ANTARES: The HTR/VHTR project at Framatome ANP

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ABSTRACT: Framatome ANP is developing a Very High Temperature Reactor (VHTR), relying on its previous experience with high temperature reactor concepts, from its participation in the MODUL and the GT-MHR designs. While being a major actor in the nuclear reactor business with proven light water technology, AREVA wishes to be ready to meet the new challenges calling for small grid requirements, high temperature process heat and cogeneration. The Framatome ANP VHTR design for electricity production is based on an indirect cycle coupled to an "off-the-shelf" combined cycle gas turbine. Although direct cycle HTR's are being promoted for their high efficiency, preliminary evaluations show that the Framatome ANP design efficiency is on par with a direct cycle while avoiding PGS (Power Generation System) developments and keeping the PGS contamination free. Moreover, the nuclear heat source of the indirect cycle could also be used to meet the heat supplies from a standard design.

0. INTRODUCTION

Developed countries are addressing major challenges related to energy security and the environmental impacts of fossil fuels, including global warming. Solutions to these issues include carbon-free electricity generation and transportation fueled with hydrogen. The Very High Temperature Reactor (VHTR) has long been recognized as a promising technology for high efficiency electricity generation and high temperature process heat applications. As a complement to its line of light water reactor product, AREVA has decided to launch the design of such a high temperature reactor model in order to meet the future demands of medium sized grids for electricity generation but also industrial heat requirements, in particular the production of hydrogen from a carbon free source : water. As such, it is a leading technology candidate for the next generation of commercial nuclear reactors, following the advanced LWR designs being marketed today. The advantages of the VHTR derive from its ceramic-based fuel system, graphite moderator and helium coolant. These attributes provide for a high temperature capability that is unique among established reactor concepts. Based on this capability, the present modular VHTR designs eliminate the possibility of fuel damage through inherent and passive means, without reliance on AC powered active systems or prompt operator actions.

The much higher operating temperatures (reactor outlet temperatures 500-700ºC higher than present advanced LWRs) enable higher efficiency electrical production and expand the role of nuclear energy to high-temperature process heat applications, notably hydrogen production. Competitive costs are further derived from a modular design and construction approach that allows a more flexible match with uncertain load growth. Finally, the flexibility offered by the VHTR coated particle fuel system facilitates further reduction of nuclear waste via actinide burning and provides an option to more fully consume surplus weapons grade plutonium or plutonium recycled from reprocessed LWR spent fuel.

For all of the above reasons, Framatome ANP has accelerated its ongoing development of the VHTR as a priority commercial product. The purpose of this paper is to summarize Framatome ANP's development strategy for the VHTR.

1. AREVA COMMITMENT TO HTR

AREVA has engaged into the HTR development with an old and strong background.

On one hand, from its German legacy, Framatome-ANP inherited the developments made at INTERATOM in the 60's and 70's which led in the 80's to the concept of the MODUL, the basis of all modular HTR's today. High temperature materials and components were developed and tested on the KVK loop.

On the other hand, Framatome collaborated with General Atomics on the development of the MHTGR first in the 80's and then later in the 90's on the GT-MHR in the frame of a common development with Russian Institutes and FUJI Electric. The latter development which lasted several years gave an insight of the specific challenges raised by the direct cycle.

Based on these experiences and in order to minimize extensive developments in the power conversion system, Framatome-ANP decided to pursue an indirect combined cycle design using today's gas turbine technology after extensive evaluations proved the superior efficiency of that concept. This choice allows to focus the development to the IHX (intermediate heat exchanger) while at the same time providing a flexible heat source for heat supply or cogeneration without any modification of the nuclear loop. It should also lead to an earlier deployment than technologies requiring extensive developments.

Mid 2003, a dedicated project organization was set up to organize and implement the design. This team spreads over from Germany to the US and France. Its main goal is to design a commercial electric plant at first; when the DOE NGNP program is defined, adaptations may be needed to meet NGNP requirements but it should be emphasized that the indirect cycle is particularly well suited to such adaptation thanks to the relative decoupling of the heat source from the power generation system.

2. STRATEGY FOR VHTR DEVELOPMENT

The essence of the Framatome ANP VHTR strategy is to develop a common, simple, passively safe and highly reliable VHTR nuclear heat source that can be utilized for a family of applications, that will support an expanded role for electricity generation in both developed and developing nations and serve emerging markets for hydrogen production, as well as other process energy applications.

Consistent with this development strategy, Framatome ANP has selected the prismatic block fuel system and indirect cycle architecture as the basis for its nuclear heat source (NHS). The nuclear heat source is coupled to the applications of interest through an intermediate heat exchanger (IHX), thus establishing the basis for a common heat source design and minimizing the development challenges associated with the reactor and primary heat transport system. In the remaining application-specific systems, the approach is to select proven and established component and system designs wherever possible.

- The Framatome ANP commercial product will initially support the expanding worldwide demand for safe, economic and environmentally responsible electricity production. In this product, the nuclear heat source is coupled via the IHX to a secondary loop combined cycle (Brayton plus Rankine) Power Generation System. The secondary Brayton Cycle employs a working fluid that has nitrogen as its principal constituent. This allows the use of conventional air-based gas-turbine technology. The Rankine bottoming cycle is also based on conventional technology.
- As the technologies for hydrogen production are developed and demonstrated through the NGNP initiative, the Framatome ANP VHTR product capabilities will be available to serve this emerging market.

The Framatome ANP strategy is highly synergistic with the emerging NGNP initiative, both in its objectives and approach. Key elements of the NGNP initiative that directly support the Framatome ANP product concepts include advanced fuel and materials development for higher temperature reactor operation, IHX design and testing, full-scale demonstration of the Power Generation System, plus development and demonstration of multiple hydrogen production technologies. On this basis, Framatome ANP intends to play a lead role in the NGNP demonstration project initiative and, in support thereof, will bring to bear its 20-plus years of experience in HTR development as well as its unmatched capabilities as a global supplier of commercial nuclear power products.

The following sections respectively address the key features of the Framatome ANP VHTR design and the basis for their selection, an overview of the Framatome ANP VHTR concept for the NGNP demonstration and a summary of how the Framatome ANP demonstration concept addresses key NGNP functions and requirements.

3. VHTR DESIGN APPROACH

The nuclear heat source selected for the Framatome ANP VHTR product family is an evolution of the GT-MHR (Ref. 2) conceptual design that was developed, with Framatome ANP participation, for the U.S./Russian Plutonium Disposition Program.

The reactor (Fig. 1) applies the block-type (prismatic) core design, in which the coated particle fuel, a common feature of all HTRs, is contained within prismatic graphite blocks that are arranged to form an annular core geometry. The 102 column, 10 block high active core utilizes a once-through low enriched uranium (LEU) fuel cycle and operates in the epithermal neutron spectrum. The core is sized to produce 600MW of thermal power, with a target core outlet temperature of 1000ºC for advanced electricity generation and hydrogen production applications (Fig. 3). Helium is used as the primary heat transport medium.

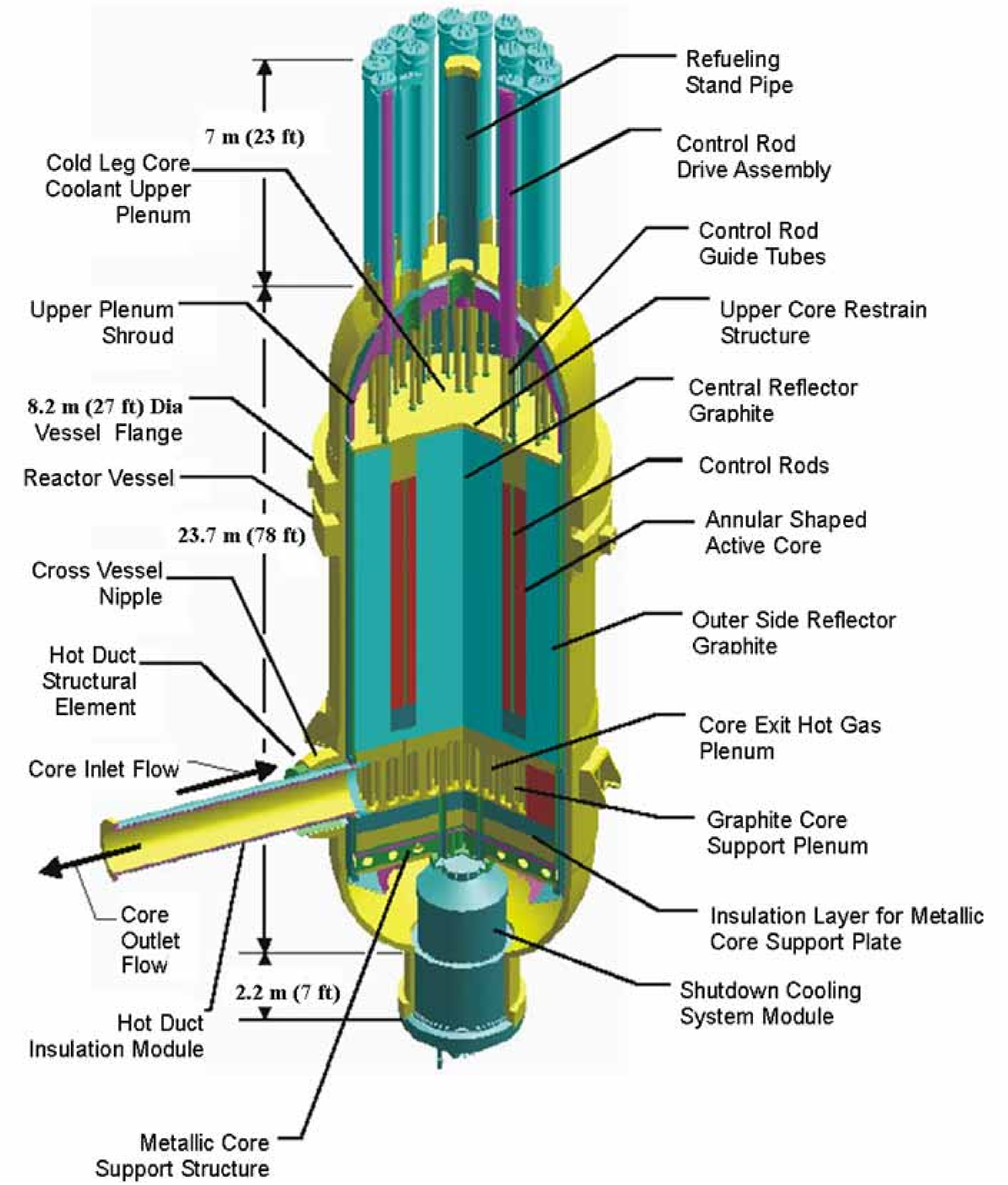

Figure 1: VHTR Nuclear Heat Source based on prior U.S. DOE Prismatic Modular HTGRs

The thermal power produced in the core is transferred to a secondary loop via an IHX, where it is used to drive the application of interest. The IHX (Fig. 2) is comprised of multiple modules of a compact heat exchanger design that is optimized for high effectiveness and minimum approach temperatures, while providing high reliability and maintainability.

The reactor and IHX are contained within separate steel pressure vessels. The reactor and IHX vessels are linked by a cross-vessel which contains an internally insulated hot duct for routing helium from and to the reactor. Normal coolant circulation is provided by a single helium circulator, located at the top of the IHX pressure vessel. Auxiliary cooling is provided by a shutdown cooling system module located at the lower end of the reactor vessel. The reactor vessel and the IHX vessels are housed in separate concrete enclosures that are fully embedded below ground in a silo-type structure. Above ground structures are provided to house the fuel handling system, helium processing, reactor services, reactor control systems and other plant auxiliary systems.

The Framatome ANP VHTR nuclear heat source incorporates several important innovative departures from the predecessor GT-MHR design. The most significant difference is the decision to employ an indirect combined cycle design for electricity generation, rather than the direct cycle used in the GT-MHR design.

The indirect cycle offers several advantages. First and foremost, it allows a common heat source to be used for both electricity generation and hydrogen production and minimizes the complexity and risk associated with the nuclear part of the cycle. With this configuration, initial deployment for electricity generation will provide experience and technology necessary to support very high temperature process heat applications, such as thermo-chemical hydrogen production. The indirect cycle design also eliminates the potential for contamination of the electricity generation and/or hydrogen production equipment by radionuclide carried within the primary helium coolant. In addition, separating the nuclear heat generation systems, structures and components from the industrial application processes simplifies reactor licensing, startup, operating procedures, and maintenance. The second major advantage offered by the indirect cycle design is the freedom to select a secondary coolant other than helium. The Framatome ANP design for electricity generation uses a mixture of nitrogen and helium with properties similar to air as the secondary heat transport fluid. This mixture allows the use of modified gas-turbine technology, including the same design techniques, materials and testing facilities used for conventional air-breathing gas-turbines, to be used for the VHTR electricity production application. As a result, both equipment development risk and cost are substantially reduced. Helium is the reference secondary fluid for coupling the hydrogen production application; however, with the indirect cycle design, other heat transport media can be considered.

This indirect cycle design also facilitates using a Rankine bottoming cycle to improve cycle efficiency. It is relatively straightforward to make the VHTR a combined cycle generating plant by adding a steam generator and steam turbine system to the secondary loop gas-turbine system. This is provided for in conventional natural gas-fired Combined Cycle Gas-Turbines (CCGT) where this technology is well established. This provides the potential to push the plant efficiency above what is normally expected from high temperature gas-cooled reactors and to reduce the cost of electrical power generated.

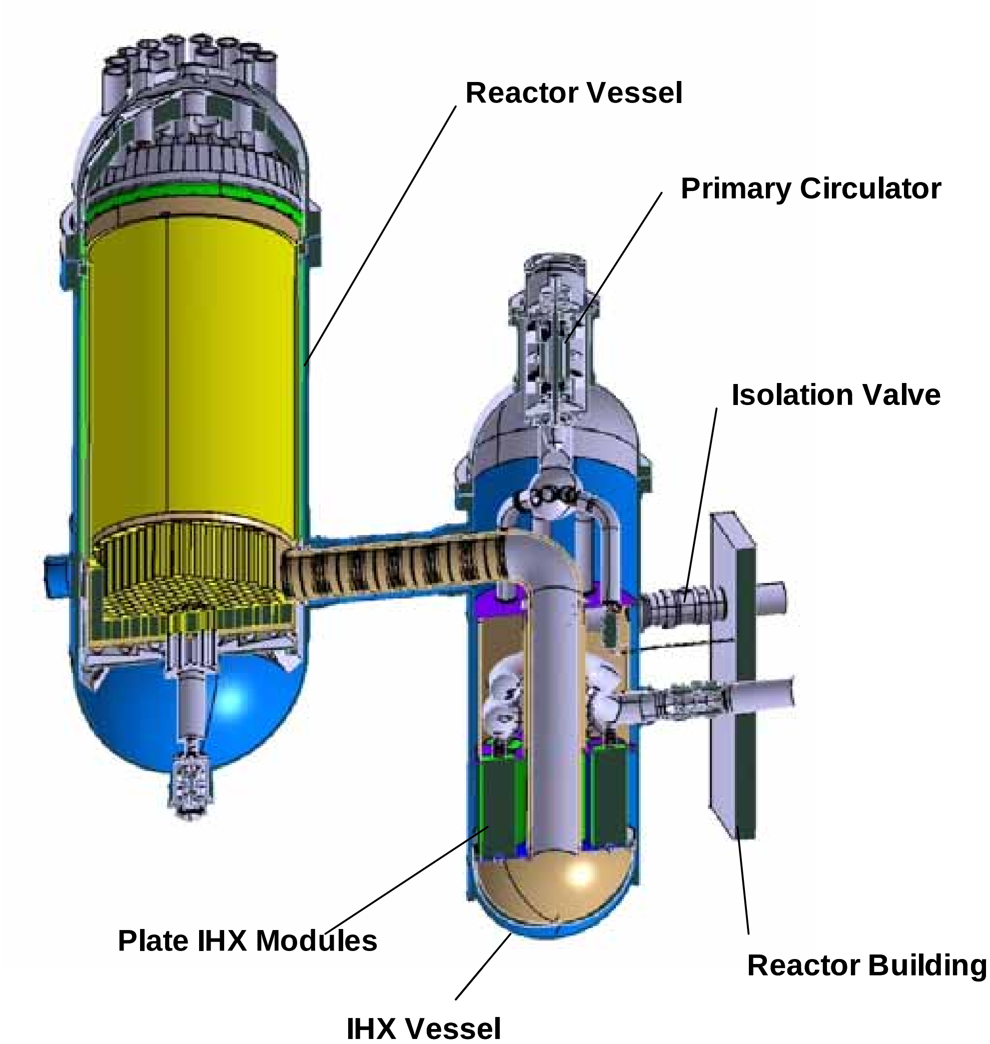

Figure 2: Vessel System Arrangement

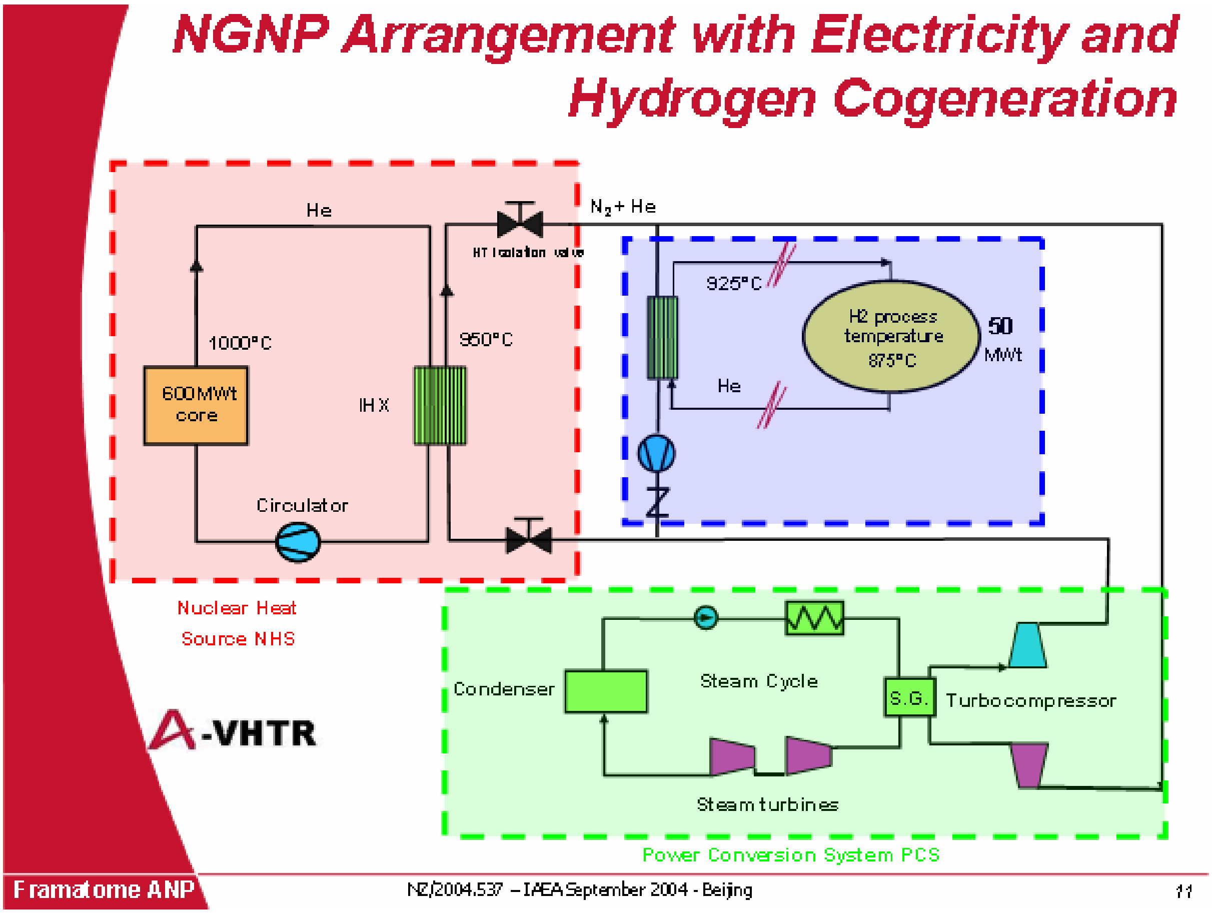
NGNP Arrangement with Electricity and Hydrogen Cogeneration
He
N_2 + He
HT Isolation valve
1000°C
950°C
600 MWt core
IHX
Circulator
925°C
H2 process temperature 875°C
50 MWt
He
Nuclear Heat Source NHS
A-VHTR
Condenser
Steam Cycle
S.G.
Turbocompressor
Steam turbines
Power Conversion System PCS
Framatome ANP
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Fig 3

Table 1: Summary of Framatome Demonstration Plant Design Parameters

Feature / Parameter	Selection
Plant Configuration	Dual purpose demonstration with H2 production and power generation in parallel • Hydrogen Production Unit of 50MWt capacity • Power Generation System of 600MWt capacity
Nuclear Heat Source (NHS) Module Configuration	Indirect cycle Helium-cooled reactor Prismatic core Single primary loop
Reactor Power	600MWt
Reactor Outlet Temperature	1000ºC
Reactor Inlet Temperature	400ºC
Primary Coolant Flow Rate	192kg/s
Primary Coolant Pressure	5MPa
Reactor Vessel Material	9Cr – 1Mo or SA 508
Core Configuration	102 columns, 10 blocks high.
Fuel Particle Type	SiC coating UCO or UO2 kernel
Operating Max Fuel Temp. Guideline	1300ºC
Accident Peak Fuel Temp. Guideline	1600ºC
IHX Design	Compact Heat Exchanger Modules
IHX Nominal Heat Load	608MWt
IHX Effectiveness	92%
IHX Primary Tin	1000ºC
IHX Primary Tout	392ºC
Secondary Fluid	Nitrogen/Helium Mixture
IHX Secondary Tout	950ºC
IHX Secondary Tin	342ºC
Secondary Flow Rate	512kg/s
Secondary Coolant Pressure	5MPa
Heat Transport Fluid Coupling HPU	Helium
Process Heat Supply Temp. to HPU	925ºC
Hydrogen Production Unit	Sulfur – Iodine or High Temperature Steam Electrolysis processes
Power Generation System	Combined Cycle Gas Turbine (Brayton cycle with Rankine bottoming cycle)

The final key difference is the selection of a reduced reactor inlet temperature, relative to the GT-MHR. This selection leads to several advantages. The temperatures seen by the reactor vessel are lower. With reduced inlet temperature, the flow rate and circulator power are lower and a reduction in the primary pressure becomes practical as a tradeoff. The lower system pressure and temperature translate to a reduced vessel wall thickness, which has significant fabrication and cost advantages. In addition, the thermal energy stored in the core is reduced, thus enhancing passive decay heat removal during certain transients. Finally, heat radiation losses during normal operation are substantially decreased.

4. NGNP DEMONSTRATION PLANT CONCEPT

The Framatome ANP concept for the NGNP Demonstration Plant combines the VHTR nuclear heat source, described in Section 3, with a dual-purpose energy utilization architecture that will demonstrate both the advanced electricity generation and hydrogen production applications. The design of the Framatome ANP NGNP Demonstration Plant is based on the following objectives:

- Develop and demonstrate an advanced VHTR nuclear heat source that supports the requirements for electricity production, hydrogen production and other advanced process energy applications, while minimizing development requirements and risk.

- Provide a flexible platform for the demonstration of various high efficiency hydrogen production technologies, including, as a minimum, high temperature thermo-chemical and steam electrolysis processes.
- Demonstrate the successful design, construction, licensing, testing and operation of the Demonstration Plant as the prerequisite for a new generation of inherently safe, commercial nuclear plants for electricity generation and/or hydrogen production.

The reference basis for the Framatome ANP NGNP Demonstration Plant design is summarized in this section. The performance objectives of the Framatome ANP Demonstration Plant are summarized in Section 5 and compared therein with key INEEL NGNP functions and requirements.

The parameters identified in Table 1 represent Framatome ANP's starting point for the NGNP Demonstration Plant preconceptual design. These parameters will be confirmed or optimized in the course of the preconceptual and conceptual design phases.

4.1 Plant/Nuclear Heat Source Configuration

The Framatome ANP NGNP Demonstration Plant is configured to demonstrate both hydrogen production and electricity generation, as shown in Figure 3. Heat from the reactor is transferred to a secondary loop in which the heat transport medium is a mixture of nitrogen and helium. The nitrogen comprises the majority component in the secondary medium, with the helium added to optimize the heat transport characteristics of the fluid. The power generation system (PGS) is the combined cycle system, described in Section 3, which incorporates a Brayton topping cycle and Rankine bottoming cycle. It is based on existing combined cycle gas turbine technology.

The electricity generation section of the cycle will be capable of utilizing the full output of the reactor, namely 600MWt. The hydrogen production section of the cycle will be capable of providing 50MWt at a minimum temperature of 925ºC at the process coupling heat exchanger in the tertiary loop. The tertiary loop is optimized for heat transport and utilizes helium as the reference heat transport medium.

Placing the hydrogen coupling heat exchanger in a tertiary loop provides maximum flexibility for the demonstration of alternate processes and minimizes the cost of the piping between the nuclear heat source and the hydrogen production facility.

4.2 Reactor Power

The reference NHS power is 600MWt. A NHS power level trade study is planned during preconceptual design in which a range will be examined. A lower power level may be optimum for achieving the very high temperature applications and as a prudent margin for the demonstration plant.

4.3 Reactor Operation Parameters

The reactor core outlet and inlet helium temperatures, helium coolant flow rate, and helium coolant pressure selected are shown in Table 1. During preconceptual design, trade studies are planned that will include consideration of a range of outlet and inlet temperatures, from 850 to 1000ºC and from 350 to 500ºC, respectively. The helium flow rate and pressure will also be varied as part of these and other trade studies.

4.4 Reactor Vessel Material

Consistent with the above reactor power and operation parameters, the material selected for the NGNP reactor vessel is 9Cr-1Mo, SA336. A reactor vessel material trade study will consider the SA508/533 low alloy steel utilized for LWRs. A lower primary coolant pressure reduces the vessel wall thickness and minimizes fabrication difficulties of 9Cr-1Mo.

4.5 Fuel Element and Coated Particle Design and Performance

The prismatic fuel element design used in the Fort St. Vrain nuclear power plant is the reference basis for the NGNP. The core arrangement is the 10 block 102 column annular arrangement of the GT-MHR. Possible optimization of the fuel-element, including other fuel-coolant-graphite prismatic configurations, sizing, and arrangements is planned for preconceptual design.

The fuel particle kernel for the NGNP may be either low enriched uranium oxycarbide (UCO) or uranium dioxide (UO2). The TRISO reference coating materials of inner and outer pyrocarbon and silicon carbide (SiC) are selected. Fuel trade studies are planned to select a reference kernel and to examine zirconium carbide (ZrC) coatings and associated diameters, burnup and other performance parameters.

The normal operation and accident peak fuel temperature guidelines for the NGNP are 1300ºC and 1600ºC, respectively. The 1300ºC guideline is an open option that will be reviewed in the preconceptual design phase.

4.6 Intermediate Heat Exchangers

The IHX design selected for the NGNP is a compact design, of either the plate fin or printed circuit type. Trade studies to further evaluate the IHX type and IHX materials are planned during preconceptual design for the range of reactor outlet temperatures up to the NGNP 1000ºC specification. Those open options will have corresponding impacts on the performance parameters provided in Table1.

Compact heat exchangers of the types being considered for the IHX are typically designed with an effectiveness ranging from 90% for typical installations to 95% for more aggressive designs. The NGNP IHX is sized for an effectiveness of 92% to achieve a 50ºC approach temperature.

4.7 Hydrogen Production Unit

Hydrogen production with the high temperature heat source of the HTR is a primary motivation of the VHTR. Based on the INEEL requirements, two hydrogen production concepts have been selected for initial consideration: the Sulfur-Iodine (S-I) thermochemical developmental process and the high temperature steam electrolysis (SE) experimental process. The most challenging of these appears to be the S-I process, but the capability for both is required for the NGNP. Additionally, as the hydrogen process development proceeds, the indirect cycle VHTR has the flexibility to accommodate variations of these and other candidate processes.

The plant configuration shown in Figure 3 has two IHXs and the process heat exchanger, resulting in a nominal temperature for the process of 875ºC. The NGNP requirement is for the hydrogen production unit (HPU) to be sized for 50MWt. For the IHX serving the HPU, a higher effectiveness (95%) is selected resulting in a 25ºC approach temperature. The smaller size of this IHX makes this particularly attractive in order to maximize the HPU process temperature.

4.8 Power Generation System

The PGS selected for the NGNP is a closed combined cycle to utilize existing CCGT technology. It utilizes a Brayton topping cycle, which meets an NGNP requirement, with a Rankine bottoming cycle. The PGS is sized at the full NHS power level of 600MWt, another NGNP requirement, which allows intermittent operation of the HPU and full demonstration of the commercially sized PGS.

5. NGNP PERFORMANCE OBJECTIVES

The design and performance objectives of the Framatome ANP NGNP Demonstration Plant concept are fully responsive to the functions and requirements that have been identified by INEEL as the basis for the NGNP project (Ref. 1). These same design and performance objectives are fully supportive of Framatome ANP’s needs for the commercial deployment of the VHTR.

The following summarizes the key performance objectives of the NGNP and describes how the Framatome ANP approach will meet those objectives.

5.1 Develop and Demonstrate a Commercial-Scale Prototype VHTR

The Framatome ANP NGNP Demonstration Plant design is based on a commercial scale nuclear heat source that will be a common element in Framatome ANP commercial products for both electricity generation and hydrogen production. This is a key advantage of the indirect cycle architecture selected for electricity generation and will support the initial commercialization of VHTR technology via the existing and expanding markets for electricity generation.

The Framatome ANP Demonstration Plant design is based on the HTR prismatic fuel system that was initially developed and demonstrated in Fort St. Vrain and further advanced through R&D supporting various concepts, including the GT-MHR. As required by INEEL, Framatome ANP's nuclear heat source design targets the average core outlet temperature at 1000ºC and brings to bear the experience base of both the GT-MHR and German fuel development work in support of that objective. Additional research and development work will be required in both fuel and materials (e.g., for the IHX) and the final core outlet temperature selected for Framatome ANP's commercial applications will be dependent on the results of that R&D.

Consistent with the INEEL requirements, the Framatome ANP Demonstration Plant design is based on a once-through low-enriched uranium core capable of high burnup. The plant will be designed for a 60 year life span and provisions will be made to replace components with shorter lifetimes. The number of primary system components to be maintained is minimized by the selection of the indirect cycle architecture and the remaining systems and components in the power generation and hydrogen processing sections will be readily available for inspection and repair/replacement. The indirect cycle design also minimizes the transient coupling of the nuclear heat source and the heat utilization systems.

The Framatome ANP Demonstration Plant and commercial designs fully apply the passive safety concepts developed for modular HTR reactors, to assure the attainment of a superior level of safety, while avoiding the need for off-site evacuation and sheltering of the public.

5.2 Develop and Demonstrate High Efficiency Power Conversion

The Framatome ANP NGNP design incorporates an indirect combined cycle power generation system that is capable of using the full thermal capacity of the reactor, 600MWt at an efficiency level that significantly exceeds the NGNP requirement (45%). The Framatome ANP design features a closed Brayton cycle that optimally utilizes the high temperature heat produced in the reactor. A Rankine bottoming cycle is included for maximum efficiency. The selection of a nitrogen-based secondary working fluid for the Brayton Cycle takes full advantage of air-based gas turbine technology that has evolved to its present advanced state as a result of decades of development. Thus, the combined cycle architecture proposed by Framatome ANP meets the efficiency objectives of the NGNP, while minimizing the cost and risk associated with both development and operation.

5.3 Obtain Licenses and Permits to Construct/ Operate the NGNP

Framatome ANP fully supports the risk-informed licensing approach that is specified in the NGNP functions and requirements document. Framatome ANP intends to license the NGNP Demonstration Plant in accordance with 10CFR50. Based on safety demonstrations of the nuclear heat source, which is common to the Framatome ANP commercial plant designs, Framatome ANP intends to certify the commercial plant designs for both electricity generation and hydrogen production/process heat under 10CFR52.

5.4 Develop and Demonstrate Hydrogen Production

The heat transport architecture of the Framatome ANP NGNP Demonstration Plant (Fig. 3) provides an optimum platform for the demonstration of high-temperature hydrogen production processes, while allowing full utilization of the reactor output for electricity generation, when the hydrogen production section is not in service. The 50MWt tertiary helium loop that supports the hydrogen process energy requirements eliminates any chance of radiological contamination, including tritium, and allows modification of the hydrogen production section, independent of operations in the electricity generation portion of the plant. The 925ºC temperature provided at the process coupling heat exchanger fully supports the NGNP efficiency requirements, based on data pertaining to the sulfur-iodine thermochemical water-splitting cycle. The tertiary loop and associated circulator further provide for independent control of heat transport to the hydrogen production process and minimizes the potential for adverse interactions with the remainder of the plant.

5.5 Include Provisions for Future Testing

As already suggested in the above section on hydrogen production, the indirect cycle architecture of the Framatome ANP NGNP Demonstration Plant, in conjunction with the energy transport architecture shown in Figure 3, provides a flexible basis for future testing, including those for demonstrating investment protection and safety margins. Note, in particular, that the primary circulator provides positive control of primary system heat transport characteristics that is functionally independent of the electricity generation section. It is worthwhile to re-emphasize that the simple and reliable design of the reactor and primary heat transport loop minimize the likelihood of unforeseen consequences that might result from unusual operating conditions associated with testing.

Needless to say, the passive safety characteristics of the NGNP Demonstration Plant, common to all modular HTRs, reduce the demands on operational staff and eliminate the potential for damage to the nuclear portion of the plant as a result of operator error.

5.6 Enable Demonstration of Energy Products and Processes

The features described above also make the Framatome ANP design an ideal platform for demonstrating other processes via the 50MWt tertiary heat transport loop, for example, future testing of direct cycle helium power conversion equipment.

6. SECONDARY-SIDE SIMULATION RESULTS

To assess the energy production capabilities of the Framatome Indirect-cycle VHTR a number of studies were performed with EDF. The hydrogen production options studied included High Temperature Electrolysis (HTE) and the Sulfur-Iodine thermochemical process (S-I). Both the indirect cycle and direct cycle electricity production were also analyzed.

6.1 Electricity Production

The modular simulation software THERMOFLEX was used to model the power generation systems comparing different direct or indirect cycles. Two indirect-cycle configurations were simulated:

- Brayton cycle with two intercoolers (2 Inter.),
- Combined cycle with two pressure level and reheats (2PRS).

The direct cycle is a helium Brayton-cycle similar to the GT-MHR (Ref. 2).

One noticeable conclusion is that indirect combined cycle 2PRS achieves higher net efficiency than Brayton direct cycle. Despite higher turbine inlet temperature (+50 °C due to the pinch temperature in the IHX), the primary disadvantage for direct Brayton cycles is that Brayton cycles have lower efficiency than combined cycles due to the absence of the condensation phase change effect for low temperature.

6.2 H2 Process Integration

Thermal power for supplying the H_2 process varies from 5 MWt to 50 MWt and depends on the choice of the process (HTE or S-I). Two configurations were studied: parallel or serial.

In the parallel configuration, heat extraction does not affect electricity efficiency, since the gas turbine inlet temperature is constant. Moreover, overall process control is easier, because circuits are separated.

The serial configuration has a disadvantage in term of electricity efficiency, since the gas turbine inlet temperature is lower and depends on heat power extraction. Calculations show that the electric efficiency does not decrease dramatically for serial configuration with low heat power extracted. Therefore, this configuration would be preferable for electrolysis because low heat power is required for this process. For the S-I process, since more heat power is required, parallel configuration would be preferable.

7. CONCLUSIONS

In summary, Framatome ANP is accelerating its development of advanced VHTR products for electricity generation and hydrogen production/process energy, based on evolving worldwide demands related to energy security and environmental responsibility. Framatome ANP has been actively involved in HTR development for over twenty years and intends to take a leadership position in advanced electricity generation and hydrogen production via a lead role in the NGNP project. To this end, Framatome ANP has adopted a strategy that is based on multiple energy utilization applications, employing a common, simple and reliable nuclear heat source. The Framatome ANP nuclear heat source applies the prismatic HTR reactor system and an indirect cycle architecture. In addition to allowing a common heat source to be used for multiple applications, the Framatome ANP concept minimizes the cost and development risk associated with the nuclear part of the plant, minimizes the impact of radiological contamination on operations and maintenance, and effectively decouples the heat source from events that occur in the heat utilization system. As a result, the Framatome ANP Demonstration Plant design provides a highly flexible platform for advancing VHTR technology. The NGNP functions and requirements are synergistic with Framatome ANP's commercial development requirements. Framatome ANP's world-class infrastructure and experience base will enhance the prospects for the successful completion of the NGNP project.

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