Proceedings of ICAPP '12
Chicago, USA, June 24-28, 2012
Paper 12342

CURRENT STATUS OF THE ADVANCED HIGH TEMPERATURE REACTOR

D. E. Holcomb, D. Ilas, A. L. Qualls, F. J. Peretz, V. K. Varma, E. C. Bradley, and A. T. Cisneros
Oak Ridge National Laboratory
P. O. Box 2008, MS-6010
Oak Ridge, TN 37831
Telephone: 865-576-7889, Fax: 865-241-4074, Email: holcombde@ornl.gov

Abstract *– The Advanced High Temperature Reactor (AHTR) is a design concept for a central station type [1500 MW(e)] Fluoride salt-cooled High-temperature Reactor (FHR) that is currently under development by Oak Ridge National Laboratory for the U. S. Department of Energy, Office of Nuclear Energy's Advanced Reactor Concepts program. FHRs, by definition, feature low-pressure liquid fluoride salt cooling, coated-particle fuel, a high-temperature power cycle, and fully passive decay heat rejection. The overall goal of the AHTR development program is to demonstrate the technical feasibility of FHRs as low-cost, large-size power producers while maintaining full passive safety. The AHTR design option exploration is a multidisciplinary design effort that combines core neutronic and fuel configuration evaluation with structural, thermal, and hydraulic analysis to produce a reactor and vessel concept and place it within a power generation station. The AHTR design remains at the notional level of maturity, as key technologies require further development and a logically complete integrated design has not been finalized. The present design space exploration, however, indicates that reasonable options exist for the AHTR core, primary heat transport path, and fuel cycle provided that materials and systems technologies develop as anticipated.*

I. INTRODUCTION

While FHRs represent a distinct reactor class, they inherit desirable attributes from other thermally based power plants whose characteristics can be studied to provide general guidance on plant configuration, anticipated performance, and costs. Molten salt reactors provide experience on the materials, procedures, and components necessary to use liquid fluoride salts. Liquid metal reactors provide design experience on using low-pressure liquid coolants, passive decay heat removal, and hot refueling. High temperature gas-cooled reactors provide experience with coated particle fuel and graphite components. Light-water reactors (LWRs) show the potentials of transparent, high-heat capacity coolants with low chemical reactivity. Modern coal-fired power plants provide design experience with advanced supercritical-water power cycles.

This paper provides an update and summary to the two AHTR design reports that were published in 2011.[1,2] The AHTR's large thermal output enables direct comparison of its performance and requirements with other large output reactor concepts. A top-down comparative economic analysis was performed and documented as part of the 2011 AHTR design process that shows that the AHTR has the potential to be a low-cost power producer.

The current AHTR design activities build upon a series of small-scale efforts over the past decade to evaluate and describe the features and technology variants of FHRs. Key prior concept evaluation reports include the SmAHTR preconceptual design report,[3] the PB-AHTR preconceptual design,[4] and the series of early phase AHTR evaluations performed from 2004 to 2006.[5-7]

II. PLANT CONFIGURATION

The AHTR plant layout resembles that for any large-output thermal power plant. Figure 1 shows a conceptual view of the AHTR plant configuration, and the high-level design characteristics are provided in Table I. The AHTR has a two-layer reactor building. The principal function of the outer shell of the reactor building is to shield the interior structures from external impacts. A low-pressure containment structure is located within the impact shield. The principal function of the containment structure is to confine any tritium, beryllium fluoride, and activation products that escape from the reactor vessel. Unlike LWRs, the containment structure is not required to withstand high internal pressure, as the building interior does not include any mechanisms for generating high pressures or energetic chemical reactions.

The AHTR employs an intermediate loop to transfer heat from the reactor building to the power conversion

building. The intermediate loop reduces the required volume of the expensive primary coolant salt and provides physical separation between the energetic power cycle processes and the reactor systems. The AHTR design employs an advanced supercritical-water power cycle and a cooling tower based ultimate heat sink. Supercritical water power-cycles are both highly efficient and the most technologically mature large-scale electricity generation cycle at FHR output temperatures due to their widespread deployment at fossil power plants.

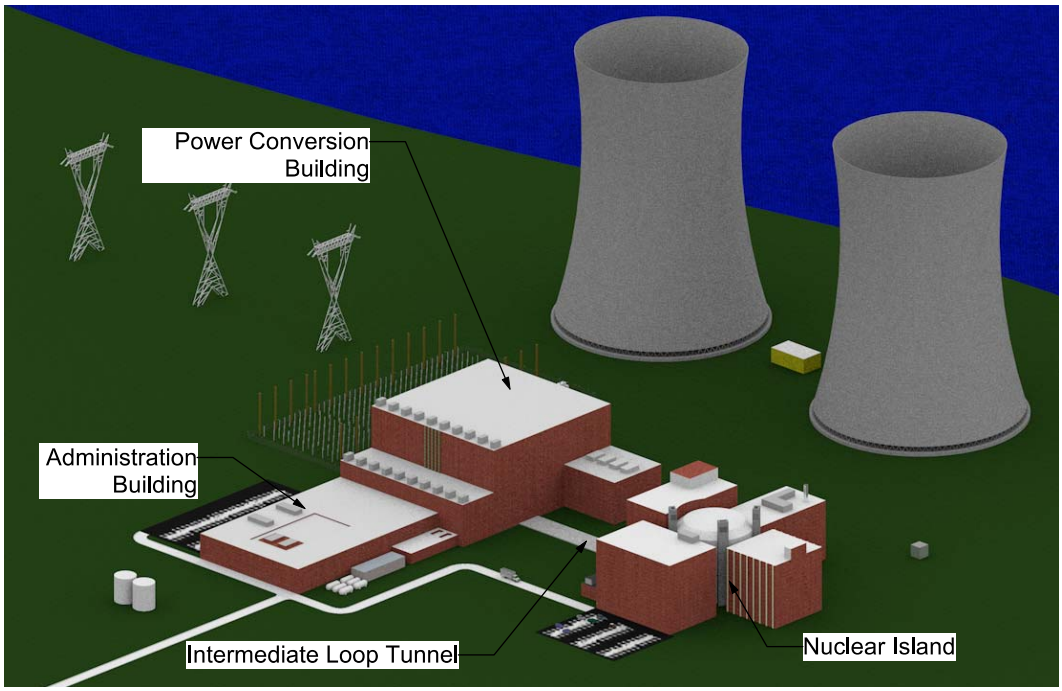

Fig. 1. AHTR site overview.

III. PRIMARY COOLANT SYSTEM

The AHTR primary system is a blend of a pool and a loop design. Heat is generated by the reactor core, which is located within a pool of primary coolant. The primary coolant selected is $2^7LiF\text{-}BeF_2$ (referred to as FLiBe), which was selected both to avoid a positive density decrease reactivity feedback as well as to minimize coolant activation. In order to avoid a positive coolant density decrease reactivity feedback, the FLiBe's lithium needs to be nearly entirely ^7Li (99.995%). An overview of the AHTR heat transport path is shown as Fig. 2.

During normal operation, primary heat removal is through three pumped loops. Decay heat removal is provided by modular decay heat removal loops known as direct reactor auxiliary cooling systems (DRACS). Three 0.25% of full power sized [8.5 MW(t) at 700°C under fully established natural circulation] DRACS systems are provided. The DRACS heat exchangers are located within the reactor vessel. The reactor vessel has no penetrations below the primary coolant piping inlet and outlet. The primary coolant inlet and outlet piping are near the top of the vessel, and a siphon break is provided on the return leg so that the vessel cannot be drained through the external piping. The DRACS heat exchangers are located slightly below the level of the primary coolant inlet and outlet. Passive decay heat removal through the DRACS would still occur with primary coolant loop piping completely broken away from the reactor vessel, avoiding the external piping having a safety role in providing decay heat removal. The entire vessel and heat transfer loop system has electrical external heating to allow for initial salt filling.

Primary coolant flow is upwards through the core into a large upper plenum. The primary-to-intermediate heat exchanger is located proximate to the reactor vessel to minimize the required volume of the expensive primary coolant salt. An integral primary coolant system design was avoided to improve the system maintainability and to reduce the complexity of the reactor vessel internals. The primary coolant pumps are located on the cold legs. The return flow is channeled downward around the reactor vessel periphery through downcomer channels maintaining the reactor vessel at the cold leg 650°C temperature. The three return flows mix in a lower vessel plenum before again flowing up through the core.

A key advantage of plate fuel assemblies over pebble bed cores is minimization of the pressure drop across the core, which increases the natural circulation flow through the core during loss-of-forced-flow accidents. The

increased fluid flow through the core directly lowers the peak accident fuel temperature as well as decreasing the normal fuel operating temperature for a given pumping power.

Table I

AHTR Overall Design Characteristics

Parameter	Unit	Value
Reactor thermal power	MW	3400
Electrical power	MW	1531.4
Net thermal efficiency	%	45.0
Primary coolant		$2^7LiF\text{-}BeF_2$
Lithium-7 enrichment level	%	99.995
Intermediate coolant	mole %	$KF\text{-}ZrF_4$ (42-58) mole %
Power cycle fluid		Water
Fuel type		UCO coated particle
Uranium-235 enrichment level	%	9
Core power density	MW/m^3	12.9
Reflector material		Graphite
Reactor vessel internals material		SiC-SiC composite
Core structural material		C-C composite
Control blade material		Mo-Hf-C alloy
Primary coolant flow rate	kg/s	28,500
Number of primary loops		3
Number of intermediate loops		3
Number of power cycle loops		2
Refueling interval	Months	6
Refueling outage duration	Days	2
Fuel format		Plates in hexagonal grid
Mixed mean core outlet temperature	°C	700
Core inlet temperature	°C	650
Number of plates per assembly		18
Number of fuel assemblies		252
Maximum fuel temperature (average assembly)	°C	854
Average coolant velocity along fuel	m/s	1.93
Vessel material		Alloy 800H
Liner material		Alloy N
Core fueled height	m	5.5
Core pressure drop for normal operation	atm	~1

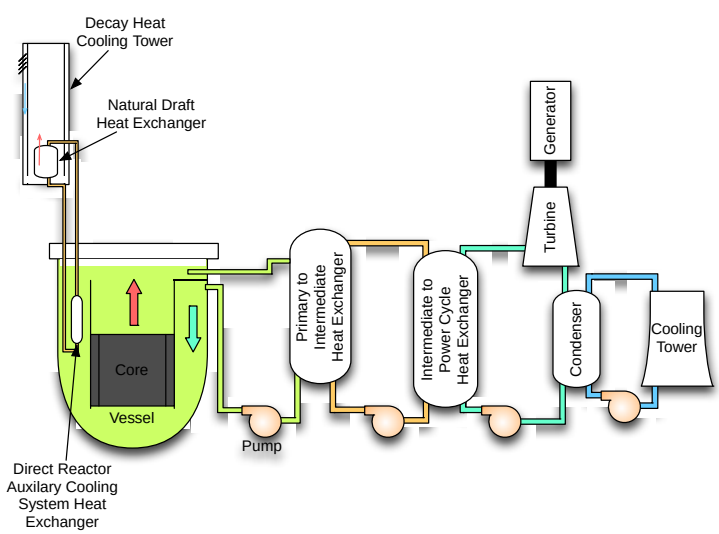

Fig. 2. AHTR heat transport path overview

The reactor vessel, primary piping, and primary-to-intermediate heat exchanger are all fabricated from Alloy 800H with a thick Alloy N liner. The reactor vessel is generally cylindrical with a short refueling lobe extension on its upper half. Figure 3 shows a vertical section of the reactor vessel and primary loop components and the refueling system. The reactor vessel support structure and reactor building are shown in Fig. 4.

The primary system ends and the intermediate loops begin at the primary to intermediate heat exchangers (P-IHXs) within the reactor building. The intermediate salt passes through the containment boundary and transports the heat from the primary system to the power conversion system. The intermediate transport piping runs in an accessible covered tunnel between the buildings that house these systems. Additional intermediate loop piping, pumps, and the components to transfer the heat from the intermediate heat transfer system to the power conversion system are housed in the nonpressurized power conversion building.

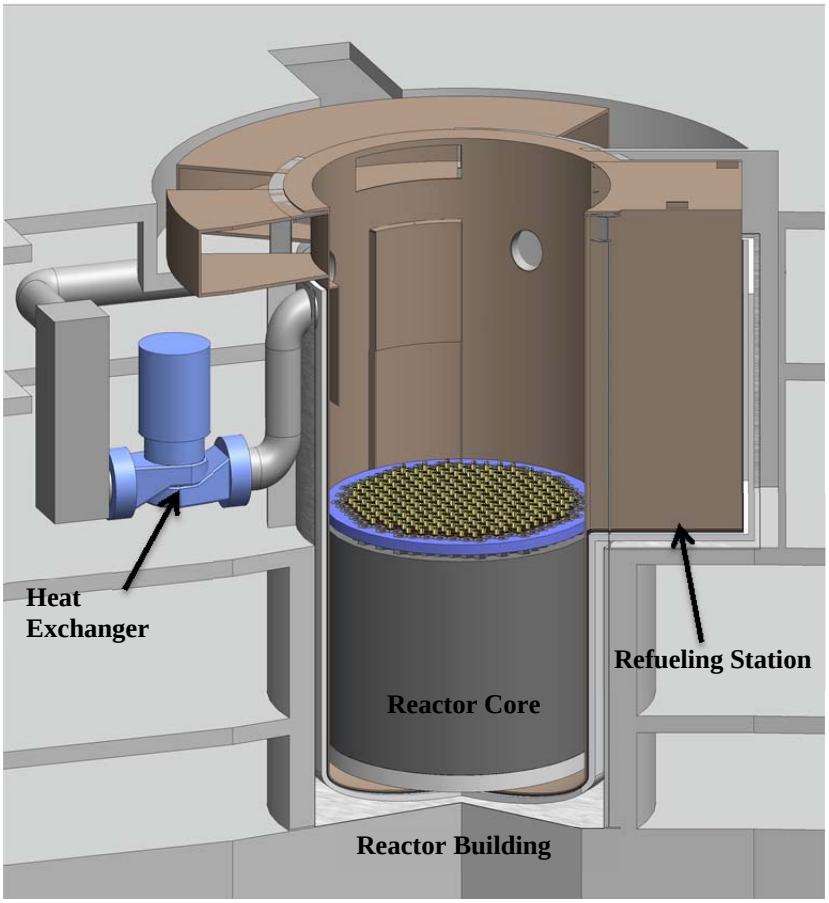

Fig. 3. Vertical section of the reactor vessel and primary loop components and the refueling system.

The low-melt point eutectic of KF-ZrF_4 has been selected as the intermediate salt. This salt was chosen in part because it does not contain lithium or beryllium. It is relatively nontoxic, and any leaks into the primary coolant will not dilute the enrichment of the lithium, which would make such leaks prohibitively expensive to rectify. The salt has a melting temperature near 400°C, and the intermediate system, like the primary system, must be heated. A heated salt storage vessel is also required during loading and draining of salt. Pressure diaphragms are required on the intermediate loop to prevent any power cycle triggered pressure transients from propagating to the primary coolant loop.

The intermediate system makes a transition from three primary loops to two power conversion trains. This is accomplished by blending the high temperature intermediate salt into a common header from which two supercritical water generator and reheat (SCWG) units are fed.

A SCWG and reheater is a single tube-and-shell heat exchanger with intermediate salt on the shell side and two independent sets of parallel tubes containing the high-pressure water. One set of tubes produces supercritical

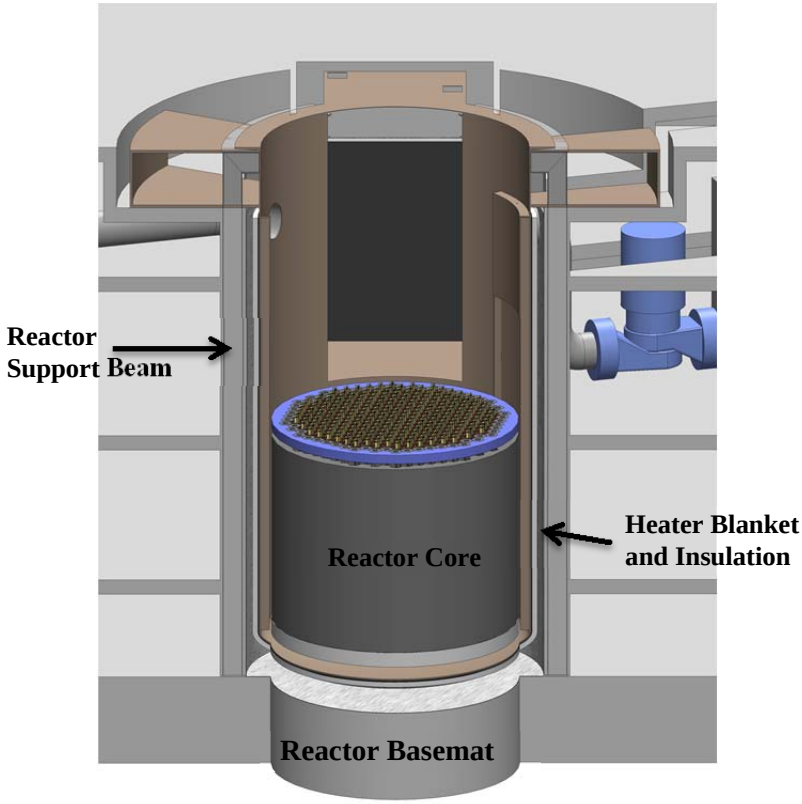

Fig. 4. Reactor vessel support structure and reactor building.

fluid at the highest system pressure and temperature, and the second set produces steam at lower pressure. The supercritical fluid passes through the high-pressure turbine (HPT) and is returned to the reheater tubes. Beyond the HPT the steam system looks much like that of a Rankine power system.

For the AHTR concept, a dual power train design has been selected as the baseline design option. The sizing of the salt-to-water SCWG becomes large for a single unit design, and the cost and risk of fabricating this equipment decrease if two are used. Also, by utilizing a dual power train, the size of the other power conversion system components falls comfortably within the range of equipment [700 to 900 MW(e)] known to result in long lifetimes and highly reliable power conversion systems. Finally, unlike a fossil-fired boiler, a reactor system has decay heat that continues after shutdown. Employing two power conversion systems decreases the probability of losing 100% of the system primary heat sink at once thereby reducing the probability of a loss of ultimate heat sink accident.

IV. CORE AND NEUTRONIC DESIGN

The AHTR core consists of 252 fuel assemblies arranged in a hexagonal lattice with roughly cylindrical shape supported by upper and lower support plates. A row of hexagonal replaceable reflector graphite columns, a permanent graphite reflector, and a C-C composite core barrel radially surround the reactor core. The downcomer region and the reactor vessel are located radially outside of the core barrel. Figure 5 shows a midplane horizontal cross section detailing the main elements of the core and reactor vessel including the downcomer segmentation. The downcomer is divided vertically into seven angular zones—three downcomer regions, three DRACS, and one refueling lobe.

The AHTR fuel cycle is based on a two-batch refueling with a 6-month refueling interval employing 9% enriched uranium oxy-carbide coated particle fuel. The current estimate is that exchange of half of the fuel could be performed in 2 days although a significant amount of additional development remains to provide a confident refueling outage length estimate.

The fuel assemblies are 6-m tall hexagonal prismatic boxes with 1-cm-thick walls made of C-C composite. A cross-sectional view of a single fuel assembly is shown in Fig. 6. The interior of the hexagonal channel box is divided into three symmetric regions by a Y-shaped structure made of C-C composite. Each of the three regions includes six equidistant fuel plates that are supported at one end by the Y-shaped structure and at the other end by the channel box.

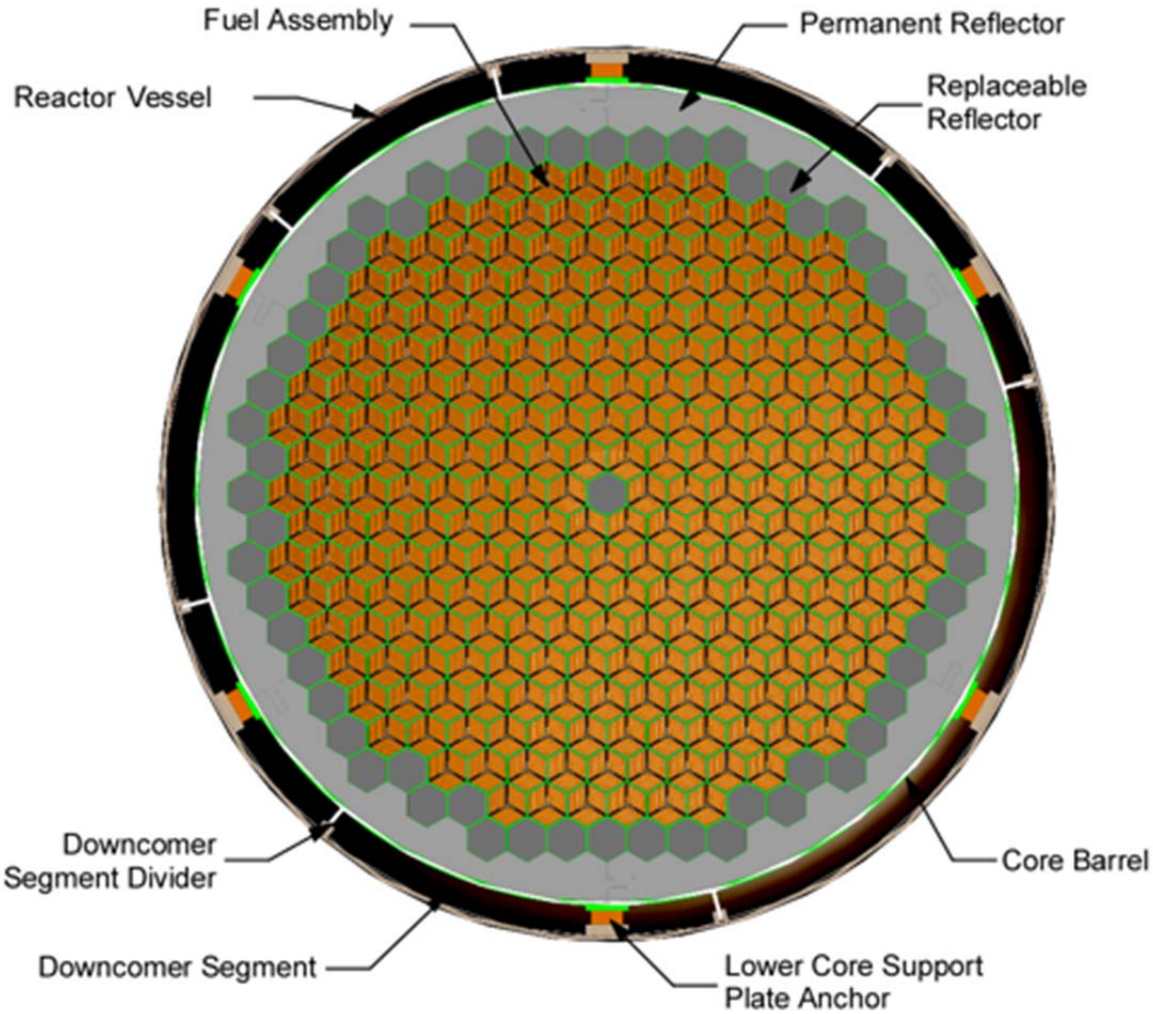

Fig. 5. Midplane horizontal cross section detailing the main elements of the core and reactor vessel including the downcomer segmentation.

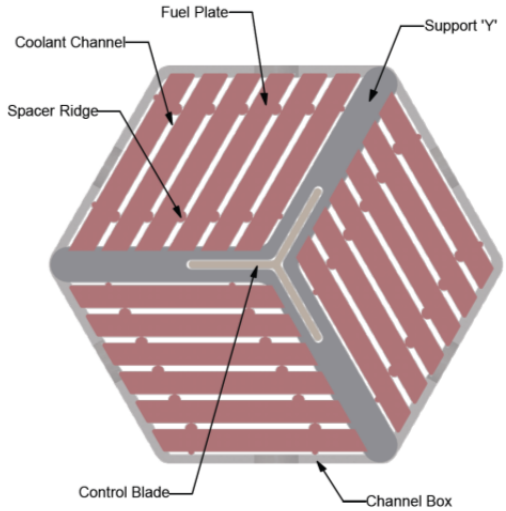

Fig. 6. Cross-sectional view of a single fuel assembly.

The channel boxes of two adjacent assemblies are separated by 1.7 cm of interassembly coolant. At the center of the Y-shape is the control blade slot, also Y-shaped.

The AHTR employs one control blade per fuel assembly with each control blade having relatively low reactivity worth. The control blade remains with the fuel assembly throughout the fuel loading and unloading procedure to preclude criticality accidents during fuel handling. The current AHTR design employs a molybdenum hafnium carbide alloy as its neutron absorber and structural material. To compensate for the large excess of reactivity of the initial core, burnable poison particles are incorporated into the central matrix material of each fuel plate. Europium was selected as the burnable poison material as it burns out at nearly the same rate as the fuel, minimizing the requirement for additional control blades. Particle-based neutron poison was selected so that the poison would be retained in the fuel during fabrication, and

because poisoning the primary coolant would result in a positive void coefficient of reactivity.

Within each plate fuel element, the fuel particles are distributed in two surface stripes separated by central carbonaceous material. A thin (~1-mm thick) sleeve of carbonaceous material separates each fuel stripe from the FLiBe coolant, preventing individual fuel particles from eroding away. The prototype for the reference coated particle fuel grain is the AGR-2 fuel described in a recent paper by Phillips et al.[8] The AHTR design employs a 40% volumetric packing fraction within for the fueled region (stripes) of the fuel plates.

V. REFUELING MECHANICS

The low-pressure, optically transparent primary coolant and robust fuel of an FHR significantly change an FHR's refueling paradigm in comparison to an LWR or a liquid-metal-cooled reactor. Time-consuming cool-down, heat-up, and fuel transfer preparation steps required in LWR refueling are not required in FHRs. Further, the robust nature of coated particle fuel avoids the requirement to unload the core and inspect the fuel for leaks at each refueling outage. FHRs must be refueled hot as the melt point of the primary coolant is 459°C, which advantageously avoids thermally cycling the components. The refueling time for an FHR is dominated by the actual fuel manipulation time, enabling significantly shorter refueling outages. Further, the relatively flat flux profile in an FHR core and the effective liquid cooling avoid any requirement to shuffle fuel assemblies within the core; the most highly depleted assemblies are simply replaced in any refueling outage. Overall, the increased reactor availability provided by online refueling is approached using more conventional, less-complex, offline fuel manipulation.

The generally cylindrical reactor vessel includes a refueling lobe protruding from the upper half of the vessel. The lobe serves as a short, permanently attached fuel transfer canal. The AHTR's refueling concept draws upon the design of recent liquid-metal-cooled reactors in that fuel assemblies are first transferred out of the core vertically and then moved horizontally into the refueling lobe of the vessel. The fuel assemblies are then lifted through an inert atmosphere; sliding up a triangular weir. Upon overtopping the weir, a fuel assembly swings, in a pendulum-like motion, to the weir's opposite side whereupon it is lowered into a transfer canal filled with lower-cost, poisoned salt.

The molybdenum alloy control blade remains with the fuel assembly when the upper core support plate is raised providing the additional mass necessary to sink the fuel assemblies in the coolant in the event of accidentally dropping the fuel assembly during handling. The fluoride salt transparency enables all fuel manipulation processes to be visually observed and confirmed, increasing the allowable motion speed and confidence in proper transfer.

VI. ECONOMICS

The primary mission for the AHTR is the generation of low-cost electricity while maintaining full passive safety.[2] A comparative model has been developed to compare the cost of electricity between an AHTR and a large pressurized-water reactor (PWR). The model is intended to be improved incrementally as AHTR-related studies are completed and as more detailed design concepts and operations data become available. The evolving economic model will serve as an aid for using cost to guide AHTR design decisions. Thus far the economic model development has focused on building the structure of the model and not on quantitative results. In particular, the current effort has addressed identification of a comprehensive cost database that will support comparative estimating techniques for capital cost and performance of the AHTR.

The development of the AHTR economics model has multiple related objectives. The methodology is structured to provide a comprehensive cost comparison. Costs are based, to the extent practical, on actual experience or credibly detailed design or development work. Where assumptions are necessary, the specific assumptions made are documented. The model is based on information that is publically available rather than on proprietary data to maintain transparency of the process. The evaluation is structured to facilitate identification and prioritization of tasks needed to advance the accuracy of the model. The cost model is based on mature technology ("n^{th} of a kind," or NOAK), with observations on areas of technology that will need to be brought to higher levels of technological maturity or higher production levels to achieve NOAK costs.

To ensure a comprehensive evaluation and to facilitate comparison with similar efforts, an established cost code of accounts was used to structure the evaluation. A cost code of accounts is a formalized accounting system that tracks cost scope in a series of documented accounts. Accounts are assigned a numeric sequence, and increasing levels of detail are tracked by adding digits to the code. The cost code of accounts used to structure this approach is one maintained by the international Generation IV Economic Modeling Working Group (EMWG).[9] Economic modeling is performed using the international EMWG Generation IV Excel Calculation of Nuclear Systems (G4-ECONS) [10] model. This spreadsheet-based model accepts input for capital and operating cost accounts, and calculates, among other parameters, the Levelized Unit Electricity Cost (LUEC).

This evaluation utilizes the Energy Economic Data Base (EEDB)[11] prepared by DOE in the 1970s and 1980s for use in comparing costs for different nuclear and nonnuclear systems. This database averages actual cost incurred in the construction of several types of reactor power plants. One of the data sets tracks cost for large

Westinghouse four-loop PWRs; at about 3400 MW(t), it is similar in size to the AHTR. Data was grouped into a set of plants with good cost experience, as well as a set that represents median experience. The result is a detailed cost database that no longer reflects the proprietary cost data of an individual plant.

The EEDB includes costs for a typical Westinghouse four-loop plant, designated PWR12, with a core thermal power of 3417 MW(t) and net electrical power to the generator step-up transformer of 1144 MW(e). The core thermal power is very close to the 3400 MW(t) used for the AHTR design, and, thus, the PWR12 reflects typical building and equipment sizes that are useful for comparison to the AHTR concept.

To use the EEDB as a basis for this current study, costs need to be expressed in current dollars. For this study, a cost escalation factor of 2.4 from 1987 to 2011 was selected. The G4-ECONS software presents an integrated economic model for assessing the LUEC for advanced energy systems. The G4-ECONS model includes both a power plant model and a fuel cycle model.

It is again stressed that this effort at this time is not meant to provide a quantitative budget estimate, either for capital cost or LUEC, and is based on many approximations and several omissions. The intent of this work is not to calculate a numeric result but to identify issues and prioritize future work. Among the items not included in the analysis are contingency and a simulator/training facility (for both the PWR12 BE and AHTR cases) and adjusted reactor design costs and several fuel cycle model details (for the AHTR cases).

The comparative results for the AHTR and PWR 12, are shown in Table II. Initial comparisons suggest that capital costs should be comparable to LWRs.

VII. CONCLUSIONS

The AHTR reactor concept has been developed to a notional level of maturity in an effort to identify major features and components. The 3400 MW(t) reactor is coupled with supercritical water power conversion technology to produce a plant that can generate electricity with an overall conversion efficiency of 45%. The reactor is cooled with low-pressure primary coolant salt, which exits the reactor vessel at 700°C. The near atmospheric pressure and the higher temperatures are fundamental differences with water-cooled reactor technology.

Although the AHTR operates at higher temperatures than existing LWR technology, the boiling point of the coolant and the damage threshold of the coated particle fuel are substantially above the normal operating temperatures of the plant. The high safety margin coupled with passive decay heat removal systems make the AHTR a "walk-away" safe concept that will passively cool itself even in the event of severe accident scenarios.

Table II

Levelized unit cost output from G4-ECONS (mills/kWh)

Reactor system	**PWR 12 better experience**	**AHTR**
Capital cost recovery	29.66	22.77
Operation and maintenance	12.60	9.31
Fuel cycle costs	5.60	10.75
Decommissioning fund	0.32	0.23
Levelized unit cost of electricity	**48.18**	**43.05**
Total capital investment cost, $/kW(e)	**4012**	**3149**

Although a good deal of uncertainty remains with the costs of the AHTR systems, initial comparisons suggest that capital costs should be comparable to LWRs and the conversion efficiency will be significantly higher. Also, because of the lack of energetic processes or chemicals within containment, the reactor containment building may have less severe design requirements and will not require safety-related pressure mitigation systems. The improved performance offered by the AHTR fundamentally changes the scale and potential for reactor accidents, potentially resulting in lower cost, yet safer, nuclear power systems.

VIII. REFERENCES

1. D. E. HOLCOMB, D. ILAS, V. K. VARMA, A. T. CISNEROS, R. P. KELLY, J. C. GEHIN, *Core and Refueling Design Studies for the Advanced High Temperature Reactor*, ORNL/TM-2011/365, September 2011.

2. D. E. HOLCOMB, F. J. PERETZ, A. L. QUALLS, *Advanced High Temperature Reactor Systems and Economic Analysis*, ORNL/TM-2011/364, September 2011.

3. S. R. GREENE, J. C. GEHIN, D. E. HOLCOMB, et al., *Pre-Conceptual Design of a Fluoride-Salt-Cooled Small Modular Advanced High-Temperature Reactor (SmAHTR)*, ORNL/TM-2010/199, Oak Ridge National Laboratory, December 2010.

4. P. BARDET et al., "Design, Analysis and Development of the Modular PB-AHTR," *Proceedings of ICAPP '08*, Anaheim, CA, June 8–12, 2008.

5. D. T. INGERSOLL et al., *Status of Preconceptual Design of the Advanced High-Temperature Reactor (AHTR)*, ORNL/TM-2004/104, Oak Ridge National Laboratory, May 2004.

6. D. T. INGERSOLL et al., *Status of Physics and Safety Analyses for the Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR)*, ORNL/TM-2005/218, Oak Ridge National Laboratory, December 2005.

7. D. T. INGERSOLL et al., *Trade Studies for the Liquid-Salt-Cooled Very High-Temperature Reactor: Fiscal Year 2006 Progress Report*, ORNL/TM-2006/140, Oak Ridge National Laboratory, February 2007.

8. J. A. PHILLIPS, C. M. BARNES, AND J. D. HUNN, "Fabrication and Comparison of Fuels for Advanced Gas Reactor Irradiation Tests," *Proceedings of HTR 2010*, Prague, Czech Republic, Oct. 18–20, 2010.

9. *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, GIF/EMWG/2007/004, Economic Modeling Working Group of the Generation IV International Forum (2007).

10. *User's Manual for G4-ECONS, Version 2.0, A Generic EXCEL-Based Model for Computation of the Projected Levelized Unit Electricity Cost (LUEC) and/or Levelized Non-Electricity Unit Product Cost (LUPC) from Generation IV Systems*, Economic Modeling Working Group of the Generation IV International Forum, March 2008.

11. *Nuclear Energy Cost Data Base: A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0095, U.S. Department of Energy. September 1988.