent on fossil fuels. Deployment of HTRs would provide a path to significantly impact this broad segment of the energy market with environmental, economic, and energy security benefits.

Increasing pressure from environmental concerns suggest that near-term solutions are required. Similarly, concerns regarding volatility of fossil fuel prices and security of supply are having an increasing impact on business planning.

In trying to facilitate the deployment of nuclear power in support of process heat applications, end-user concerns must also be considered. Process heat users such as petrochemical companies operate on a shorter planning horizon than nuclear power companies, generally five to ten years. Near-term technologies that can be deployed closer to this timeframe make industrial deployment much more viable.

### *II.B. AREVA Perspective on HTR Development*

AREVA has a long history of involvement in HTR development. AREVA and its predecessor companies have been involved in various ways with past and present European HTR programs and the international Gas Turbine – Modular Helium Reactor program. Recently, AREVA completed a four-year evaluation of the ANTARES concept [1]. Currently AREVA is supporting the US Department of Energy's Next Generation Nuclear Plant program.

AREVA's experience in HTR design and interaction with future end-users provides a unique perspective regarding the risks and benefits of potential development strategies. Risks must be reduced to manageable levels, and project strategies must balance near-term benefits with the difficulties inherent in such an undertaking.

During an earlier phase of the NGNP program, AREVA developed a VHTR concept maximizing the use of existing technology in order to minimize risk [2]. However, that concept still involved challenges associated with intermediate heat exchanger qualification, higher core outlet temperature, etc.

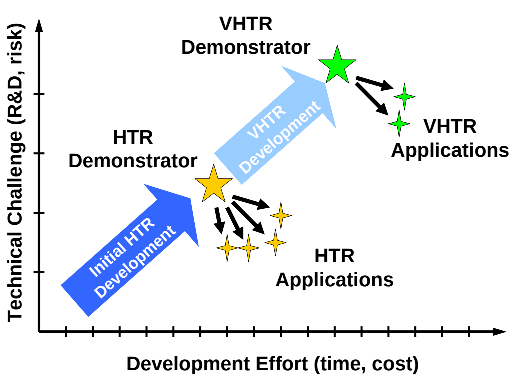


Fig. 1: Two step HTR development strategy.

Based on this experience and evaluation of the potential market, AREVA has created a vision for near-term HTR development. The goal is to impact the broader energy market rapidly in order to maximize the near-term benefits for the energy economy. This requires an HTR concept that is flexible and that minimizes technology development and project risk. The conventional steam cycle accomplishes these objectives.

## III. STRATEGY FOR NEAR-TERM DEPLOYMENT

With both near-term and long-term objectives in mind, a two stage program is envisioned (Figure 1). Initial development of the steam cycle concept allows rapid deployment into the process heat marketplace with reduced project risk. The second longer-term phase of the program would build on the initial development to extend to very high temperature applications. As Table 1 illustrates, this approach partitions key risk elements between the near-term and long-term phases of the program, thereby reducing the risk for each phase, and greatly reducing the overall program risk.

| Required Development | Steam Cycle | Future VHTR |
|---|---|---|
| Fuel Qualification | X | |
| HTR Siting | X | |
| HTR Licensing | X | |
| Process Interface Issues | X | |
| Safety Case Validation | X | |
| Very High Temperature Materials (metals, ceramics) | | X |
| High temperature fuel | | X |
| IHX development | | X |
| Very high temperature process interface | | X |

Table 1: AREVA steam cycle HTR parameters.

Conversely, direct development of VHTR concepts would have increased incremental risk, and it would delay deployment of near-term applications.

This approach provides the maximum impact on the energy market place in the near-term. And it provides a valuable stepping stone to reduce the incremental risk of future very high temperature reactor development.

## IV. AREVA STEAM CYCLE HTR

AREVA's current HTR concept builds on the experience of past HTR 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 HTRs and the further development work performed on early modular HTR concepts such as the MHTGR and the HTR-Module. The prismatic block reactor is based on AREVA's previous ANTARES concept [1] which is sized to take maximum advantage of the passive heat removal capability of modular HTRs.

Key parameters for the current system are noted in Table 2 and discussed in the following sections.

| | |
|---|---|
| Fuel Type | TRISO particle |
| Core Geometry | Prismatic block<br>102 column annular<br>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 |
| | |

Table 2: AREVA steam cycle HTR parameters.

### *IV.A. System Arrangement*

The AREVA HTR steam cycle concept is a two-loop modular steam supply system. Each module consists of one reactor coupled to two steam generators (Figure 2). The steam generators are configured in parallel, each with a dedicated main circulator.

A steel vessel system houses the entire primary circuit. The reactor vessel contains the reactor core, reactor internals, and control rods. Each steam generator is housed in a separate steam generator vessel. A separate cross vessel connects each steam generator to the reactor vessel. Each cross vessel contains a hot duct 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, so conventional LWR vessel material can be used.

Each steam generator is a helical coil tubular heat exchanger. Feed water enters the bottom of the heat exchanger and flows upward through the tubes, while hot primary coolant flows downward over the tube bundle. This steam generator is very similar to those successfully employed in previous gas-cooled reactors.

Electric motor-powered main circulators provide the primary coolant flow. The main circulator for each loop is located at the top of the associated steam generator vessel. The variable speed circulators use submerged motors with active magnetic bearings for simple operation and high reliability.

Each reactor module is located in a separate reactor building. The standard configuration uses a fully embedded below grade reactor building design. 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 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, although 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.

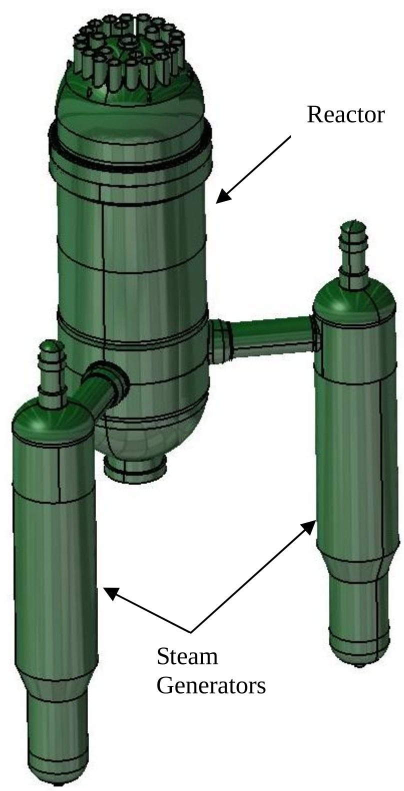


Fig. 2: Nuclear process steam supply system.

### *IV.B. AREVA Reactor Description*

The heart of the AREVA steam cycle concept is the prismatic block reactor. It is a 102 column annular core (Fig. 3). This geometry provides good radial conduction to maximize the benefits of passive decay heat removal. The active core is 10 blocks high.

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 [3], 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 is 625 MWt.

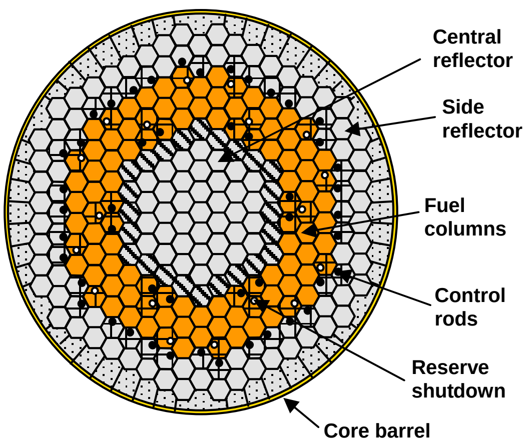


Fig. 3: Annular core layout.

*IV.C. Heat Removal Systems*

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 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.

The RCCS is a natural convection water-cooled system (Figure 4). 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 non-safety 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 is unavailable.

During normal operation, the RCCS maintains acceptable concrete temperatures in the reactor cavity. During accidents, the RCCS maintains acceptable fuel, vessel, and concrete temperatures.

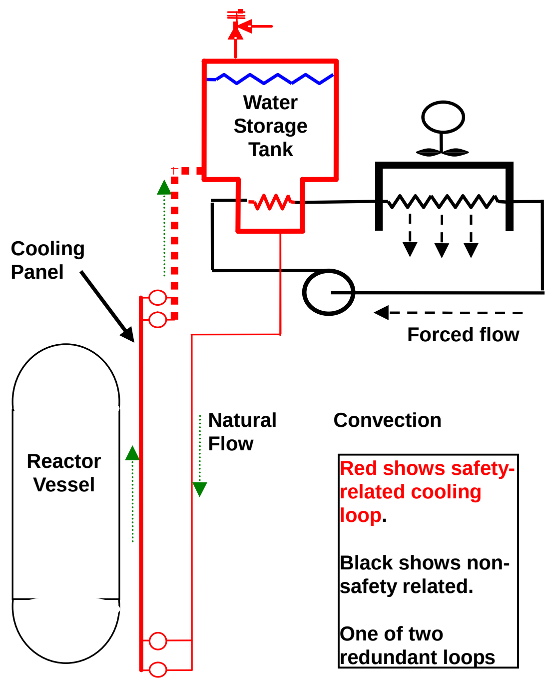


Fig. 4: RCCS schematic.

*IV.D. Safety Characteristics*

The AREVA steam cycle concept retains the excellent safety characteristics typical of modular HTRs. The TRISO fuel particles retain virtually all fission products during both normal operation and accidents.

As mentioned previously, passive cooling can maintain acceptable system temperatures even with the loss of all active systems. 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.

### *IV.E. Operation Flexibility*

The HTR steam cycle concept is extremely flexible. A single basic reactor module configuration designed to produce high temperature steam is capable of serving a wide variety of near-term markets.

High pressure steam is one of the most versatile heat transport mediums. As a result, the steam cycle HTR is well suited to supply a wide variety of process heat facilities.

The steam cycle HTR can also produce electricity. Using the conventional Rankine cycle with high temperature steam, a net efficiency of about 40% can be achieved. This makes the concept an attractive option in markets with limited grids and markets requiring incremental capacity addition.

Perhaps more importantly the steam cycle is well suited to cogeneration of electricity and process heat. Steam system equipment can be configured in a variety of ways depending on the specific needs of the facility for high temperature steam, low temperature steam, and electricity. Figure 5 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 HTR nuclear heat source.

## V. CONCLUSIONS

The AREVA near-term HTR concept provides a highly flexible solution that can economically displace limited fossil fuels from a variety of process heat and cogeneration applications. The design takes full advantage of recent modular HTR development experience. As a result, the system provides a very good option to deploy HTRs for the maximum benefit toward current energy needs in the near term.

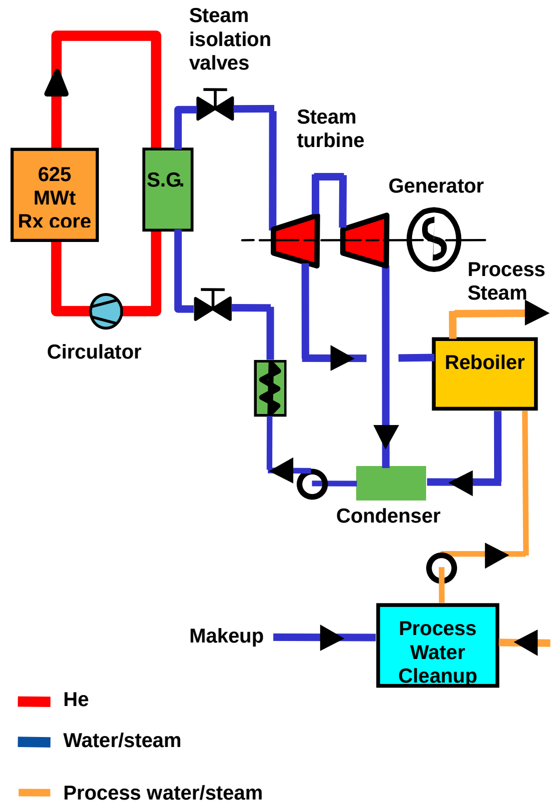


Fig. 5: Typical cogeneration plant configuration.

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