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Advanced High Temperature Reactor Systems and Economic Analysis

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Reactor and Nuclear Systems Division

ADVANCED HIGH TEMPERATURE REACTOR SYSTEMS AND ECONOMIC ANALYSIS

SEPTEMBER 2011 STATUS

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September 30, 2011

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1. INTRODUCTION

The Advanced High Temperature Reactor (AHTR) is a design concept for a large-output [3400 MW(t)] fluoride-salt-cooled high-temperature reactor (FHR). 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 AHTR's large thermal output enables direct comparison of its performance and requirements with other high output reactor concepts. As high-temperature plants, FHRs can support either high-efficiency electricity generation or industrial process heat production. The AHTR analysis presented in this report is limited to the electricity generation mission.

FHRs, in principle, have the potential to be low-cost electricity producers while maintaining full passive safety. However, no FHR has been built, and no FHR design has reached the stage of maturity where realistic economic analysis can be performed. The system design effort described in this report represents early steps along the design path toward being able to predict the cost and performance characteristics of the AHTR as well as toward being able to identify the technology developments necessary to build an FHR power plant.

While FHRs represent a distinct reactor class, they inherit desirable attributes from other thermal power plants (as shown in Fig. 1) 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.

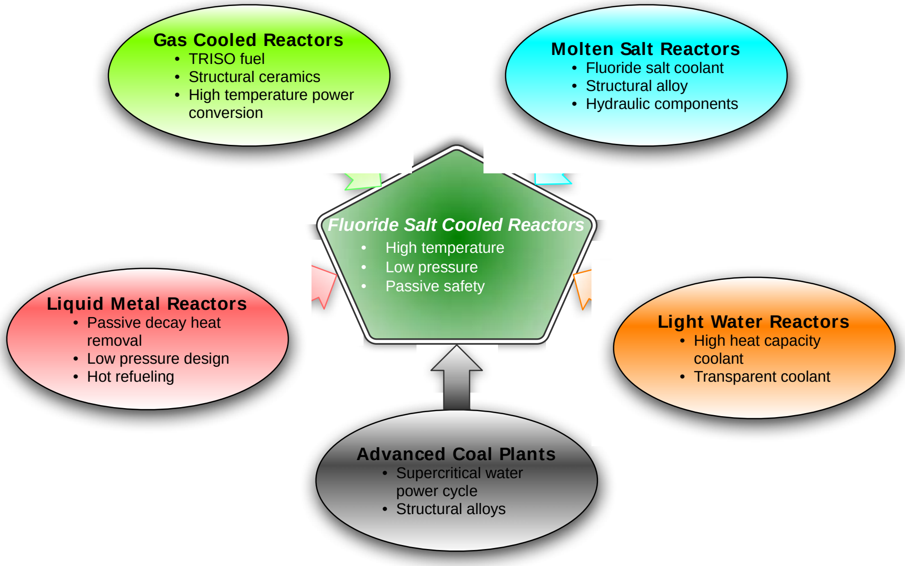

Fig. 1. FHR attribute inheritance from earlier power plants.

The current 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,[1] the PB-AHTR preconceptual design,[2] and the series of early phase AHTR evaluations performed from 2004 to 2006.[3-5]

This report provides a power plant–focused description of the current state of the AHTR. The report includes descriptions and sizes of the major heat transport and power generation components. Component configuration and sizing are based upon early phase AHTR plant thermal hydraulic models. The report also provides a top-down AHTR comparative economic analysis. A commercially available advanced supercritical water-based power cycle was selected as the baseline AHTR power generation cycle both due to its superior performance and to enable more realistic economic analysis. The AHTR system design, however, has several remaining gaps, and the plant cost estimates consequently have substantial remaining uncertainty. For example, the enriched lithium required for the primary coolant cannot currently be produced on the required scale at reasonable cost, and the necessary core structural ceramics do not currently exist in a nuclear power qualified form.

The report begins with an overview of the current, early phase, design of the AHTR plant. Only a limited amount of information is included about the core and vessel as the core design and refueling options are the subject of a companion report.[6] The general layout of an AHTR system and site showing the relationship of the major facilities is then provided. Next is a comparative evaluation of the AHTR anticipated performance and costs. Finally, the major system design efforts necessary to bring the AHTR design to a pre-conceptual level are then presented.

2. AHTR DESIGN SUMMARY

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 notional power generation station. The AHTR design concept remains at a notional design level of maturity in that required systems and components remain loosely defined and only cursorily analyzed. However, an initial AHTR plant layout has been developed to better understand the major AHTR systems requirements and to visualize how the reactor components interact to create a complete power plant. A view of the AHTR baseline plant configuration is shown in Fig. 2.

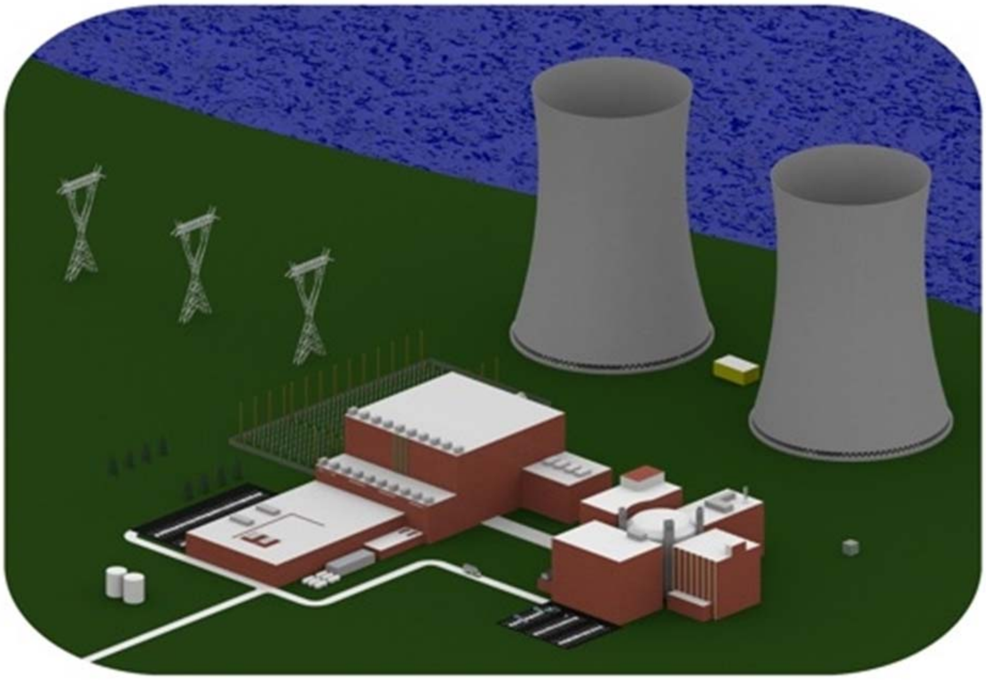

Fig. 2. Overview of the AHTR plant site and major structures.

The AHTR is a 3400 MW(t) fluoride salt–cooled high-temperature reactor (FHR) concept with a mixed mean reactor coolant outlet temperature of 700°C. FHRs are inherently high-temperature reactors. As the primary coolant temperature increases, the number of potential industrial uses for the high temperature heat expands and the electricity production efficiency increases. The low vapor pressure of the fluoride salt coolant allows operation at near atmospheric pressure, which reduces primary system strength requirements and reactor system containment structural requirements. The potentially corrosive nature of the fluoride salt coolant, however, necessitates maintaining a highly pure coolant including active control of its cleanliness and composition.

The power plant aspects of FHRs are similar to those of other thermal power plants, including LWRs. After several decades of experience, LWRs have now achieved high plant availability; however, existing and near-term LWRs are not fully passively safe and have inherent features that make them complex and expensive. The goal is for the AHTR to be a low-cost supplier of electricity and a preferred provider of process heat while maintaining full passive safety.

Fluoride salts are used in the AHTR as the primary coolant for heat transport in the intermediate system and for decay heat removal in the Direct Reactor Auxiliary Cooling System (DRACS).

Comparisons of fluoride salt properties and their nuclear and heat transfer performance have been performed previously.[7,8,9] For this baseline AHTR concept, $2^7LiF\text{-}BeF_2$ (enriched in ^7Li to 99.995%), referred to as FLiBe, was selected for the primary coolant because it has the most favorable nuclear properties, including a negative void coefficient and low activation enabling easier primary system maintenance. A 47% KF 53% ZrF_4 (mole percent) fluoride salt mixture was chosen for the intermediate loop as a compromise among heat transfer performance, melting temperature, and cost. In particular, $KF\text{-}ZrF_4$ does not contain lithium or beryllium, which reduces the potential impact (dilution of the expensive isotopically separated lithium) of a leak from the intermediate to primary system and mitigates concerns about toxicity. The DRACS has not yet been investigated thoroughly, and as a baseline, $KF\text{-}ZrF_4$ has been chosen for it because of the same criteria associated with its use in the intermediate loop.

While FLiBe is a reasonably well known fluoride salt coolant and its properties are included in the current version of RELAP,[10] even the melt point of $KF\text{-}ZrF_4$ is in doubt, with a 40°C discrepancy (390°C vs 430°C) between the two published phase diagrams.[11] Thus, the analyses performed to date are preliminary, and additional certainty in coolant parameters is required for later analyses.

The reactor core and vessel are part of the primary loop, which is entirely contained within a reactor containment structure. A basic design criteria for an FHR's containment is that it not contain materials that present potential for either pressurizing containment or having an energetic chemical reaction such as hot sodium with water. Thus, the design requirements for the AHTR's containment structure differ from that for an LWR or liquid metal–cooled reactor (LMR) due to the lack of potential energy sources in containment. The structural purpose for an FHR's containment is, thus, primarily to serve as an impact shield against external forces rather than as confining internal accidents. The toxic nature of the FLiBe coolant, however, will necessitate an internal confinement within the containment to control beryllium fluoride vapor migration.

The AHTR primary coolant system couples to an intermediate fluoride salt system that transports the heat generated within the core away from the primary coolant loop and any reactor components. The heat is ultimately transferred from the intermediate salt to the working fluid within a power conversion loop. Preliminary analysis of the performance of the primary and intermediate heat transport systems and their coupling to a power conversion loop is the principal focus of this notional design report. The technical focus of the current design effort is to begin to define the major AHTR power plant systems and components and their basic requirements and interfaces.

The technology options for these systems and components and their maturity levels are assessed. Technology improvements that are relatively near-term are considered, but the design focus is on existing technology or relatively mature emerging technology. Enhanced technologies that would improve the AHTR's performance, but are substantially more than a decade from maturity, are identified but are not assumed.

The outlet temperature of the reactor coolant is limited in the present evaluation to 700°C. As advanced structural alloys are developed, the outlet temperature can be increased. At 700°C, heat can be delivered to the power conversion system at temperatures comparable to those of coal-fired power plants, which means that the AHTR system can produce electricity at efficiencies comparable to those of coal-fired plants. Higher temperature heat would also be available for industrial process heat applications. The Next Generation Nuclear Plant's (NGNP) primary market is intended to be industrial process heat, and several recent reports have studied the potential market for nuclear generated process heat.[12] Due to its liquid coolant, FHRs can deliver heat over a narrower temperature band than a gas-cooled concept, which increases the utility of the reactor for process heat provision.

The currently available power conversion options for the AHTR include the subcritical steam and supercritical and ultra-supercritical water cycles. Advanced power conversion systems include the closed cycle Brayton systems and the supercritical carbon dioxide (CO_2) Brayton and Rankine cycles. These power conversion systems were evaluated for the FHR SmAHTR concept,[1] and it was concluded that the Brayton system options were not sufficiently mature and that they would not provide a large benefit until higher reactor outlet temperatures were achieved. Supercritical CO_2 systems, although not currently demonstrated at power levels of interest, offer higher conversion efficiency at lower temperatures and are thought to be workable to temperatures approaching 750°C. Eventually, the high efficiencies afforded by supercritical CO_2 cycles and the high temperatures at which they can operate will make them an attractive power conversion system for the AHTR. This combination of technology can potentially produce power systems with conversion efficiencies exceeding 50%. Beyond 750°C, helium Brayton systems offer good efficiency and do not suffer from working fluid decomposition, but practical experience with large helium Brayton systems has demonstrated that the equipment is difficult to build and operate. The open-air Brayton cycle is a mature technology which has recently been given preliminary consideration in conjunction with high temperature reactors. However the current AHTR reactor coolant outlet temperature is too low to effectively couple to this technology.

Assuming that the initial version of the AHTR will have a reactor coolant outlet temperature of 700°C, water-based power conversion systems currently appear to be the only realistic power cycle. Subcritical steam systems operate at temperatures approaching 550°C. The nominal turbine inlet temperature of a supercritical power conversion system is 565°C. Supercritical water power conversion systems are similar to subcritical steam cycles, but the highest temperature and pressure section of the loop forces the working fluid into the supercritical phase. The working fluid passes first through a high temperature and pressure turbine before entering what is essentially a traditional steam cycle. Subcritical and supercritical water power conversion systems are mature technologies that have been in use in the fossil-fired electricity market since the 1950s. Plants constructed in the early 1960s are still operational today.

3. AHTR REACTOR CORE AND PRIMARY SYSTEM

The reactor core produces 3400 MW(t) of fission power within 252 fuel assemblies inside the reactor vessel, as shown in Fig. 3. The upper temperature limit of 700°C arises from the decrease in strength with increasing temperature of alloy N,[13] which is the near-term structural alloy selected for the reactor vessel and primary piping. The temperature increase across the core is held by design to 50°C. A primary coolant flow rate of 28,500 kg/s is required to maintain the 50°C temperature increase across the core at full power.

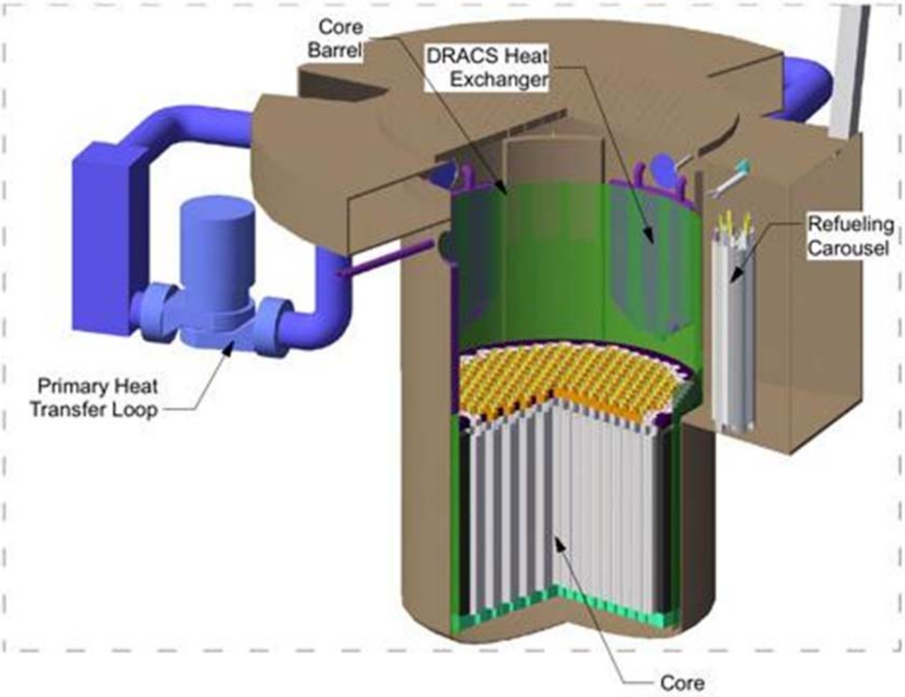

Fig. 3. Cutaway view of the AHTR core and vessel.

The primary coolant enters the reactor vessel through three segmented downcomer sections that direct the cold-leg coolant downward to the lower plenum. The coolant flows upward from the lower plenum to cool the fuel assemblies. The fuel assemblies are composed of 18 fuel planks suspended from a central "Y"-shaped support structure as shown in Figs. 4 and 5.

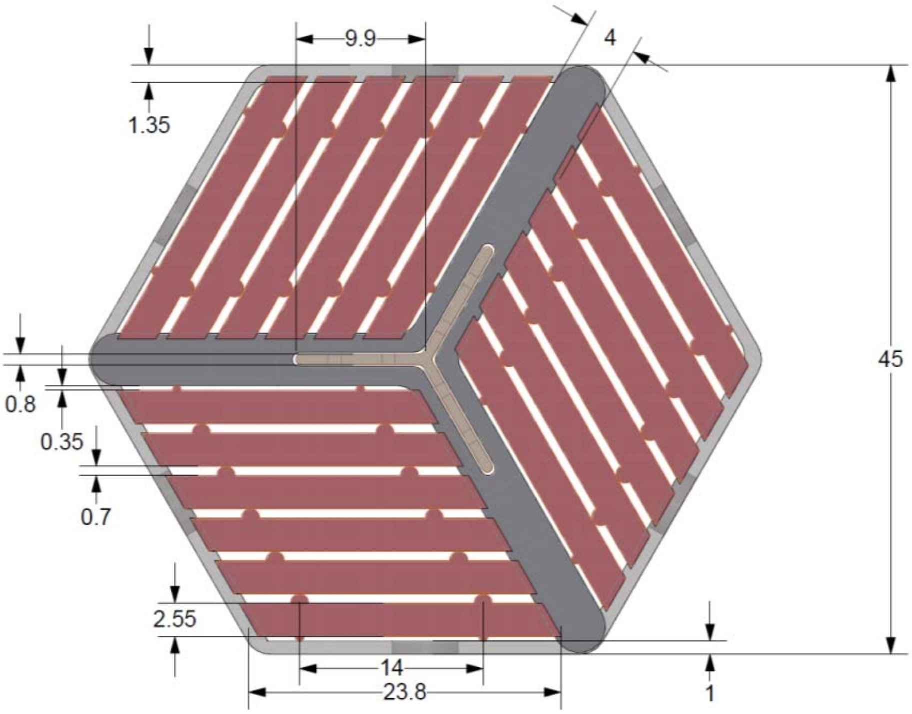

Fig. 4. Top view of an AHTR fuel bundle containing 18 fuel elements.

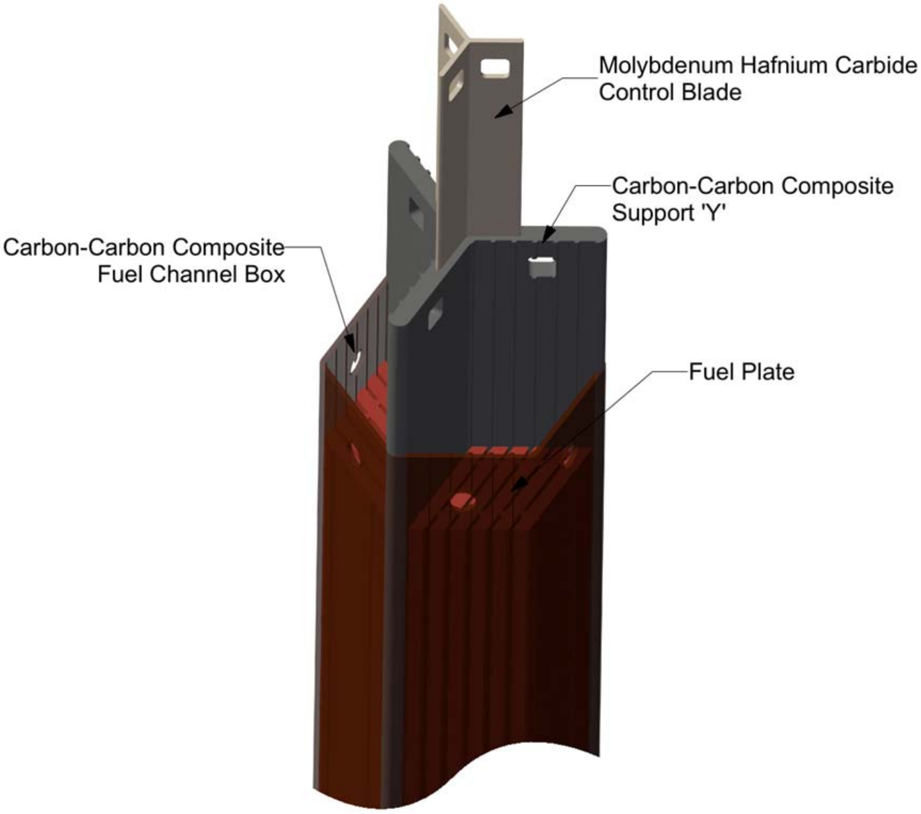

Fig. 5. View of an AHTR fuel bundle and supporting structure. Eighteen fuel plates are hung from the support “Y” and the entire assembly is surrounded by a fuel channel box.

Each inner fuel plank is cooled by two ~24 cm by 0.7 cm interior coolant channels, and the outer planks are cooled by one interior channel and an outer channel with approximately half the thickness and coolant flow. Only half of the heat generated in an outer plank enters the thinner channels; thereby, the coolant experiences the same temperature increase as that in the inner channels. Overall, the AHTR has a mixed pool and loop primary coolant design, as shown in Fig. 6. The normal operation flow of the primary coolant is subdivided into multiple external loops. The number of loops could reasonably range from two to four. A three primary loop option was selected for the baseline design. The Clinch River Breeder Reactor (CRBR) design employed a three-loop power system and a low-pressure refueling system, providing a convenient, well-documented analog to the AHTR.

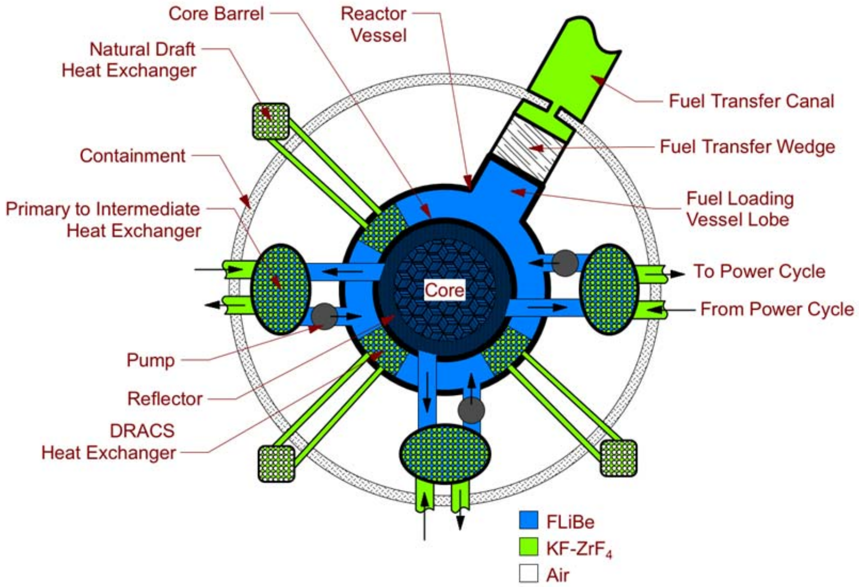

Fig. 6. Schematic showing the features of the AHTR reactor system including the P-IHX and the DRACS.

The primary coolant flow rate is split evenly over three primary coolant legs, and the velocity in the connecting primary system piping is limited by design to 4 m/s. The inner diameter (I.D.) required for maintaining the flow velocity is approximately 1.24 m. The reactor pressure vessel has three primary outlet pipes and three return pipes. These six ports are positioned on the perimeter of the cylindrical portion of the reactor vessel in an upper plenum below the top flange.

Three primary-to-intermediate loop salt-to-salt heat exchangers (P-IHX) transfer heat from the primary system to the intermediate system. These heat exchangers are located near the reactor vessel within the primary containment structure, and each heat exchanger handles one-third of the primary coolant flow and transfers one-third of the fission power to the intermediate salt heat transfer system.

After exiting the vessel, the primary coolant enters the P-IHXs and flows downward to the P-IHX outlets, where electrically driven pumps force it back to the vessel. The primary coolant enters the vessel at the same level as the outlet piping and flows into downcomer channels that direct the flow downward along the reactor vessel wall. This arrangement allows the vessel wall to operate near the lowest primary coolant temperature—650°C. Flow from the downcomers enters a lower plenum and reverses direction to flow up through the core. The lower core support structure contains orifices to distribute flow to the channels within individual fuel assemblies.

The salt coolants have a melting temperature greater than ambient temperature; therefore, the reactor primary and intermediate loops must be heated prior to the initial loading of the fluids. The systems must also remain above the salt melting temperatures whenever it is filled with salt. A notional heating arrangement for the vessel is shown in Fig. 7. The salt may be siphoned out for major maintenance once the core is unloaded, and heated salt storage vessels are required for both the primary and intermediate systems.

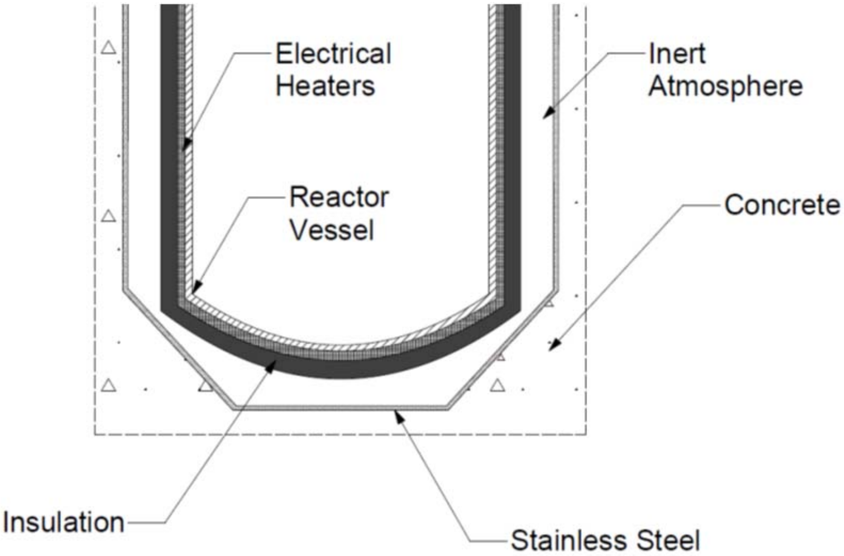

Fig. 7. Notional arrangement of the reactor vessel within a reactor cavity. The vessel is encased in heaters and insulation and is isolated from the concrete with a dry inert gas-filled gap. The melting point of the primary coolant is 459°C.

3.1 PASSIVE SAFETY

FHRs operate at low pressures and, although they are high-temperature reactors, they operate substantially below the boiling point of the salt coolants (in excess of 1400°C) and the failure temperature of coated particle fuel. The large thermal margin to coolant boiling and fuel damage as well as the chemically inert nature of the primary coolant greatly reduces the possibility of radioactive material release.

Profitable power plant operation, however, is based on operating the plant for its intended lifetime. Transients that negatively impact the integrity of major components, specifically the reactor vessel, are practically the limiting operational transients in a LWR. Although the AHTR's vessel is made of higher temperature material, it also operates at higher temperature. And FHR reactor vessels operate with a reactor vessel temperature margin that is comparable to that of an LWR. The AHTR reactor vessel is intended to have a design life of 60 years and be a plant lifetime component. However, Alloy N is not yet fully qualified for high-temperature reactor applications and, if creep-fatique testing indicates that it has unanticipated and undesirable long-term performance, vessel replacement is a possibility. An FHR's reactor vessel is substantially thinner than that of an LWR due to the lower pressure requirements and, consequently, it is possible that an FHR vessel could be replaced during a major maintenance outage if necessary.

FHRs have substantially larger negative reactivity thermal feedback than LWRs due to their coated particle fuel. The AHTR's strong negative temperature feedback coefficient of reactivity will cause the reactor power to decrease as temperatures increase during an accident scenario (even in the absence of other control action). This passive safety feature is the first line of defense against reactor core and vessel damage. Actively inserted control blades are the next line of defense against overpower accidents. A neutron absorbing salt injection system with provision for both passive and active operation is included on the AHTR as a secondary shutdown system. A companion report detailing the in- and near-vessel system provides additional details about the AHTR reactivity coefficients and both its primary and secondary shutdown mechanisms.

The primary system is designed to passively reject fuel decay heat via the DRACS to the environment. DRACS are preferable for FHRs because the vessel is well-insulated to limit heat loss and possible salt freezing during outages. Thus decay heat must be removed from the salt directly because it cannot be effectively removed through the vessel. The DRACS transfers heat from the reactor primary coolant and dissipates it to the atmosphere via a three-in-parallel, three-loop natural circulation system, shown schematically in Fig. 8. The primary coolant is the first fluid in the three-loop system. The coolant temperature rise due to the core decay heat provides the buoyancy force for primary coolant flow upward through the core upon loss of forced flow. The DRACS heat exchangers remove the heat and are located near the top of the primary coolant loop to maximize gravity-driven natural circulation down the downcomer and upward through the core. The second loop is an enclosed salt loop transferring heat from the DRACS in-vessel salt-to-salt heat exchanger to a natural draft salt-to-air heat exchanger outside the containment. The DRACS intermediate heat transfer system piping, therefore, requires penetrations through the reactor containment structure. The DRACS is intended to remain fully functional even with the primary coolant piping entirely sheared from the reactor vessel. Thus, the DRACS piping must be protected as a nuclear safety component against external assaults that would challenge its mechanical integrity. Air is the third fluid in the DRACS and the ultimate heat sink.

Analysis of the DRACS is preliminary, but the current AHTR design has three independent DRACS loops. The loops will ultimately be sized so that two of the three loops will prevent damage to reactor components following major accident scenarios. The current design assumes that each DRACS can remove 0.25% of full reactor power (8.5 MW) at 700°C mixed-mean coolant temperature under fully established natural circulation flow after a loss-of-forced-flow accident.

During normal operation, 650°C primary coolant flows in the reverse direction (upward) at a reduced rate over the DRACS heat exchangers. Fluidic diodes below the DRACS heat exchangers limit the amount of coolant flow that can flow upward over the DRACS heat exchangers during normal operation so that the majority of the primary coolant flow passes upward through the core. If the primary pumps lose power and stop, the pressure distribution within the core changes due to buoyancy effects and flows through the fluidic diodes reverse and increase. This pulls warmer coolant from the upper plenum and passes it downward over the DRACS heat exchangers where it is cooled. The remainder of the downcomer length acts as a low-temperature, high-density leg of a natural circulation loop. The heated salt within the DRACS heat exchanger begins to rise and flow outside the containment building where it passes through an air-to-salt heat exchanger and is cooled by the natural updraft of air within three separate, impact resistant cooling towers. The normal DRACS bypass flow maintains the intermediate DRACS salt loop in a liquid state without the need for electrical heaters. The DRACS is, therefore, operational under normal operating conditions, and the plant suffers a modest thermal and pumping power loss for having the safety feature in hot standby. As the core temperature initially increases during a loss-of-forced-flow accident, the flow rates in the DRACS loops increase until equilibrium is established. Detailed AHTR DRACS hydraulic analysis has yet to be performed; however, key performance parameters include the size of the heat exchangers, the fluid used, the overall resistance to flow through the system, and the difference in elevation of the heat exchangers.

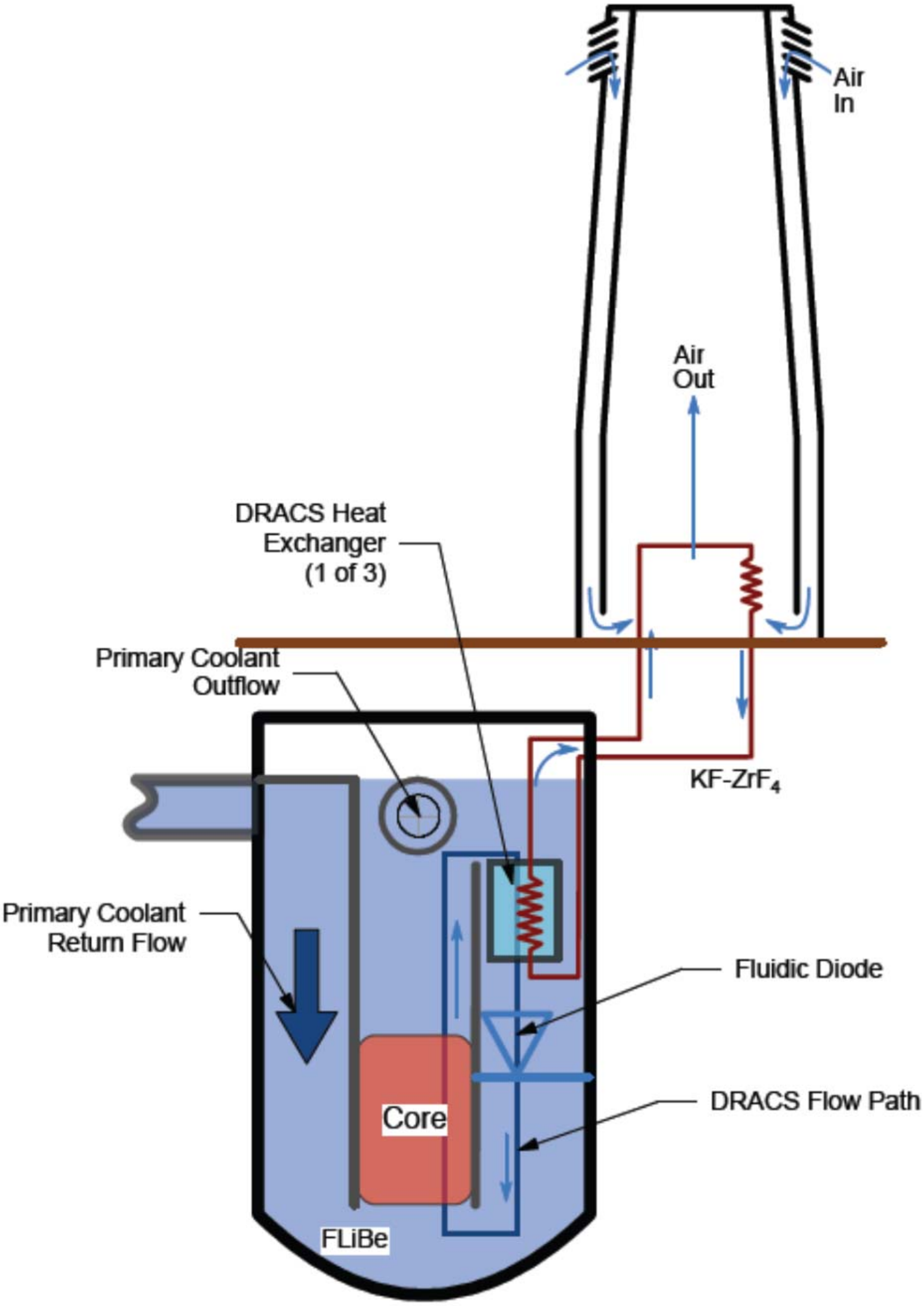

Fig. 8. Diagram of the reactor primary coolant arrangement within the vessel and the DRACS.

The downcomer section along the perimeter of the reactor vessel is segmented angularly to form enclosed inlet flow channels extending from the inner surface of the vessel cylindrical shell to the outer surface of the core barrel. These three enclosed segments direct the primary coolant downward to the lower vessel plenum, which serves as a common manifold for the three primary inlet regions—the reactor core and three smaller angular sections between the inlet sections. These smaller sections are defined by the outer surface of the core barrel and the vessel inner surface at the same radial position as the downcomer sections, but they are open from the upper to the lower plenums. The DRACS heat exchangers are housed in these sections and positioned below the primary inlet piping.

The DRACS heat exchangers will not become uncovered even if the vessel were to be drained to the lowest surface of the inlet piping. Placing both the inlet and outlet piping above the core allows siphon breaks in the piping to prevent the loss of enough coolant from the vessel to uncover the core or the DRACS heat exchangers in the event of an ex-vessel primary system leak. If a P-IHX were to leak at a low point, when enough coolant is drained to uncover the primary inlet ports, the siphon will be broken and the vessel will contain an enclosed pool of coolant. Below the primary inlet piping, the vessel contains no penetrations. The primary coolant flows within the vessel due to natural circulation whenever there is heat coming from the core, and this flow is directed over the DRACS heat exchangers, which remove heat from the primary coolant during extended accident scenarios.

Additionally, sufficient primary salt is provided in the reactor vessel that if it were to fail, the primary salt would be contained in the surrounding guard vessel (indicated as the stainless steel liner in Fig. 7) in an arrangement that keeps the DRACS heat exchanger covered with salt.

The transient response of reactor core flow due to the loss of primary pump power proceeds as follows.

1. Pressure at the reactor vessel inlet is reduced as the primary pumps coast down, resulting in reduced flow through the core.
2. Temperature increases within the core begin to increase natural circulation forces in the core due to volumetric expansion of the coolant.
3. The pressure difference across the fluidic diodes reverses; upward flow through the HXs stops and then reverses.
4. A natural circulation pattern within the core is established with upward flow through the reactor core and downward flow over the DRACS heat exchangers through the fluidic diodes and into the lower plenum.
5. The DRACS remove heat from the primary coolant, heating the fluid within the DRACS heat exchangers and increasing the natural circulation driving potential of the DRACS secondary flow loop.

If the reactor fission power is shut down in the initial minutes of a loss-of-forced-flow transient, the fuel temperature rise will be limited and of short duration. If no control action were to be taken, the fission power will decrease as core temperatures increase and the passive and thermally driven secondary, poison salt–based, shutdown system will activate, providing high assurance that the reactor fission power production will cease in over-temperature transients. A later, more detailed analysis of the reactor system, including the DRACS and shutdown systems, will be performed to understand the integrated active and passive safety system performance.

4. INTERMEDIATE HEAT TRANSPORT SYSTEM

The primary system ends and the intermediate loops begin at the P-IHXs within the reactor containment building (RCB). The intermediate salt passes through the containment boundary and transports the heat from the primary system to the power conversion system. The nominal distance between these systems is currently set at 100 m. The intermediate transport piping runs in an accessible covered tunnel between the buildings that house these systems. (The AHTR will not have inaccessible piping runs.) 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 (PCB).

The intermediate system salt is KF-ZrF_4. This salt was chosen in part because it does not contain lithium or beryllium. It is relatively benign to personnel, 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. Pressure diaphragms are required on the intermediate loop to prevent any power cycle triggered pressure transients from propagating to the primary coolant loop. Surges would direct intermediate salt flow to the salt storage tank.

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.

The temperature change of the intermediate salt through the P-IHX was set at 75°C to reduce flow rate requirements. The heat capacity of KF-ZrF_4 is 1.05 J/g-K, and approximately 14,400 kg/s of KF-ZrF_4 flows through each of the three legs of the intermediate system for a total flow rate of 43,200 kg/s. This flow is split into two flow streams of 21,600 kg/s to feed the SCWGs.

A supercritical water generator 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 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 (HTP) and is returned to the reheater tubes. The fluid from the reheater tubes passes through the intermediate pressure turbine (IPT) and then through the low pressure turbine (LPT) after moisture separation. Beyond the HPT the steam supply system looks much like that of a subcritical steam supply system. The power split among the three turbines is roughly a 1/3, although individual manufacturers balance these loads differently.

Power to the pump motors is used to adjust flow in the three intermediate loops. Flow balancing valves, placed either beyond the hot-leg manifold or after the SCWGs, balance flow of intermediate salt between the two SCWGs. These valves have partial restriction for flow balancing and do not have a sealing requirement.

4.1 POWER CONVERSION SYSTEM

Subcritical steam systems allow coal-fired power plants to produce electricity at net conversion efficiencies approaching 40%, and modestly supercritical systems have net efficiencies approaching 42%. “Ultra-supercritical” plants are simply systems that increase the pressure and temperature beyond nominal supercritical levels. Ultra-supercritical power conversion systems now operate with turbine inlet temperatures of 600°C. Systems operating beyond 600°C are denoted “advanced” supercritical systems in this report. Existing ferritic-martensetic steels are functional to approximately 650°C, and today’s advanced supercritical coal-fired plants are operating near those temperatures. Supercritical and ultra-supercritical steam cycles are well understood and their costs are known. Some extrapolation is required to assess the performance of advanced supercritical systems with the AHTR. Technology is currently under development to increase supercritical system temperatures to 750°C, but these systems are not technically mature.

The difference between coupling an AHTR to a supercritical water power conversion system is that the supercritical water generator is a tube-and-shell, once-through heat exchanger with intermediate salt on the shell side as opposed to a being a combustion flue-gas heat exchange chamber with hot combustion products flowing over the outer surface of the water tubes. The heat transfer of the clean liquid fluoride salt of an AHTR SCWG is substantially better than that of the combustion products, enabling the AHTR SCWG to have a significantly smaller heat transfer surface area.

The electrical output of the AHTR is nominally 1500 MW(e). Roe and Burns[14] performed a preliminary analysis of a power conversion system of approximately this size in conjunction with conceptual design work related to the Supercritical Water Reactor (SCWR) concept and concluded that a single, 1800 RPM supercritical power train of this size was a feasible extrapolation beyond current practice. Supercritical steam systems in fossil-fired plants are routinely sized to 1000 MW(e), and designs are currently being considered for 1200 to 1300 MW(e).

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. Having two power conversion systems decreases the probability of losing 100% of the system primary heat sink at once. Having half of the heat sink available is a much less severe situation than losing all of it. The power train subdivision is only preliminary and will require further evaluation.

An overview of the intermediate system and the power conversion system is shown in Fig. 9. Three primary loops feed three intermediate loops which feed a common hot salt manifold. Two legs from this manifold feed two independent SCWG units, and mixing valves are used to balance the flow between them. Salt from the two generators exits into a common plenum, and three intermediate loop salt pumps force the cooler salt back to the three P-IHXs.

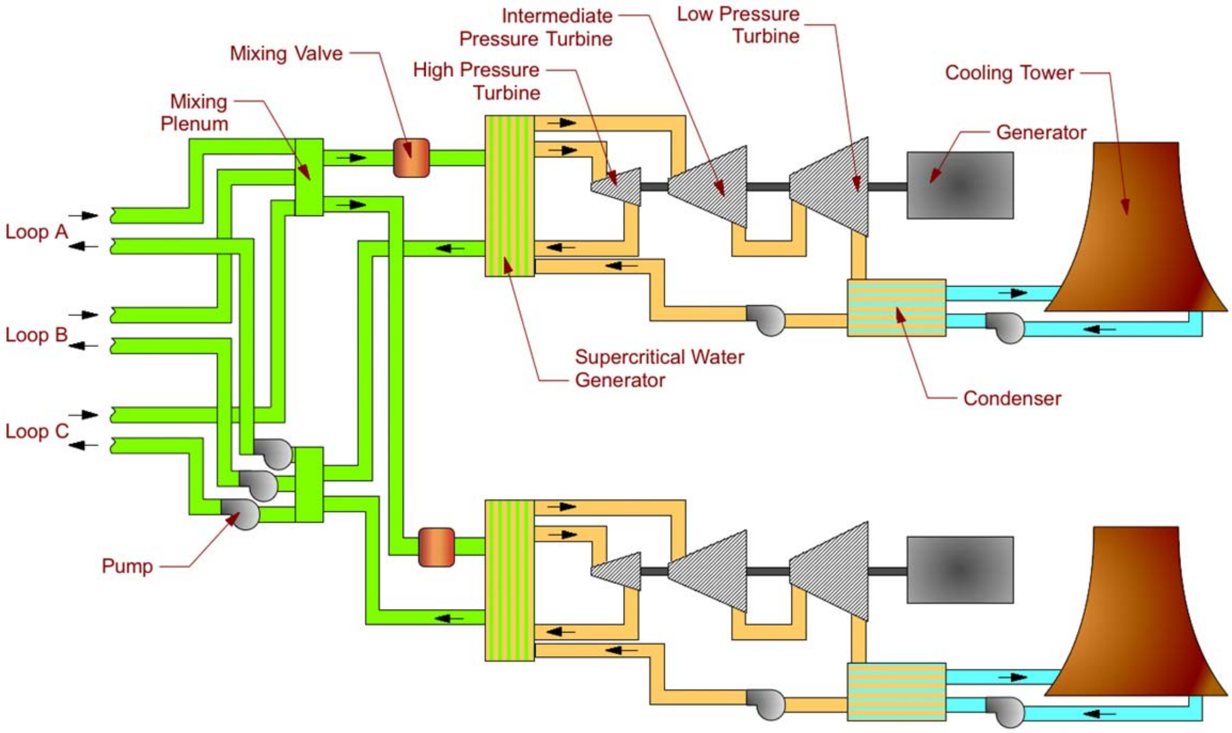

Fig. 9. Schematic of the AHTR reactor system coupled to two supercritical power conversion systems.

5. AHTR PERFORMANCE EXPECTATIONS

Supercritical water power generation has a well-documented history of performance from coal-fired plants. Beyond the heat exchanger components, the power conversion system would be essentially the same in an AHTR system. The difference in plant performance is mainly due to internal loads associated with coal handling. For reactor systems, the major internal load is pumping power and that can differ significantly for direct vs indirect power cycles. In the SCWR concept, the core is cooled by the water used in the power conversion system. Its primary pumps are the main feedwater (MFW) pumps, much like that in a boiling-water reactor. A pressurized-water reactor has primary pumps in addition to the MFW pumps. The AHTR has intermediate system pump loads in addition to the primary pump loads and the power conversion system pump loads.

Five plant concepts were compared. Three of the concepts—(1) a coal-fired supercritical plant, (2) the SCWR, and (3) the AHTR—were assumed to be coupled to an identical supercritical water power conversion system (although the SCWR design was for a lower reactor outlet temperature than is used for the supercritical power conversion system used in the comparison). The fourth concept was the AHTR reactor coupled to an ultra-supercritical water power conversion system with a turbine inlet temperature of 593°C, and a fifth concept was the AHTR reactor coupled to an advanced supercritical water power conversion system with a turbine inlet temperature of 650°C.

Trade-offs exist among the temperature drop allowed from the primary coolant to the power conversion system working fluid, heat exchanger size, and plant performance. A 700°C primary coolant outlet temperature would couple to an existing 565°C supercritical water power conversion system with 135°C of available temperature drop. This temperature drop would be taken up over the P-IHX and the salt-to-water SCWG. The temperature drop can be reduced with increased heat exchanger capacity to increase the peak operating temperature of the power conversion system, which will increase cycle efficiency and overall plant performance. To attain a turbine inlet temperature of 650°C, the allowable temperature drop from the reactor outlet temperature is 50°C or, on average, 25°C per heat exchange.

Table 1 lists the loop temperatures and the log mean temperature difference (LMTD) for the P-IHX and the SCWG in moving the turbine inlet temperature between 565°C and 650°C. The primary coolant temperatures were fixed, and the temperature drop to the intermediate salt was varied. The values in the first column represent operation of an advanced supercritical plant, and the values in the last column approximately represent a nominally supercritical plant. The LMTD varies for the P-IHX from 36°C to 105°C; thus, the P-IHX for the ultra-supercritical system is expected to be over twice the size of the P-IHX for the nominally supercritical system. The benefit is reflected in increased cycle efficiency, which in theory is approximately 3 percentage points higher for the advanced supercritical plant.

Table 1. Temperatures (°C) for the primary, intermediate, and water loops of the AHTR coupled to supercritical water power conversion systems ranging from nominally supercritical plants to current state-of-the-art advanced supercritical plants

	ASC								**USC**
Primary-hot	P700	700	700	700	700	700	700	700	700
Primary-cold	650	650	650	650	650	650	650	650	650
Intermediate-hot	**675**	**665**	**655**	**645**	**635**	**625**	**615**	**605**	**595**
Intermediate-cold	600	590	580	570	560	550	540	530	520
SCW-hot	**650**	**640**	**630**	**620**	**610**	**600**	**590**	**580**	**570**
SCW-cold	320	315	310	305	300	295	290	285	280
DT P-I	25	35	45	55	65	75	85	95	105
LMTD	36.1	46.4	56.6	66.7	76.8	86.9	97.0	107.0	117.1
DT I-W	25	25	25	25	25	25	25	25	25
LMTD	105.6	104.3	103.0	101.7	100.3	99.0	97.7	96.4	95.1
Total DT	50	60	70	80	90	100	110	120	130
Carnot efficiency (cycle)	67.5	67.1	66.8	66.4	66.0	65.6	65.2	64.8	64.4

The primary coolant flow rate of 28,500 kg/s is split over the three P-IHXs at a rate of 9500 kg/s. In order to limit the flow velocity to between 2 and 3 m/s in a tube-and-shell heat exchanger, approximately 6000, 2.2-cm-I.D. tubes are required per heat exchanger. The primary coolant would have a heat transfer coefficient within the tubes of approximately 6000 W/m^2-°C. The spacing of the tubes on the shell side of the P-IHX determines flow velocity and, therefore, the heat transfer coefficient. For this baseline study, the flow was limited to 3 m/s with a resulting heat transfer coefficient of approximately 8000 W/m^2-°C.

Figure 10plots the shell body length (excluding plenums) and the expected volumetric power density of a U-Tube tube-and-shell AHTR P-IHX. The inlet and outlet temperatures of the primary salt are 700°C and 650°C, respectively, and for these calculations. The intermediate salt temperature is varied while keeping the temperature change a constant 75°C. The cross-sectional area of the heat exchanger was calculated assuming a square grid, and a large pitch-to-diameter ratio of 1.3 was used to limit the shell side coolant velocity to below 3 m/s. The length required to achieve peak intermediate salt temperature increases sharply above 680°C, making 675°C a reasonable design objective.

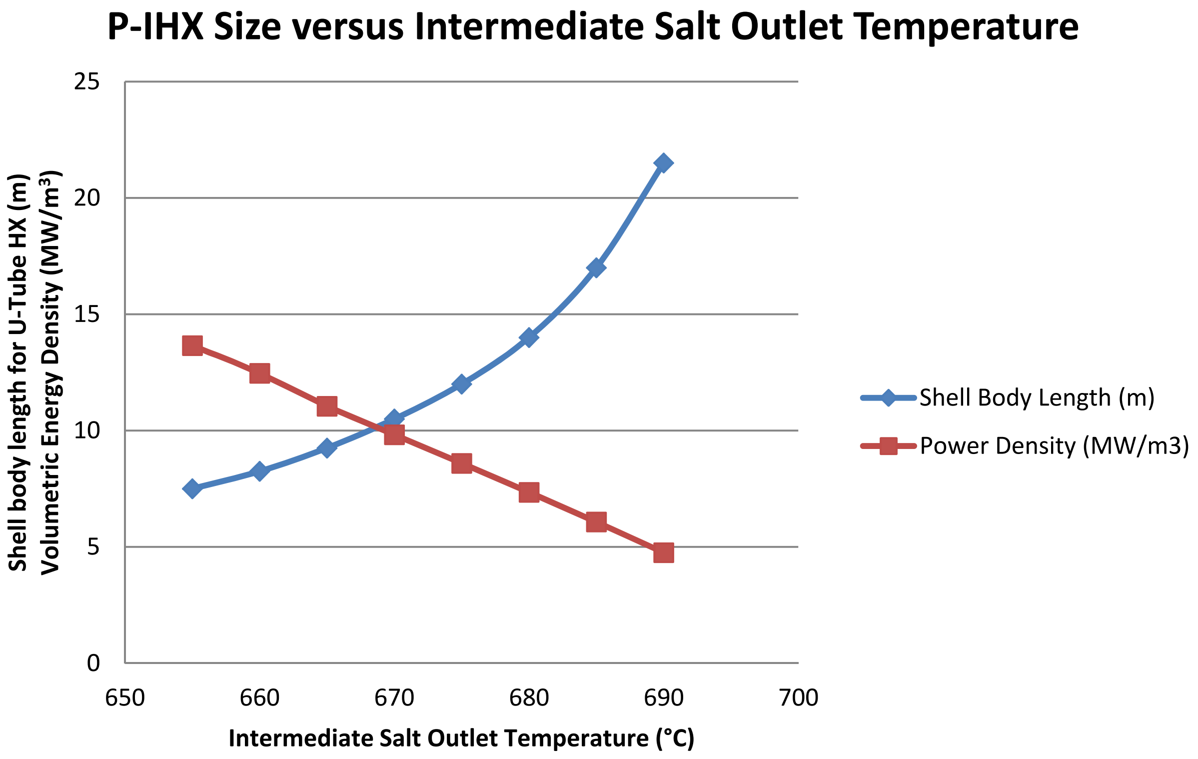

Fig. 10. Traditional U-Tube, tube-and-shell heat exchanger lengths (excluding plenums) for the P-IHX as a function of intermediate salt temperature. The temperature difference across the intermediate system side of the heat exchangers is 75°C.

For the AHTR coupled to an advanced supercritical plant, the heat transfer temperatures are listed in Table 2.

Table 2. Heat exchange parameters for the AHTR reactor coupled to a 650°C supercritical power conversion system

	P-IHX (°C)	LMTD (°C)
Primary inlet temperature	700	36
Primary outlet temperature	650	
Intermediate inlet temperature	600	
Intermediate outlet temperature	675	
	SCWG (°C)	
Intermediate inlet temperature	675	105
Intermediate outlet temperature	600	
Water inlet	320	
Supercritical water outlet	650	

Enhanced heat exchanger technologies, such as the finned tube heat exchanger, are mature technologies that could reduce the heat exchanger volume. Developers of compact heat exchanger designs are projecting heat exchange power densities of 50 MW(t)/m^3 with a LMTD of 30°C.[15] An AHTR P-IHX heat exchanger with this capacity would require an overall volume of 22.7 m^3. Assuming a characteristic dimension of 2 m on a side to accommodate 1.24-m-I.D. primary piping, the length of a P-IHX with this capacity would be approximately 5.7 m. The current baseline design of the AHTR has a 36°C LMTD across the P-IHX and should, therefore, be somewhat shorter.

5.1 HEAT EXCHANGE TO THE POWER CONVERSION SYSTEM

The equipment used to transfer the heat from the intermediate salt to the water in the power conversion system is significantly different from that used for coal-fired plants. For both systems, the water passes through parallel tube arrangements in a once-through arrangement and the heating fluid passes over the outer surface. For the AHTR, this places the intermediate system salt on the shell side of what is essentially a traditional tube-and-shell heat exchanger. Typically, tubing runs of 30 to 40 m are required in large coal-fired combustors. The combustion gases are at a higher temperature than the intermediate salt but also at orders-of-magnitude lower density. Therefore, the heat transfer coefficient on the hot side of a tube in a combustion furnace is lower and the tubes can become fouled, which is why the piping length must be so long.

The water side of the SCWG is a once-through "boiler" arrangement, although in a supercritical system no boiling actually occurs. Water enters the tubes "compressed" (at pressures above the critical pressure but below critical temperature) from the condenser and feedwater heater arrangement. As the water increases in temperature and passes into the supercritical phase, the density, specific heat, and viscosity change significantly. The heat transfer coefficient on the inside of the tubes increases during this transition phase and can peak at values ranging from 12,000 to 50,000 W/m^2-K depending on flow and tube surface conditions. Beyond the transition area, the heat transfer coefficient gradually stabilizes and decreases. Values ranging from 5000 to 4000 W/m^2-K are typical. The heat transfer coefficient for a representative pass through a coal-fired SCWG is shown in Fig. 11.[16] The average heat transfer coefficient for the data in Fig. 11 is approximately 7000 W/m^2-K, but the peak heat transfer coefficients are sensitive to tube conditions and can significantly impact actual values.

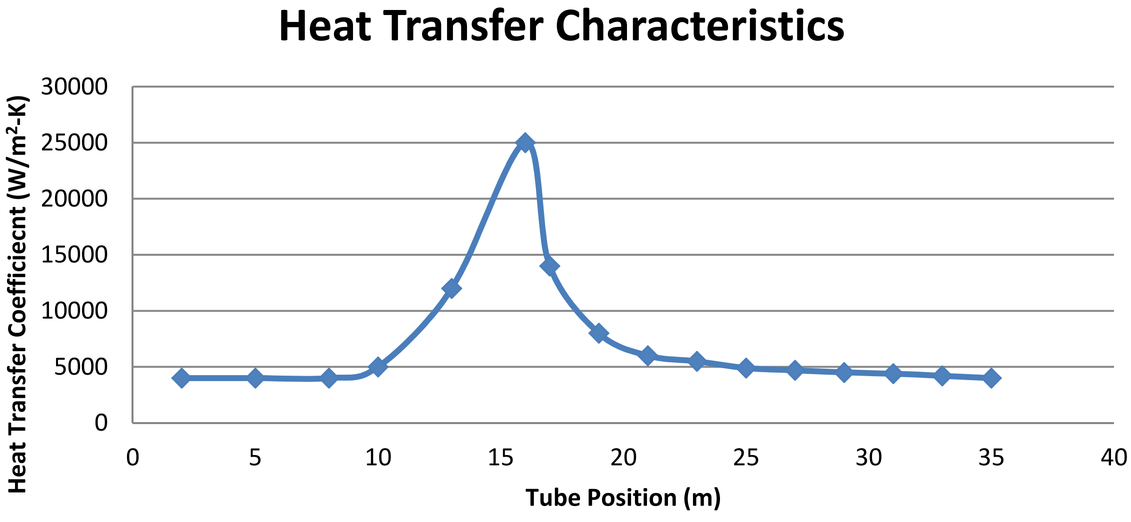

Fig. 11. Representative heat transfer coefficients along a supercritical water generator tube in a coal-fired combustion chamber.

Alloy N has been selected as the baseline design material for the interface between the intermediate salt and the supercritical water. The flow conditions on the shell side of the SCWG are currently set to be equal to those in the P-IHX. The wall thickness of the tubes, however, must be increased over those in the

P-IHX because of the high pressure on the water side. Tube wall thickness increases in going from the lower temperature supercritical cycles to the higher temperature cycles as well.

The full flow of supercritical water passes from the SCWG to the high pressure turbine (HPT) and returns to the SCWG as traditional steam. The steam is reheated, typically to the same exit temperature as the supercritical water, in a separate set of tubes. The total heat transferred into these two loops is equal to that lost by the intermediate salt, and the balance is roughly three-quarters of the heat going to the supercritical tubes and one-quarter of the heat going to the reheat tubes.

In the dual power train system, half of the heat transferred to the intermediate loop salt is transferred to each SCWG—approximately 1700 MW(t). The flow rate of supercritical water within the power conversion loop required to generate power has been estimated to be approximately 0.74 kg/s of flow per megawatt of power generated at the turbine shaft. This scaling factor was taken from the operation of existing supercritical plants. The flow rate for each 750 MW(e) power train of the AHTR is approximately 590 kg/s. The water enters the generator at 320°C in an advanced supercritical water power conversion system and exits at 650°C.

The peak temperature of the intermediate coolant is 675°C, and it loses 75°C through the SCWG. Thus, the flow rate of the intermediate salt through the shell side of the supercritical water generator is 21,600 kg/s, and the average temperature of the salt is 637.5°C. The LMTD for this arrangement is 105°C, which is considerably higher than that available in the P-IHX.

For each of the five compared plants, the heat rate was normalized to 3400 MW(t), and internal plant loads were scaled linearly with thermal power. Table 3 summarizes some of their important performance characteristics. The coal-fired plant has a significantly higher internal load than the reactor systems, and the SCWR has the lowest internal load. The increased load in the AHTR is due mainly to the primary and intermediate pumping loads.

Table 3. Comparison of heat rates, internal loads, and operating efficiencies of plants using supercritical water power systems

	BR-SCW	SCW	AHTR-SCW	AHTR-USCW	AHTR-ASCW
Heat rate (MW)	3400	3400	3400	3400	3400
Turbine inlet temperature (°C)	565	565	565	593	650
Cycle efficiency	43.2	43.2	43.2	44.7	47.1
Shaft power (MW)	1467.5	1467.5	1467.5	1518.5	1600.1
Generator output (MW)	1442.0	1442.0	1442.0	1492.2	1572.3
Transformer output to grid (MW)	1438.6	1438.6	1438.6	1488.6	1568.6
Internal loads (MW)	81.9	27.4	36.8	37.0	37.2
Net electrical production (MW)	1356.7	1411.2	1401.8	1451.6	1531.4
Net electrical efficiency	39.9	41.5	41.2	42.7	45.0

Excellent performance data exists for representative subcritical, supercritical, and ultra-supercritical fossil-fired plants.[17] The turbine inlet temperature for the supercritical case is 565°C, and the net plant efficiency is 39.9%. For the ultra-supercritical case, the turbine inlet temperature is 593°C, and the net plant efficiency is 41.4%. If the same power conversion systems are used for the AHTR and internal loads associated with air, coal, and ash handling are removed, then ~1.3% efficiency gain is expected. Thus, the AHTR with the 565°C supercritical system should operate with ~41.2% net efficiency. In going from the 565°C case to the 593°C case, another 1.5% efficiency improvement is reported. Therefore, the AHTR coupled to the ultra-supercritical power conversion system with 593°C turbine inlet temperature should have a net efficiency of ~42.7%. We do not have operational data for supercritical systems operating with turbine inlet temperatures of 650°C. However, if it is assumed that performance scales with Carnot efficiency, a performance gain of 2.3% would be expected in going from 593°C to 650°C, and the AHTR coupled to this system would have a projected net efficiency of 45.0%. This is the current AHTR baseline configuration.

In addition to the internal loads in the system, these power systems differ in the number and size of components and the temperature and pressure ratings for those components. The major system components for the AHTR and several competitive systems are listed in Table 4. The SCWR has lower internal loads than the AHTR and the fewest "major" components because the reactor coolant and the power conversion system working fluid are one in the same and there are no intermediate heat transfer components between the reactor core and the power conversion system. The trade-off with this arrangement is that all components within the reactor and power train are part of the reactor primary coolant boundary and are part of the nuclear safety envelope. Also, many of them operate at high pressure and temperature, requiring them to be thick-walled and expensive to fabricate and qualify; however, they do not have to be made of the more expensive nickel-based alloys.

Table 4. Number of major reactor system components in the compared power systems

	Salt-to-salt heat exchanger	Reactor system	MFW pump	Primary pump	Intermediate pump	Salt-to-water heat exchanger	Fuel handling loads
Fossil plant	0	0	1	0	0	0	1
Three-loop LWR	0	1	1	3 (water)	0	1	0
SCWR	0	1	1	0	0	0	0
AHTR	3	1	1	3 (salt)	3 (salt)	2	0

The AHTR, like the SCWR, has steam-driven MFW pumps. These pumps would have performance characteristics similar to those of the SCWR, but they would not be primary reactor system components. They should, therefore, be less expensive. The AHTR will have electrically driven primary salt and intermediate salt pumps. The primary loop piping and pumps are not nuclear safety components on the AHTR because they are not necessary to prevent core damage or contain radionuclides. These components also operate at low pressure. The intermediate loop is also a low-pressure, nonsafety system. Both the primary and intermediate systems are made from Alloy N.

Table 5 lists the major components of the AHTR power system, and Fig. 12 shows a simplified schematic of the major loops. The AHTR has six salt pumps, three salt-to-salt low pressure heat exchangers, and three salt-to water supercritical water generators. These components represent technology development activities.

Table 5. AHTR major system components and performance parameters

	Hot side fluid/flow rate (kg/s)	Cold side fluid/flow rate (kg/s)	Peak temperature (°C)	Peak pressure (MPa)
Reactor vessel	28,500	NA	700	~0.5
Primary piping	9,500	NA	700	~0.5
Primary heat exchanger	9,500	14,400	700	~0.5
Primary pumps	9,500	NA	650	~0.5
Intermediate loop piping	14,400	NA	675	~0.5
Intermediate loop pumps	14,400	NA	600	~0.5
Supercritical water generator and reheater	21,600 (shell side)	~592	650	~31
Reheater tubes	common with above	~592	650	~8.5
Cooling tower makeup	NA	~1000	44	~0.3

5.2 WASTE HEAT REJECTION

The baseline AHTR waste heat rejection system is hybrid cooling, in which the condensers are cooled with water from a local source, and the majority of the waste heat is rejected to the atmosphere using natural draft cooling towers. Hybrid cooling allows for decreased water usage and minimizes the temperature at which water is discharged back to the local water supply. For the AHTR, 900 kg/s (14,850 GPM) to 1100 kg/s (18,150 GPM) of water is evaporated in total from the cooling towers.

Traditional once-through water flow can be used at locations where the water supply is more plentiful and makeup water could be pumped to drier sites for use in cooling towers, as is done for the Palo Verde Nuclear Generation Station in Arizona.

Forsberg et al.[18] address the possibility of utilizing dry cooling for AHTRs. The key features are the need to reject only about half of the waste heat per unit of electricity generated compared to an LWR and the increased operating temperature. These features open the possibility of waste heat rejection using dry cooling technology without an especially severe economic penalty at locations that do not have sufficient water for wet or hybrid cooling. The available temperature for waste heat rejection is an important determinant of plant operating efficiency and, while dry cooling would not result in efficiencies comparable to wet cooling systems, the penalty may be small enough to open up the number of available plant locations. This may be particularly true if the AHTR is used to power an open-air Brayton system.

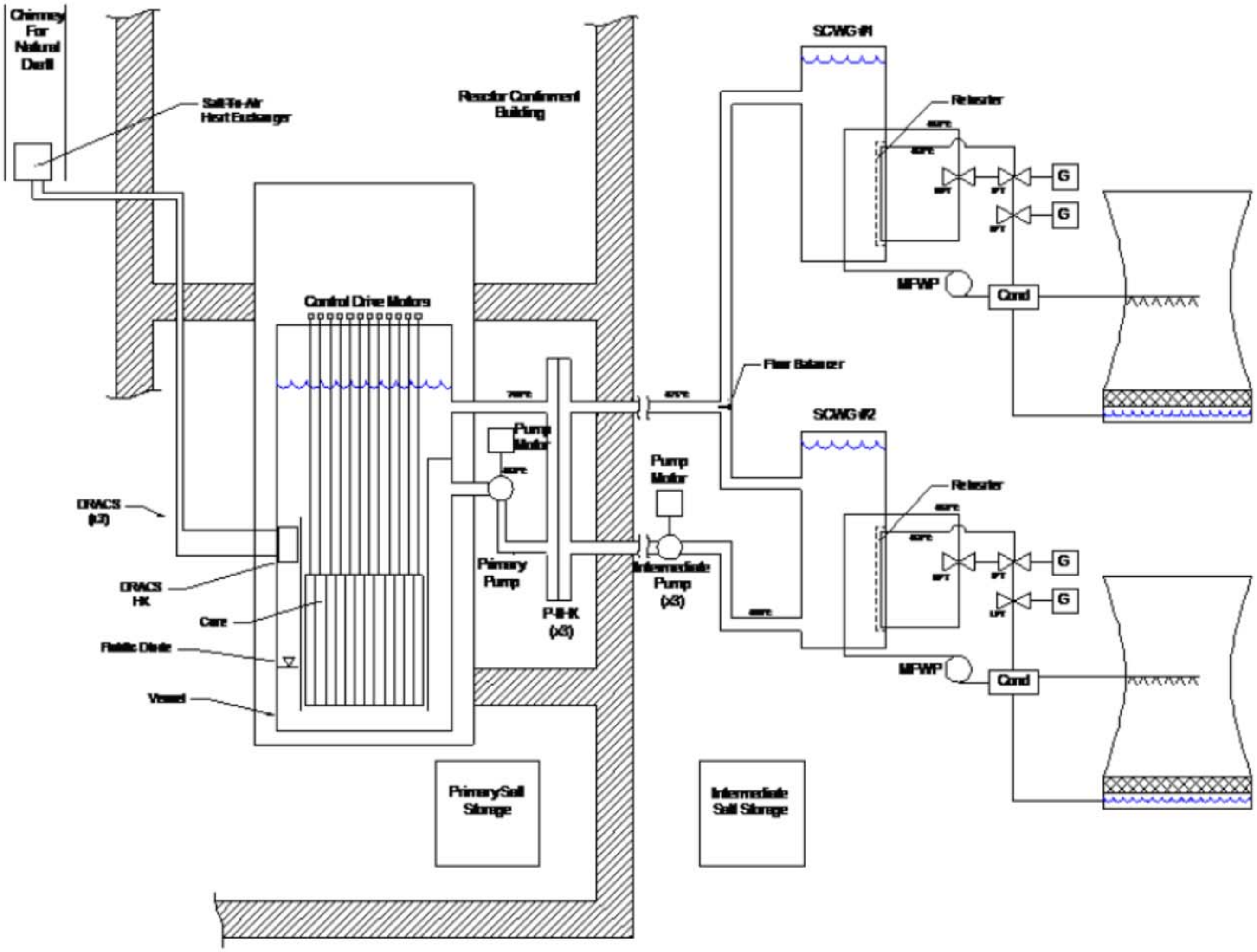

Fig. 12. Schematic of the flow loops of the 1531 MW(e) AHTR with hybrid heat rejection.

6. AHTR SITE LAYOUT

Figure 13 shows a representation of the functional areas of the AHTR. These areas are similar to that of a traditional LWR with the addition of facilities to handle and maintain the salts. Power conversion, people, and services share commonality with other reactors. Consequently, parking lots, cooling towers, switchyards, and coolant water intake structures should look no different from those of other plants of comparable size. The fuel services for the AHTR may differ if some form of online refueling were adopted, but the plant operators will have to contend with storage and loading of fresh fuel and removal, storage, and disposal of spent fuel just like other reactors even if not. The salt systems are perhaps the biggest differentiators between the AHTR and other reactor systems. The closest analogy in LWR operation is water chemistry control, but with salts, thermal management is an additional requirement.

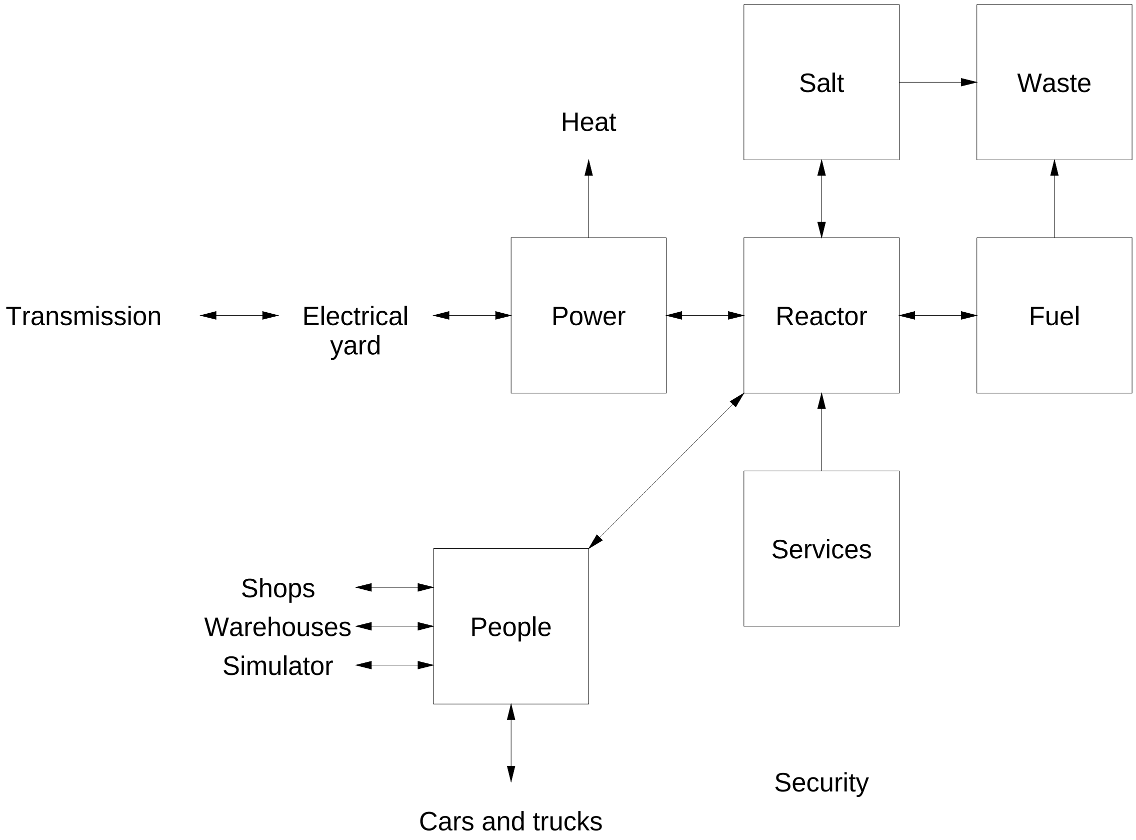

Fig. 13. Functional areas of an AHTR generating station.

In a fossil-fired supercritical water plant, the coal pulverizers, air handling equipment, combustion chambers, and supercritical water generation and reheat equipment are contained within massive structures at the site. For the AHTR, this equipment is removed or replaced with smaller salt-to-water tube-and-shell heat exchangers. The SCWGs and the steam condensing system could potentially be located with the turbine and generating equipment within a common building. Thus, the AHTR would have two main large buildings—the Reactor Containment Building (RCB) and the Power Conversion Building (PCB). The AHTR intermediate system is used to connect the primary system to the power conversion system. The distance between these systems, ~100 m, determines the distance between the two buildings.

The intermediate system begins in the RCB at the P-IHX. Intermediate salt transport piping and perhaps some instrumentation are located within the tunnel between RCB and the PCB. The balance of the intermediate loop, including its salt storage equipment, is co-located with the supercritical water generators, turbines and generators, and condensers in the PCB.

The reactor containment building will house the vessel, three P-IHXs, the piping and pumps of the three primary loops, and the salt storage tanks, as shown in Fig. 14. The AHTR core and reactor vessel are large compared to that of traditional LWRs. This requires more space to house the vessel and additional floor space to handle the large top hatch during maintenance. Thus, the containment building is comparable in size to that of an LWR, but it will have thinner walls because of reduced pressure requirements. The 18-m-tall reactor vessel is contained mostly below grade, and the primary salt storage vessel is below the vessel. Therefore, the excavation of the AHTR RCB runs deeper than that of a traditional LWR. Depending on the site location, the reactor building may also be placed on a seismic isolation structure.

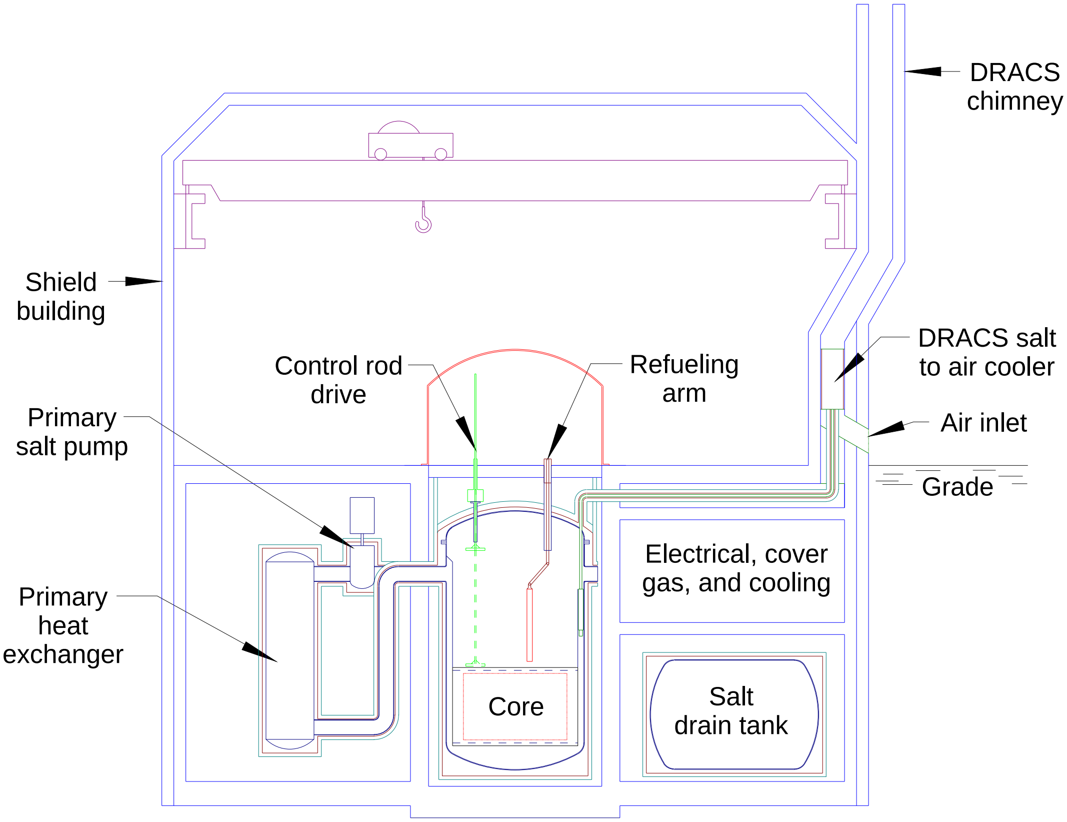

Fig. 14. Schematic showing the reactor pressure vessel and a P-IHX within the containment structure. The DRACS and the intermediate system piping (not shown) penetrate containment.

The pipes between the P-IHX and the pumps and between the pumps and the vessel have an inner diameter of 1.24 m. These pipes will need to expand and contract with changing temperature. The heat exchangers and pumps will either need to move to accommodate stresses in the piping or the piping will have to be bent to accommodate them. The size of the required bends would be large for a primary reactor system operating between ambient temperature and 700°C.

An overhead crane sufficient to lift the reactor vessel top hatch will be required in the reactor containment building, and sufficient floor space to store the hatch is needed as well. The main working floor in the reactor building is currently assumed to be level with the reactor top hatch. The top hatch is lifted to remove it and the attached control rod drive systems from the reactor vessel. The hatch and the drive assemblies are stored on an elevated working platform above the main working floor away from the open reactor vessel.

A significant difference in the AHTR reactor containment building and that of an LWR is the elimination of systems to mitigate internal pressure. This is because the reactor coolant is a low-pressure salt, and the amount of water permitted inside the reactor containment is limited by design. A reactor containment cooling system (RCCS) will be required to keep the containment concrete surrounding the vessel below boiling temperature during normal operation. As it is undesirable to introduce a water-based cooling system into the primary containment of an AHTR, either a heat-pipe system to transfer heat into the surrounding soil or a gas-based cooling system will be employed.

A complete loss of forced primary coolant flow will result in the passive DRACS systems actively removing excess heat and transferring it to the atmosphere. The DRACS salt-to-air heat exchangers are outside the containment building, and containment penetrations for them must be provided.

While the AHTR reactor system is unique, much of the remaining infrastructure is consistent with other plant designs. The basic needs are similar: new and used fuel handling and storage, coolant storage, and chemistry control, etc. The buildings and structures that complete the site would potentially include the following:

1. Main gate guard house,
2. Security fence,
3. Security building,
4. Administration and simulator building,
5. Control building,
6. Essential switchgear building,
7. Control room emergency air intake structures,
8. Reactor service building,
9. Fuel services building,
10. Plant services building,
11. Radioactive waste process building,
12. Condensate storage tank,
13. Circulating water and service water pump house,
14. Main cooling towers,
15. Warehouse and shop building,
16. Makeup water intake structure,
17. Demineralized water storage tank,
18. Diesel generator building *(nonsafety related)*,
19. Makeup water pre-treatment building,
20. Technical support building,
21. Fire pump house,
22. Nonessential switchgear building,
23. Transformer yard,
24. Switchyard,

25. Waste water treatment buildings and holding basins, and
26. Rail lines.

The AHTR plant site is shown notionally in Fig. 15.

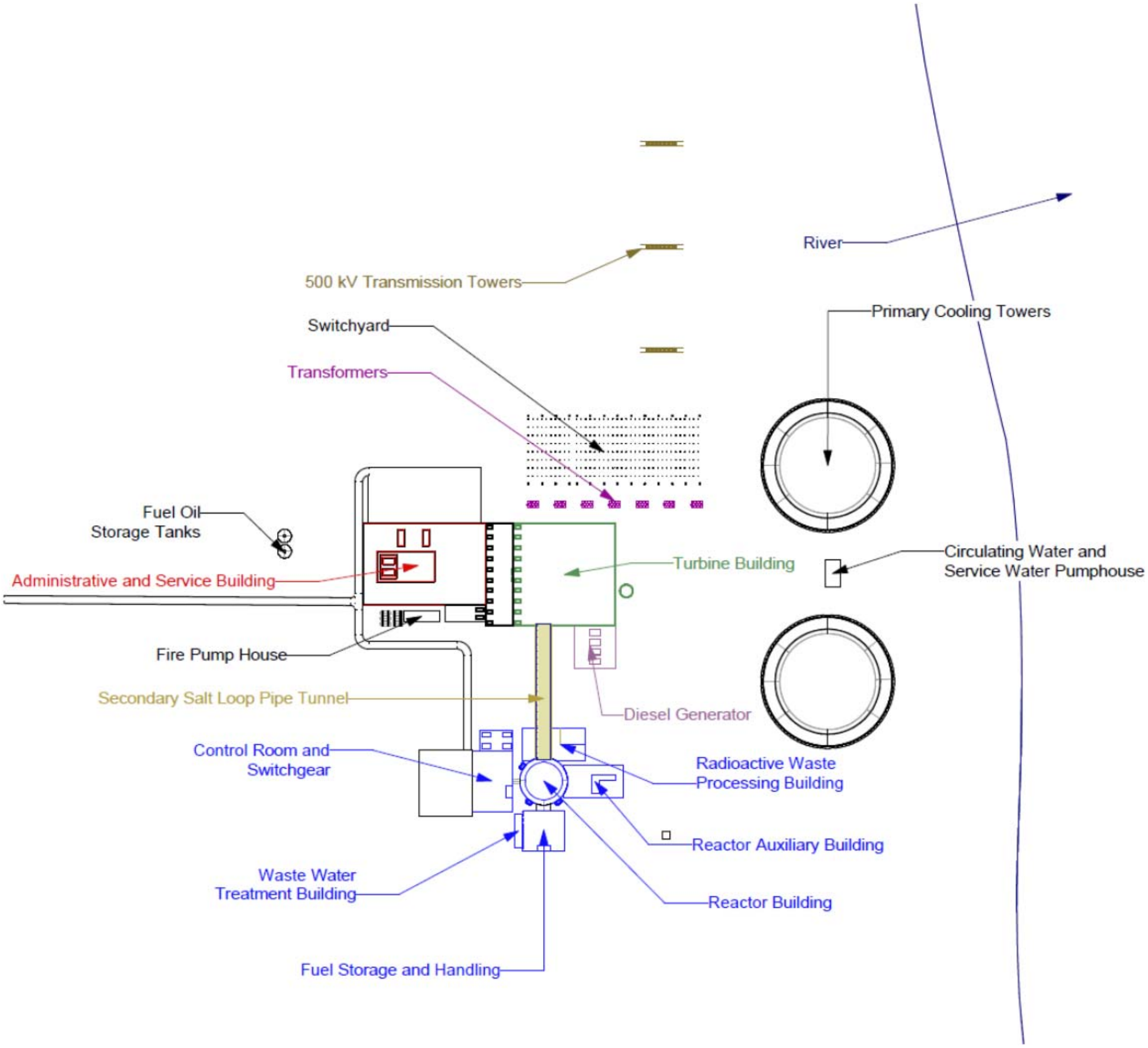

Fig. 15. Schematic of AHTR site layout.

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7. SYSTEM ANALYSIS

7.1 TRANSIENT RESPONSE TO ACCIDENT SCENARIOS

The plausible list of transient scenarios and design basis accidents for the AHTR system has not been rigorously investigated, and the probability of initiating events and the severity of the resulting consequences are currently unknown. A meaningful accident progression analysis will be completed as the design evolves and matures. In the absence of this information, some transient scenarios have been proposed for consideration. Reactivity insertion events and individual primary and intermediate pump failures will be studied. The primary and intermediate pumps are perhaps the components that would initiate more frequent and significant reactor transients. In the power conversion system, the loss of a turbine or generator is a plausible transient initiator. A more likely scenario is a loss-of-offsite-power (LOOP) transient impacting the entire plant.

A dynamic system model is under development to run transients related to these event initiators. The AHTR transient model is currently a Mathlab™ Simulink™ based model that tracks heat and fluid flows within the system. The reactor core is modeled as 24 separate nodes with fixed radial and axial power profiles imposed on them. Three inner zones are fueled regions, and all of the 3400 MW(t) is assumed to be generated within the 18 nodes comprising those zones. The outer zone represents an unfueled blanket region. Each zone is made up of a fixed number of fuel bundles and associated coolant channels.

Each radial zone is modeled as a series of six axial nodes. The outlet temperature of a single channel in each radial zone is calculated, and the mixed temperature of the coolant in the upper plenum is calculated based on the number of channels modeled in each zone.

The reactor's negative temperature feedback is modeled using a point kinetics model with the temperature of a single central fuel channel used as temperature feedback. The negative temperature coefficient of reactivity, coupled with the fact that the mass of the fuel, vessel, and coolant is substantial, leads to inherently long response times for credible transients that do not include a sudden loss of coolant. (The vessel has no penetrations below the coolant inlet and outlet piping, therefore accidents in which the core or the DRACS heat exchangers become uncovered are thought to be incredible.) Because of long response times and large fuel temperature safety margins, reactor transient scenarios that quickly threaten fuel integrity are difficult to postulate. It is more likely that transient scenarios in which the temperature slowly increases over periods of several days would be of primary concern. The AHTR is designed to be a "walk away" reactor that requires no action for several days or perhaps weeks during even severe reactor accident scenarios.

The primary and intermediate loops are modeled as counterflow tube-and-shell heat exchangers. Simple pressure drop correlations are used to calculate the pressure drop across the heat exchangers and the reactor core as a function of coolant flow. The pressure drops in the 1.24-m-I.D. primary and intermediate piping are ignored. The time lags associated with the primary piping lengths are ignored. The lag associated with the 100-m lengths of intermediate salt piping between the RCB and the PCB is not currently modeled, but it is planned to include this feature in a future model revision. The mixing of the intermediate salt into the common hot and cold manifold is modeled similarly to that done for the reactor upper and lower plenums, but the DRACS and fluidic diodes between those plenums need to be added to the model.

Each power conversion system is modeled as a supercritical water generator, three turbines, a condenser, and a generator. The complicated flow pattern of the feedwater reheat system is not yet modeled. The efficiencies of the turbines are artificially adjusted to yield the correct total power when the inlet temperature and pressure drop across the turbine are at nominal operating conditions. This simplified modeling is considered to be sufficient because the focus of the model is currently the temperature and pressure response within the primary and intermediate systems.

The system model will be transitioned in 2012 to DYMOLA, a modeling platform based on the software Modelica. The fidelity of the modeling of the power conversion system will be evaluated during this transition, and the fluidic diodes and DRACS will be incorporated into the model.

8. ECONOMICS

8.1 METHODOLOGY

8.1.1 Purpose and Approach

The purpose of this task is to develop a model that can be used to assess the cost of electricity produced by the AHTR power plant. The model is to be a user-friendly system that can be improved incrementally as AHTR-related studies are completed and as more detailed design concepts and operations data become available. The use of an evolving economic model will serve as an aid for using cost to guide AHTR design decisions. Accomplishments this fiscal year were focused on building the structure of the model and not on quantitative results. In particular, work this year addressed identification of a comprehensive cost data base that will support comparative estimating techniques for capital cost and performance of the AHTR.

The approach taken in the development of the AHTR economics model addresses several goals. The methodology used ensures that the costs are comprehensive in scope. Costs are based, to the extent practical, on actual experience or credibly detailed design or development work. Where assumptions are necessary, the use of assumptions is documented and, if practical, based on documented rationale. 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 (“nth 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.

The costs address the construction and operation of the AHTR power plant, as described in this report and the companion core and refueling studies design report.6 The reference core used for this study utilizes uranium fuel, enriched to 19.75 wt % ^{235}U. The entire set of fuel assemblies are replaced once every 2 years. Only a once-through fuel cycle is considered.

Near the end of this study an alternate core was identified. This core uses uranium enriched to 9% ^{235}U, and half of the fuel assemblies are replaced every 6 months. Because of a significant difference in fuel cycle cost, the AHTR utilizing this core is evaluated as a separate case.

To ensure a comprehensive evaluation and to facilitate comparison with similar efforts, an established cost code of accounts is used to structure this 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).[19] It was initially developed for use by DOE and its predecessor agencies in the early 1970s and evolved into a system now used by the DOE Office of Nuclear Energy (DOE-NE) and, in similar form, by the International Atomic Energy Agency.

Economic modeling is performed using the international EMWG Generation IV Excel Calculation of Nuclear Systems (G4-ECONS)[20] 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)[21] 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 pressurized-water reactors (PWRs); at about 3400 MW, 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. Data is escalated to January 2011 for this evaluation.

Detailed cost data for the better experience plants, taken from the final update of the EEDB,[22,23] is used to establish a reference for direct and indirect capital cost. Comparative techniques are then used to adjust this cost to represent the AHTR concept. The cost code of accounts used by the EMWG is based on the system used in the EEDB, with a few exceptions. Second-level accounts from the EEDB are modified to reflect the EMWG accounts, but, in some cases, lower level accounts are left in the EEDB format for convenience. The full set of digits is carried in numbers to facilitate checking (avoiding round-off errors), but accuracy beyond two digits is not implied.

Cost data from the median experience data set and another EEDB case that evaluates improvements in PWR design and construction techniques were also considered. In general, the increased cost seen in the median experience case offers insight into aspects of reactor design and construction that have led to cost overruns. Conversely, the improved PWR case offers suggestions as to how improved design and construction techniques can be used to lower reactor construction cost.

Preliminary analyses of AHTR refueling and maintenance schedules are used to predict planned downtime. At this time, a plant-specific evaluation of most operating and fuel costs has not been performed. Data reflecting existing cases used by the EMWG as example applications in the G4-ECONS spreadsheet are escalated for use with the AHTR. In particular, an example case describing a large PWR, based on the System 80+ design, has proven useful for this effort. A once-through fuel cycle is presumed. Development of an appropriate AHTR fuel model, identification of operating staff levels, and assessment of other operating and maintenance costs are recommended as future tasks.

Special cases of materials costs, such as ^{7}Li enrichment and BeF production needed for the primary FLiBe salt, are entered in the model as capital cost. A discussion of the basis for the values entered and the necessary tasks to develop improved cost values is also given.

The result of this task is a structured comparative evaluation that can be used to estimate the levelized electricity cost. Again, work performed this fiscal year focused on developing a well-documented model that will be expanded in the future, and the actual LUEC values should not be considered quantitative results. However, trends identified in this initial effort are appropriate for prioritizing future work. Digits carried in the tables to facilitate cross checking do not reflect the accuracy of the analysis.

8.1.2 Energy Economic Data Base

The EEDB was developed for the Nuclear Energy Cost Data Base Program of DOE-NE to provide a transparent, detailed cost data base for use in making comparisons between different nuclear and nonnuclear (primarily coal) power generating systems. United Engineers and Constructors, Inc., an architect-engineering firm with experience in the design and construction of several commercial light-water power reactors, performed the assessments under contract to ORNL. Actual cost data from a number of power reactor projects was collected and grouped consistent with reactor type and schedule/cost experience, averaged, and re-allocated to a standardized cost code of accounts. The result is a detailed cost data base that no longer reflects the proprietary cost data of an individual plant.

The original EEDB was assembled in 1978, based on earlier efforts beginning around 1970. A series of updates were prepared, with the final, ninth, update issued in 1988.[22] This final update was expressed in January 1, 1987, dollars. The final update included costs for a typical Westinghouse four-loop plant, designated PWR12, with a core thermal power of 3417 MW (Ref. 23) and net electrical power to the generator step-up transformer of 1144 MW. The core thermal power is very close to the 3400 MW used for the AHTR design, and, thus, the PWR12 reflects typical building and equipment sizes that are useful for comparison to the AHTR concept.

Many nuclear plants that were constructed during the 1970s and 1980s experienced protracted delays and cost increases. Data collected for the EEDB was grouped into plants with median and better experience in terms of meeting cost and schedule objectives. The better experience plants are more likely to represent expected cost performance. The median experience is useful to show areas where cost increases have occurred. Detailed data reports are available for both the EEDB better experience (BE) and median experience (ME) cases. Data from the BE reports have been converted into a detailed Excel spreadsheet, allowing generation of tables that identify cost by structure or major system.

A Technical Reference Book[23] lists the basic plant parameters for the PWR12 and other concepts evaluated in the ninth update. Reports also include supporting bills of material and labor summaries for many of the PWR12 BE and ME accounts.

A number of estimates for alternative reactor concepts were developed and documented in the EEDB reports. These were not always full bottom-up estimates but were adjustments of the data drawn from actual experience, such as PWR12. In particular, an improved PWR12 case was developed to assess the impact of improved safety and construction concepts. Only summary data and the discussion in the Technical Reference Book are available for the improved PWR12 case.

Table 6 summarizes the total cost for the better experience, median experience, and improved PWR cases as documented in January 1, 1987, dollars.

Table 6. Total costs from EEDB BE, ME, and improved PWR cases (1987 dollars)

Account	**Account description**	**PWR12 BE total cost**	**PWR12 ME total cost**	**Improved PWR12 total cost**
211	Yardwork	24,992,519	32,518,044	25,641,072
212	Reactor containment building	64,836,041	100,710,559	62,341,201
213	Turbine room and heater bay	23,152,330	37,872,452	24,016,964
214	Security building	1,361,955	1,914,689	1,312,224
215	Primary auxiliary building and tunnels	18,472,145	27,163,800	19,114,786
216	Waste processing building	14,367,318	22,378,826	13,883,581
217	Fuel storage building	9,879,103	13,030,890	9,603,975
218	Other structures	43,682,687	67,910,574	42,196,228
21	*Structures and improvements subtotal*	*200,744,098*	*303,499,834*	*198,110,031*
220A	Nuclear steam supply (NSSS)	179,340,000	179,340,000	173,959,800
221	Reactor equipment	10,516,879	11,191,741	10,304,492
222	Main heat transfer transport system	9,898,419	20,509,935	9,526,332
223	Safeguards system	12,416,260	24,389,226	11,541,651
224	Radwaste processing	20,942,407	30,865,919	19,885,175
225	Fuel handling and storage	3,167,160	4,248,375	3,103,137
226	Other reactor plant equipment	37,759,511	67,363,994	33,544,955
227	Reactor instrumentation and control	21,555,270	23,607,427	21,329,518
228	Reactor plant miscellaneous items	7,452,275	9,123,977	7,218,621
22	*Reactor plant equipment*	*303,048,181*	*370,640,594*	*290,413,681*
231	Turbine generator	133,984,273	137,755,009	131,357,864
233	Condensing systems	28,981,986	38,244,984	25,749,941
234	Feedwater heating system	23,588,801	32,713,168	19,800,879
235	Other turbine plant equipment	22,323,194	40,286,456	18,690,726
236	Instrumentation and control	6,854,212	7,980,222	6,216,009
237	Turbine plant miscellaneous items	8,045,900	9,463,985	7,795,486
23	*Turbine plant equipment*	*223,778,366*	*266,443,824*	*209,610,905*

Table 6. Total costs from EEDB BE, ME, and improved PWR cases (1987 dollars) (continued)

Account	Account description	PWR12 BE total cost	PWR12 ME total cost	Improved PWR12 total cost
241	Switchgear	11,946,283	11,946,368	11,225,531
242	Station service equipment	20,163,388	20,318,526	19,039,791
243	Switchboards	2,048,898	2,091,797	1,858,720
244	Protective equipment	4,261,386	4,975,308	4,308,153
245	Electric structure and wiring contnr.	22,301,683	46,674,779	12,419,117
246	Power and control wiring	20,601,086	33,229,737	13,390,443
24	*Electric plant equipment*	*81,322,724*	*119,236,515*	*62,241,755*
251	Transportation and lifting equipment	5,993,830	6,360,616	6,607,780
252	Air, water and steam service systems	28,725,654	51,096,666	26,656,904
253	Communications equipment	6,415,046	7,272,235	6,139,079
254	Furnishings and fixtures	2,735,984	2,901,892	2,637,261
255	Waste water treatment equipment	2,831,384	3,024,845	2,577,283
25	*Miscellaneous plant equipment subtotal*	*46,701,898*	*70,656,254*	*44,618,307*
261	Structures	4,332,720	5,726,470	4,197,560
262	Mechanical equipment	44,648,245	50,886,018	43,643,719
26	*Main condenser heat rejection system*	*48,980,965*	*56,612,488*	*47,841,279*
	Total direct costs	**904,576,232**	**1,187,089,509**	**852,835,958**
91	Construction services	226,915,000	411,147,000	185,639,000
92	Engineering and home office services	212,742,000	487,254,000	90,716,000
93	Field supervision and field office services	111,400,000	443,845,000	79,262,000
	Total indirect costs	**551,057,000**	**1,342,246,000**	**355,617,000**
	Total Base Cost	**1,455,633,232**	**2,529,335,509**	**1,208,452,958**

8.1.3 Escalation and Cost Indices

To use the EEDB as a basis for this current study, costs need to be expressed in current dollars. A number of cost indices are available in the public domain, including the Civil Works Construction Cost Index maintained by the U.S. Army Corps of Engineers.[24] Taking a ratio of the composite index for January 2011 to the index for January 1987 yields a value of 2.07.

Several proprietary services provide more specific data for nuclear power plants, some with different indices for different parts of the country. Several indirect references to the commonly used proprietary Handy-Whitman index suggest a factor slightly over the Corps of Engineers value. The IHS-CERA Power Plant Capital Cost index, including nuclear, shows a sharp increase in cost during the mid-2000s (see http://www.ihsindexes.com/). After using the Corps of Engineers index to the IHS-CERA base year of 2000, the IHS-CERA PCCI from 2000 through 2011 would give an overall factor of 3.02. The index peaks in 2007, then declines with the recent recession, and again approaches its peak in 2011.

For this study, an escalation factor of 2.4 was selected. This value trends closer to the Corps of Engineers and Handy-Whitman guidance but does take into consideration the IHS-CERA analyses. Table 7 presents the cost for the better experience, median experience, and improved PWR escalated to January 1, 2011, dollars.

Table 7. Total costs from EEDB BE, ME, and improved PWR cases (2011 dollars)

Account	Account Description	PWR12 BE Total cost	PWR12 ME Total cost	Improved PWR12 Total cost
211	Yardwork	59,982,046	78,043,306	61,538,573
212	Reactor containment building	155,606,498	241,705,342	149,618,882
213	Turbine room and heater bay	55,565,592	90,893,885	57,640,714
214	Security building	3,268,692	4,595,254	3,149,338
215	Primary auxiliary building and tunnels	44,333,148	65,193,120	45,875,486
216	Waste processing building	34,481,563	53,709,182	33,320,594
217	Fuel storage building	23,709,847	31,274,136	23,049,540
218	Other structures	104,838,449	162,985,378	101,270,947
21	*Structures and improvements subtotal*	*481,785,835*	*728,399,602*	*475,464,074*
220A	Nuclear steam supply (NSSS)	430,416,000	430,416,000	417,503,520
221	Reactor equipment	25,240,510	26,860,178	24,730,781
222	Main heat transfer transport system	23,756,206	49,223,844	22,863,197
223	Safeguards system	29,799,024	58,534,142	27,699,962
224	Radwaste processing	50,261,777	74,078,206	47,724,420
225	Fuel handling and storage	7,601,184	10,196,100	7,447,529
226	Other reactor plant equipment	90,622,826	161,673,586	80,507,892
227	Reactor instrumentation and control	51,732,648	56,657,825	51,190,843
228	Reactor plant miscellaneous items	17,885,460	21,897,545	17,324,690
22	*Reactor plant equipment*	*727,315,634*	*889,537,426*	*696,992,834*
231	Turbine generator	321,562,255	330,612,022	315,258,874
233	Condensing systems	69,556,766	91,787,962	61,799,858
234	Feedwater heating system	56,613,122	78,511,603	47,522,110
235	Other turbine plant equipment	53,575,666	96,687,494	44,857,742
236	Instrumentation and control	16,450,109	19,152,533	14,918,422
237	Turbine plant miscellaneous items	19,310,160	22,713,564	18,709,166
23	*Turbine plant equipment*	*537,068,078*	*639,465,178*	*503,066,172*
241	Switchgear	28,671,079	28,671,283	26,941,274
242	Station service equipment	48,392,131	48,764,462	45,695,498
243	Switchboards	4,917,355	5,020,313	4,460,928
244	Protective equipment	10,227,326	11,940,739	10,339,567
245	Electric structure and wiring	53,524,039	112,019,470	29,805,881
246	Power and control wiring	49,442,606	79,751,369	32,137,063
24	*Electric plant equipment*	*195,174,538*	*286,167,636*	*149,380,212*
251	Transportation and lifting equipment	14,385,192	15,265,478	15,858,672
252	Air, water and steam service systems	68,941,570	122,631,998	63,976,570
253	Communications equipment	15,396,110	17,453,364	14,733,790
254	Furnishings and fixtures	6,566,362	6,964,541	6,329,426
255	Waste water treatment equipment	6,795,322	7,259,628	6,185,479
25	*Miscellaneous plant equipment subtotal*	*112,084,555*	*169,575,010*	*107,083,937*

Table 7. Total costs from EEDB BE, ME, and improved PWR cases (2011 dollars) (continued)

Account	Account Description	PWR12 BE Total cost	PWR12 ME Total cost	Improved PWR12 Total cost
261	Structures	10,398,528	13,743,528	10,074,144
262	Mechanical equipment	107,155,788	122,126,443	104,744,926
26	*Main condenser heat rejection system*	*117,554,316*	*135,869,971*	*114,819,070*
	Total direct costs	**2,170,982,957**	**2,849,014,822**	**2,046,806,299**
91	Construction services	544,596,000	986,752,800	445,533,600
92	Engineering and home office services	510,580,800	1,169,409,600	217,718,400
93	Field supervision and field office services	267,360,000	1,065,228,000	190,228,800
	Total indirect costs	**1,322,536,800**	**3,221,390,400**	**853,480,800**
	Total Base Cost	**3,493,519,757**	**6,070,405,222**	**2,900,287,099**

8.1.4 G4-ECONS

Part of the international Generation IV Roadmap Project involved the creation of the EMWG, tasked with developing a standardized cost estimating protocol to provide decision makers with a credible basis to assess and compare future nuclear energy systems, taking into account a robust evaluation of their economic viability. The Cost Estimating Guidelines for Generation IV Nuclear Energy Systems[19] provide a uniform code of accounts and cost estimating guidelines to be used in developing cost estimates for advanced nuclear energy systems. This cost code of accounts is in many respects the same as used in the EEDB. Terminology is updated, and the code of accounts for indirect capital cost has been moved and expanded.

As part of its task, the EMWG developed the Microsoft Excel-based G4-ECONS model, described in detail in the *G4-ECONS User's Manual*.[20] The model was constructed with relatively simple economic algorithms and was designed to be transparent with all algorithms and cell contents visible to the user.

The model consists of several sections, each of which computes a component of the LUEC. The four components are (1) recovery of capital, including financing costs; (2) nonfuel operations and maintenance costs; (3) fuel cycle costs; and (4) funding of decommissioning via an escrow fund. All costs are calculated on a constant-dollar levelized annual cost basis, and it is assumed that capital and financing costs are repaid over the operating life of the plant. Annual electrical production is also considered at a constant value over the life of the plant, based on an average lifetime capacity factor.

The G4-ECONS model has been tested on a number of systems for which cost input could be obtained. One of these model cases is for the System 80+ PWR, a reactor similar to the PWR12 used in the EEDB evaluation. This provided a basis for comparison to the PWR12 BE data used as a starting point for estimating AHTR costs. In cases where relevant data for operations and maintenance models are not yet available, data from the System 80+ example has been carried forward so a complete input set is available and initial output data could be obtained.

8.1.5 Molten Salt Breeder Reactor Evaluations

Starting with the Aircraft Reactor Experiment, which operated in 1954, ORNL developed a series of reactors fueled and cooled with liquid fluoride salt. The Molten Salt Reactor Experiment operated at ORNL from 1965 through 1969, and numerous component and chemistry test loops were built and operated. In 1971, ORNL prepared *Conceptual Design Study of a Single-Fluid Molten Salt Breeder Reactor* (ORNL-4541),[25] which included a cost estimate prepared using a similar methodology as this report. An early 1970 cost model for a large PWR was used as the basis for a comparative cost estimate. It was demonstrated that the cost of a fluid-fueled Molten Salt Breeder Reactor (MSBR) would be competitive with the large light-water power reactors just entering service at that time.

Although the PWR cost basis has evolved over the years and the MSBR was a fluid-fueled reactor, not a solid fuel, salt-cooled reactor like the AHTR, there is much useful information in this study. In particular, techniques for comparing costs of reactor vessels and other major components are documented.

A review of ORNL-4541 was recently performed at ORNL[26] as an aid to building a contemporary fuel cycle model for a fluid-fueled fluoride salt reactor. This study may also provide useful guidance in the development of a fuel cycle model for the AHTR.

8.1.6 Other Fluoride-Salt-Cooled High-Temperature Reactor Concepts

A number of other conceptual designs of a fluoride-salt-cooled reactor have been developed recently at locations including ORNL and the University of California–Berkeley (UC–Berkeley). Several reports document early conceptual studies of reactors with solid, graphite-based fuel and fluoride-salt heat transfer fluids.[3,5] One of these, ORNL/TM-2004/104, includes a comparison-based estimate relative to the Gas-Turbine Modular High Temperature Reactor (GT-MHR) and the S-PRISM sodium-cooled reactor.

Work on the development of a pebble-bed, fluoride-salt-cooled reactor continues at UC-Berkeley. Various cost studies, based on student projects, have been prepared for this concept.

8.1.7 Liquid-Metal Reactors

Many features are shared by solid-fuel, fluoride-salt-cooled reactors and liquid-metal-cooled reactors (LMRs). These include passive methods for decay heat removal, use of intermediate coolant circuits, and the need to preheat systems before introducing the coolant fluids.

A number of LMRs have been designed, and some have been built. In the United States, a number of early sodium-cooled demonstration reactors were built and operated, and a prototype 94 MW(e) power reactor was built at the Fermi site in Michigan. Later, the Fast Flux Test Facility was built and operated at the Hanford site. The Clinch River Breeder Reactor (CRBR) was designed, and site preparation was initiated before it was cancelled in 1982. Sodium-cooled reactors have been built and operated in other countries, including France, India, and Russia.

Considerable information is available on the CRBR design, which has been used as reference information for this study. However, a detailed cost plan has not been located.

More recent studies include the Advanced Liquid-Metal Reactor (ALMR) and the General Electric PRISM concept. These reactor designs are mainly conceptual in nature, and only summary-level cost data has been located.

8.1.8 Fossil Power Plant Evaluations

Although few nuclear power reactors have been built in the United States for some time, the construction of fossil-fueled power plants continues. This includes pulverized coal plants with both subcritical and supercritical power systems.

An ultra-supercritical water power cycle has been selected as the initial AHTR concept. Coal-fired plants using this technology provide both a technological and cost basis for this power cycle. The AHTR operates at a slightly higher temperature than most existing coal-fired supercritical plants, allowing it to achieve a higher thermal efficiency. More recently, a few pulverized coal plants have been built that increase the temperature of supercritical fluid and reheated steam entering the turbines. The MSBR described in ORNL-4541[25] was also based on a high-temperature supercritical water power system.

Several fossil plant studies compare subcritical, supercritical, and ultra-supercritical power cycles against each other and against competing power systems. The *Market-Based Advanced Coal Power Systems, Final Report*[17] issued by the DOE Office of Fossil Energy in May 1999 includes reasonably detailed cost summaries; a similar report[27] was issued by the National Energy Technology Center in 2007. These reports not only provide cost data for different turbine-generator sets but also provide a basis for comparing escalated cost derived from the EEDB to other recent experience.

The Tennessee Valley Authority (TVA) operates a 900 MW(e) pulverized-coal, supercritical power station at the Bull Run site near Oak Ridge. A tour of the site was taken as part of this study, and a very detailed report[28] was obtained which provides many technical and cost details associated with the construction of that plant. Although somewhat dated (Bull Run entered commercial operation in 1967), this has proven to be a useful reference for this study.

8.1.9 Other Reactor Cost Data

Several other sources of reactor cost data may be explored in the future to improve the current AHTR modeling effort. Considerable data exists in the commercial industry but is generally proprietary and released only in broad summary format. This includes data on new commercial reactors such as the Westinghouse AP1000, the GE-Hitachi Advanced Boiling Water Reactor (ABWR) and Economic Simplified Boiling Water Reactor (ESBWR), the AREVA EPR, and the Mitsubishi US-Advanced Pressurized Reactor (US-APWR).

Similar information is being developed for smaller, modular power reactor systems such as the Babcock and Wilcox mPower or the NuScale developed by NuScale Power, Inc. Again, cost data is proprietary; these reactors are also further removed in scale from the AHTR that is the subject of this report.

Considerable new reactor construction is under way in China, but cost models are not made public and may not apply to the U.S. financial system. Serious attention has been given to construction techniques and schedules in Japan; optimization of construction equipment led to a number of reactors being constructed on schedules of 40 months or less from first concrete to initial core loading.

Other DOE studies for which cost data may be available include the NGNP being developed by DOE-NE, the earlier New Production Reactor design effort, and a number of other DOE-sponsored reactor concept projects. In some cases, the most comprehensive design and cost work has been performed by industrial firms under proprietary agreements, and comprehensive cost data is not readily available.

8.2 DIRECT CAPITAL COST EVALUATION

8.2.1 Methodology

In the EMWG nuclear energy systems cost code of accounts, direct capital cost is tracked in the 20 series of accounts. These accounts are generally the same as used in the EEDB; no significant adjustments of EEDB data are needed to generate input for G4-ECONS. In the EEDB data sets, some of the minor structures are assigned to detailed cost codes different from those used in the EMWG system, but since these are at a much lower level than the data input into G4-ECONS, the EEDB codes are retained. The account series for heat rejection equipment and miscellaneous equipment are swapped between the G4 and EEDB systems, but this global change is easily accommodated.

The capital cost evaluation is performed by converting the escalated EEDB PWR12 better experience cost data to a series of tables corresponding (for direct capital cost) to three-digit account codes. Each table lists the escalated EEDB cost for factory (vendor) cost, site labor, and site materials. A column is provided for adjustments needed to reflect the AHTR; discussions of these adjustments are given in the accompanying text. In some cases, additional rows are provided to incorporate AHTR features not seen in the PWR12 data base.

Because the thermal power of the PWR12 and the AHTR are both essentially 3400 MW, no power factors are needed to compare the two concepts. Since the thermal efficiency of the AHTR is higher than that of the PWR12 (45% as opposed to 33%), the electricity generated by the AHTR is higher [1530 MW(e) instead of 1144 MW(e)] and the AHTR turbine-generator set is larger. Conversely, the heat rejection system for the PWR12 is larger. In many cases, other factors (such as higher temperatures and the use of the supercritical power cycle in the AHTR) are more significant than the design ratings of the equipment.

Observations are made as to the differences in the PWR12 ME and the improved PWR12 data sets when significant. In many cases, the features used for the improved PWR12 are similar to features of the AHTR. Care must be used to ensure that changes are not counted twice, relative to the original PWR12.

Detailed files on the PWR12 BE and working files associated with summarizing and cross-checking data are too large to be reproduced here and will be maintained by project staff.

8.2.2 Structures and Improvements—Account 21

Accounts 211 through 218 address site preparation and yardwork, and construction of the various buildings and structures on the site. Building estimates generally cover excavation, subsurface concrete, and superstructures. Building estimates also cover standard building services but not process-related piping, ventilation, and equipment. Excavation and backfill for the main nuclear island structures is covered in one lot under account 211.

In the PWR12 BE data base, the structures and improvements account represents about 14% of the overall capital cost and 22% of the direct capital cost. The reactor containment building is about a third of this account; site preparation, the reactor auxiliary building, and the turbine building account for another third. Discussions for each three-digit account follow.

Account 211—Site Preparation/Yardwork

Escalated cost for site preparation and yardwork is shown in Table 8. This account includes general site preparation and site features, as well as all excavation and backfill associated with the main reactor buildings.

The overall size of the AHTR power plant site is not expected to be appreciably different than the size of a typical LWR power plant site. Because the reactor building is set slightly deeper than a typical LWR, with the reactor assembly itself below grade, an adjustment has been made to the structure-associated open cut line.

Several features in the generic LWR data base may or may not apply to a given AHTR site. Examples include provisions for rail access or the need for a dedicated sanitary sewer facility. No changes are made to these costs at this time.

Table 8. Site preparation/yardwork—account 211 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
General cut and fill	0	1,822,392	881,062	2,703,454		2,703,454
Roads, walks and parking areas	0	1,760,897	1,951,082	3,711,979		3,711,979
Fencing and gates	0	250,505	266,592	517,097		517,097
Sanitary sewer facility	682,260	2,241,187	378,475	3,301,922		3,301,922
Yard drainage storm sewers	0	1,081,126	2,382,523	3,463,649		3,463,649
Roadway and yard lighting	0	961,608	776,160	1,737,768		1,737,768
Settling basins	0	204,247	371,707	575,954		575,954
Railroads	0	3,652,922	3,390,749	7,043,671		7,043,671
Structure-associated open cut	0	11,599,980	4,012,570	15,612,550	2,000,000	17,612,550
Structure-associated fill/backfill	0	11,235,598	10,078,404	21,314,002		21,314,002
Account 211 total cost	**682,260**	**34,810,462**	**24,489,324**	**59,982,046**	**2,000,000**	**61,982,046**

A comparison of the PWR12 ME data base to the PWR12 BE data base shows about $5 million additional in materials, but $13 million additional in labor hours. This is presumably associated with scheduling issues.

A comparison of the improved PWR12 data base to the PWR12 BE actually shows a modest increase in cost. The improved PWR likely incorporates more below-grade structures in the same way as does the AHTR concept.

Account 212—Reactor Building

At this stage in AHTR, the reactor building is presumed to be about the same size but set deeper into the ground. Excavation of the main nuclear island was covered in 211, so no cost adjustment is made here.

Because the AHTR is not a pressurized system and no large sources of water are present in the reactor building, reactor upset conditions do not lead to large pressure rises. Containment is not carried to the top of the reactor building but generally ends at the operating floor level. An enclosure that forms part of the containment encloses the control drive assemblies that extend above the reactor floor. A concrete shield building covers the structure, protecting the reactor assembly from external events. The shield building has a ventilation system designed to filter radioactive material.

The AHTR does have a high-quality cover gas over the salt-containing equipment. This largely coincides with the containment boundary; thus, a gas-tight steel shell accomplishes both the containment and cover gas enclosure functions. The remaining portion of the building is inerted but with more modest requirements.

Several adjustments to the PWR12 BE cost basis arise from these changes. Because the above-grade building shell does not serve as a pressurized containment boundary, it will not be as thick and costs for the shell are reduced. Similarly, there is not a large, thick containment dome, and the cost for the shield building enclosure is assumed to be about half that amount. Finally, the cost allocated to containment liner is reduced; the containment liner covers the lower portions of the building but not the above-grade structure. Thus, the area covered by the liner is reduced. The reduction in cost for the containment liner is partially offset by airtight construction to preserve the general inert building atmosphere.

The resulting changes can be seen in Table 9. No changes have been made to building services accounts at this time. The “safety related” HVAC cost is retained to account for contamination control and inert atmosphere requirements.

Table 9. Reactor building—account 212 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavating work	0	0	0	0		0
Substructure concrete/access ramp	0	6,384,763	6,082,548	12,467,311		12,467,311
Containment shell	0	14,861,294	8,343,960	23,205,254	–10,000,000	13,205,254
Containment dome	0	6,011,210	3,478,651	9,489,862	–5,000,000	4,489,862
Interior concrete	3,618,000	24,960,209	10,074,175	38,652,384		38,652,384
Removable plugs	0	437,772	178,229	616,001		616,001
Structural and miscellaneous steel	0	1,744,442	2,948,546	4,692,989		4,692,989
Containment liner	28,944,000	19,404,000	970,200	49,318,200	–10,000,000	39,318,200
Painting	0	6,622,387	1,883,112	8,505,499		8,505,499
Plumbing and drains	161,736	625,951	158,561	946,248		946,248
Heating, ventilation, air conditioning	183,720	40,428	4,044	228,192		228,192
Special HVAC (safety related)	1,129,200	2,302,152	694,582	4,125,934		4,125,934
Lighting and service power	0	2,039,772	1,030,546	3,070,318		3,070,318
Elevator	211,200	70,097	7,010	288,307		288,307
Account 212 total cost	**34,247,856**	**85,504,478**	**35,854,164**	**155,606,498**	**–25,000,000**	**130,606,498**

A comparison of the PWR12 ME data base to the PWR12 BE data base shows about $15 million additional in materials, but $70 million additional in labor hours, likely as a result of quality assurance concerns and protracted schedules.

A comparison of the improved PWR12 data base to the PWR12 BE actually shows a modest decrease in both factory and site cost. The improved PWR likely utilizes newer construction techniques to reduce construction cost, as well as improved safety systems to reduce loads on containment. Since the AHTR concept already reduces load on containment, no further adjustment is made at this time.

Account 213—Turbine-Generator Building

A review of turbine building size for several nuclear and coal-fired plants suggests that size is relatively independent of plant type and even power level. Plants with single shaft arrangements tend to be slightly longer and narrower; Bull Run Fossil Plant has a cross-compound configuration with the high and intermediate turbines on a separate shaft than the low pressure turbines, and the two shafts and generators set in a side-by-side arrangement. Thus, the turbine-generator building is shorter and wider. The current AHTR concept calls for two shafts, each with a full set of high-, intermediate-, and low-pressure turbines. Thus, it is likely to be both long and wide, and adjustments are made to the substructure concrete and superstructure entries to account for this. Because of the larger building, ventilation system cost is also increased. The impacts of these changes can be seen in Table 10.

Table 10. Turbine-generator building—account 213 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	8,238,324	4,293,048	12,531,372	2,000,000	14,531,372
Superstructure	0	14,237,318	21,666,715	35,904,034	5,000,000	40,904,034
Plumbing and drains	28,481	2,362,495	678,218	3,069,194		3,069,194
Heating, ventilation, air conditioning	1,251,715	1,043,398	204,017	2,499,130	500,000	2,999,130
Fire protection	0	0	0			0
Lighting and service power	0	874,188	412,219	1,286,407		1,286,407
Elevator	211,200	58,414	5,842	275,455		275,455
Account 213 total cost	**1,491,396**	**26,814,137**	**27,260,059**	**55,565,592**	**7,500,000**	**63,065,592**

In the PWR12 data base, excavation for the turbine-generator building is included with the reactor island excavation in the site preparation and yardwork account. For the AHTR, the turbine building is set at some distance from the reactor building. Excavation is not extensive, however, and separating turbine building excavation from the 211 account is not attempted at this time.

Comparison to the median experience data base shows increases of $15 million in material and $21 million in labor cost. Comparison to the improved PWR data actually shows a very small increase in cost.

Account 214—Security Building

The security building is a relatively small, windowless building representing less than 1% of the structures and improvements cost, as seen in Table 11. No adjustment to security building cost is considered at this time. Excavation for the security building is included in account 211.

Table 11. Security building—account 214 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	134,093	78,638	212,731		212,731
Superstructure	0	1,427,441	592,663	2,020,104		2,020,104
Building services	124,610	700,958	210,288	1,035,857		1,035,857
Account 214 total cost	**124,610**	**2,262,492**	**881,590**	**3,268,692**	**0**	**3,268,692**

No significant cost changes are identified by comparing security building costs to the median experience or improved PWR data sets.

Account 215—Reactor Service (Auxiliary) Building

The reactor service (or auxiliary) building is an important structure, representing 9% of the total structures and improvements cost. However, as of this time no assessment of changes in building size and configuration has been attempted, and thus no changes are indicated in Table 12. Excavation for the reactor service building is part of the general reactor island excavation covered in account 211.

Table 12. Reactor service (auxiliary) building—account 215 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	935,873	794,911	1,730,784		1,730,784
Superstructure	0	18,141,811	9,140,102	27,281,914		27,281,914
Plumbing and drains	8,138	1,018,985	280,958	1,308,082		1,308,082
Heating, ventilation, air conditioning	6,277,766	3,909,538	930,864	11,118,168		11,118,168
Special HVAC	922,080	257,623	25,769	1,205,472		1,205,472
Lighting and service power	0	874,188	360,691	1,234,879		1,234,879
Elevator	333,360	109,536	10,954	453,850		453,850
Account 215 total cost	**7,541,345**	**25,247,554**	**11,544,250**	**44,333,148**	**0**	**44,333,148**

About $20 million additional cost (the greater part being site labor) is seen in comparing these costs to the PWR12 ME data set, and a small ($1.5 million) reduction is seen in the improved PWR data set.

Account 216—Radioactive Waste Building

The radioactive waste building typically houses system and storage areas for solid, gaseous, and liquid radioactive waste. The EEDB PWR12 scope includes liquid waste processing and solidification systems; many plants now provide connections for off-site vendor treatment systems but do not maintain their own solidification system. It is assumed that the gaseous treatment system occupies a relatively small portion of the building, and it is equally divided between solid and liquid waste handling areas.

Because the AHTR does not use water coolant, many of the traditional sources of liquid radioactive waste are not present. Space for aqueous waste streams may be reduced.

The AHTR will require salt treatment systems for both the primary and the secondary/DRACS salts. The location of the processing systems has not yet been determined; if they are located in a radioactive waste building they may more than take up the space released by aqueous waste processing facilities. Alternately, the salt system could be located in the reactor service building, and the size of the radioactive waste building could be reduced.

Tritium removal will be required for primary and intermediate salt circuits, as well as for the confinement atmosphere around the primary circuit equipment. This may add to space required for the radioactive waste building.

Because of the dependence on future decisions, no changes have been made to the data base for the radioactive waste building at this time. The cost from the PWR12 BE data base is shown in Table 13.

Table 13. Radioactive waste building—account 216 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	1,952,837	1,495,766	3,448,603		3,448,603
Superstructure	0	16,546,493	8,791,783	25,338,276		25,338,276
Plumbing and drains	0	836,359	192,211	1,028,570		1,028,570
Heating, ventilation, air conditioning	1,224,473	1,627,255	513,713	3,365,441		3,365,441
Lighting and service power	0	582,792	257,638	840,430		840,430
Elevator	338,160	110,986	11,098	460,243		460,243
Account 216 total cost	**1,562,633**	**21,656,722**	**11,262,209**	**34,481,563**	**0**	**34,481,563**

A $19 million increase in cost for the radioactive waste building is seen in the PWR12 ME data set, compared to the PWR12 BE data. A small ($1 million) decrease is seen in the improved PWR data set.

Account 217—Fuel Service Building

The fuel service building contains the spent fuel pool, cask loading and decontamination areas, new fuel receipt and inspection areas, and the necessary truck locks and handling equipment.

Because the AHTR fuel assemblies are longer and the core has a larger diameter, it is likely that the fuel service building facilities will be commensurately larger. The substructure concrete and superstructure lines are increased by about a third to reflect this.

Some increase in building services might also result, but much of the increased size is in pools or other facilities that do not have full building services. At this time, no change is made to the service categories.

Increased excavation costs may be incurred; excavation cost for the fuel service building is part of the reactor island excavation addressed in account 211.

Changes to the PWR12 BE cost data base are indicated in Table 14.

Table 14. Fuel service building—account 217 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	2,963,647	6,831,576	9,795,223	3,000,000	12,795,223
Superstructure	0	6,443,333	3,155,870	9,599,203	3,000,000	12,599,203
Plumbing and drains	8,138	249,266	141,802	399,206		399,206
Heating, ventilation, air conditioning	203,160	852,516	261,466	1,317,142		1,317,142
Special HVAC (safety-related)	2,182,800	99,310	9,931	2,292,041		2,292,041
Lighting and service power	0	203,978	103,054	307,032		307,032
Account 217 total cost	**2,394,098**	**10,812,050**	**10,503,698**	**23,709,847**	**6,000,000**	**29,709,847**

No significant changes are seen in the PWR12 ME or improved PWR12 data sets.

Account 218A—Control and Diesel Generator Building

A brief review of the PWR12 sketches in the EEDB Technical Reference Book suggest a 70%/30% split in cost between the multilevel control structure and the diesel generator structure.

Although control systems have become simpler in recent years and some reductions in cable spreading areas are likely, the overall floor plan for the control room is set as much by personnel needs as by instrumentation. Thus, no change is made to the control building cost at this time.

The safety case for the AHTR does not rely on continued electrical power to pumps or equipment, and thus safety-related diesel generators are not needed. Emergency generators will still be useful to minimize disruptions at the site but need not be in a safety-class structure. The cost assigned to the diesel generator portion of the structure is reduced by half.

No changes are made to building services. It is assumed that the special, safety-related ventilation system is for control room ventilation and that such a system will still be required.

The resulting cost adjustments are seen in Table 15. Excavation is part of the reactor island excavation covered in account 211.

Table 15. Control and diesel generator building—account 218A (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	729,934	529,891	1,259,825		1,259,825
Superstructure	0	18,853,159	10,755,919	29,609,078	–5,000,000	24,609,078
Plumbing and drains	0	1,377,329	468,588	1,845,917		1,845,917
Special HVAC (safety related)	3,513,149	4,707,168	898,054	9,118,370		9,118,370
Lighting and service power	0	1,165,584	437,981	1,603,565		1,603,565
Account 218A total cost	**3,513,149**	**26,833,174**	**13,090,433**	**43,436,755**	**–5,000,000**	**38,436,755**

The PWR12 ME data set shows an additional $30 million for the control and diesel generator building, likely the result of changing requirements for safety-class electrical systems and plant monitoring systems during the 1970s. The improved PWR12 set shows only a small decrease in cost.

Account 218B—Administration and Service Building

The size of the administration and service building, which contains offices and shop facilities, is a function of staff size and definition of maintenance activities. Because staff and maintenance requirements have not yet been evaluated for the AHTR, no change is made at this time. Excavation is covered in account 211.

The special HVAC system is presumed to address radiological control ventilation systems in shops that may handle contaminated materials. Unadjusted cost for account 218B is shown in Table 16.

Table 16. Administration and service building—account 218B (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	1,071,437	564,982	1,636,418		1,636,418
Superstructure	0	3,824,969	4,188,538	8,013,506		8,013,506
Plumbing and drains	0	732,622	399,934	1,132,555		1,132,555
HVAC	1,853,146	1,884,624	375,634	4,113,403		4,113,403
Special HVAC	24,552	14,100	1,411	40,063		40,063
Lighting and service power	0	582,792	309,163	891,955		891,955
Elevator	91,200	29,210	2,921	123,331		123,331
Account 218B total cost	**1,968,898**	**8,139,754**	**5,842,582**	**15,951,233**	**0**	**15,951,233**

The PWR12 ME data set shows an additional $8 million for the administration and service building account. There should be little regulatory impact on this building, so it is likely that this is part of a general escalation of cost, especially labor cost. The improved PWR12 data set shows only a small decrease in cost, presumably associated with construction techniques. This might be considered for adoption in the future, but its impact is likely less than would result from an improved assessment of building needs and size.

Account 218J—Main Steam and Feedwater Pipe Enclosure

In traditional light-water reactors, the turbine-generator building is set outside the containment structure and is often further separated by a portion of the service or auxiliary building. Thus, the main steam and feedwater pipe enclosure is needed to transport reactor steam and feedwater between the reactor building and the turbine building. This structure is part of the hardened reactor island structures, and thus its cost is not trivial, as seen in Table 17.

Table 17. Main steam and feedwater pipe enclosure—account 218J (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Excavation work	0	0	0	0		0
Substructure concrete	0	1,419,758	1,105,944	2,525,702		2,525,702
Superstructure	0	9,645,298	4,642,459	14,287,757		14,287,757
						0
Plumbing and drains	0	937,754	198,317	1,136,071		1,136,071
Heating, ventilation, air conditioning	79,704	332,069	41,398	453,170		453,170
Lighting and service power	0	349,675	128,818	478,493		478,493
Account 218J total cost	**79,704**	**12,684,554**	**6,116,935**	**18,881,194**	**0**	**18,881,194**

In the case of the AHTR, the supercritical fluid or reheated steam will be generated in a bay contiguous to the turbine-generator building, and a separate steam and feedwater pipe enclosure is not needed. However, the turbine-generator building is set some distance from the reactor building, with heat carried between the two by the intermediate salt. This piping would be located in an enclosure.

This account will be used to reflect the below-grade enclosure through which the intermediate salt passes from the reactor building to the salt-to-water heat exchanger bay adjacent to the turbine hall. Although the function is similar, there are several key differences. The AHTR intermediate salt pipe enclosure is below grade, while the PWR enclosure is above grade and integrated into other structures. The PWR enclosure is safety related; the AHTR enclosure is not safety related but is an important plant investment feature. The AHTR structure is likely less structurally intensive than a PWR steam and feedwater pipe enclosure, but because of the 100-m distance between reactor building and turbine hall, it is likely a longer structure. The AHTR enclosure may require a relatively larger ventilation system because of the relative temperatures of the enclosed piping.

Because the total cost for the PWR steam and feedwater pipe enclosure is only $18 million, it is unlikely that the relative cost difference between the PWR enclosure and the intermediate salt enclosure would be as high as $10 million. Without the low level of definition of the AHTR intermediate salt pipe structure and supporting services, no adjustment is made.

Accounts 218E—Emergency Feed Pump Structure, and 218T—Ultimate Heat Sink Structure

These two accounts address cost for systems that are not part of the AHTR concept. Because the DRACS is used as a passive means for transport of decay heat from the reactor directly to the atmosphere, the AHTR is not reliant on feedwater or service water to cool the reactor. There is no need for a separate safety-related emergency feed pump structure or a separate ultimate heat sink structure. Costs for these two accounts, shown in Table 18, are deleted in their entirety.

Table 18. Emergency feed pump and ultimate heat sink structure—accounts 218E and 218T (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Emergency feed pump building						
Excavation work	0	0	0	0	0	
Substructure concrete	0	421,925	269,825	691,750	–691,750	0
Superstructure	0	3,280,944	1,396,234	4,677,178	–4,677,178	0
						0
Plumbing and drains	0	215,098	79,608	294,706	–294,706	0
Special HVAC (safety related)	53,575	69,626	15,629	138,830	–138,830	0
Lighting and service power	0	116,558	77,292	193,850	–193,850	0
Account 218E total cost	**53,575**	**4,104,151**	**1,838,587**	**5,996,314**	**–5,996,314**	**0**
Ultimate heat sink structure						
Excavation work	0	581,743	367,034	948,778	–948,778	0
Substructure concrete	0	372,331	325,214	697,546	–697,546	0
Superstructure	0	6,201,631	2,636,534	8,838,166	–8,838,166	0
Plumbing and drains	0	32,234	2,412	34,646	–34,646	0
Heating, ventilation, air conditioning	102,526	113,090	28,632	244,248	–244,248	0
Lighting and service power	0	203,978	64,409	268,387	–268,387	0
Account 218T total cost	**102,526**	**7,505,009**	**3,424,236**	**11,031,770**	**–11,031,770**	**0**

Other Account 218 Structures

A set of other, minor structures in the PWR12 data base are shown in Table 19. These represent less than $10 million in total scope. Many of the functions represented by these structures remain applicable to the AHTR, but as the site plan evolves, they may or may not appear as discrete structures. No changes are made to these accounts at this time.

Table 19. Other structures (various 218 subaccounts) (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Fire pump house, including foundations						
Earthwork	0	3,132	1,130	4,262		4,262
Substructure concrete	0	305,258	113,129	418,387		418,387
Superstructure	0	131,539	199,906	331,445		331,445
Plumbing and drains	40,318	36,833	13,800	90,950		90,950
Heating, ventilation, air conditioning	54,360	53,074	6,806	114,240		114,240
Lighting and service power	0	44,875	20,222	65,098		65,098
Account 218D total cost	**94,678**	**574,711**	**354,994**	**1,024,382**	**0**	**1,024,382**
Manway tunnels (RCA tunnels)						
Excavation	0	0	0	0		0
Substructure concrete	0	137,369	102,031	239,400		239,400
Superstructure	0	922,502	366,240	1,288,742		1,288,742
Building services	0	233,777	66,643	300,420		300,420
Account 218F total cost	**0**	**1,293,648**	**534,914**	**1,828,562**	**0**	**1,828,562**
Electrical tunnels						
Building structure (included in 218E)	0	0	0	0		0
Plumbing and drains	23,119	31,279	11,297	65,695		65,695
Lighting and service power	0	69,938	27,014	96,953		96,953
Account 218G total cost	**23,119**	**101,218**	**38,311**	**162,648**	**0**	**162,648**
Non-essential switchgear building						
Excavation work	0	0	0	0		0
Substructure concrete	0	180,907	94,997	275,904		275,904
Superstructure	0	313,486	356,602	670,087		670,087
Plumbing and drains	0	64,476	49,378	113,854		113,854
Heating, ventilation, air conditioning	45,960	47,832	6,451	100,243		100,243
Lighting and service power	0	87,420	38,645	126,065		126,065
Account 218H total cost	**45,960**	**694,121**	**546,072**	**1,286,153**	**0**	**1,286,153**

Table 19. Other structures (various 218 subaccounts) (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Pipe tunnels						
Excavation work	0	0	0	0		0
Substructure concrete	0	90,943	58,385	149,328		149,328
Superstructure	0	317,498	127,361	444,859		444,859
Drains and piping	0	43,956	20,506	64,462		64,462
Lighting and service power	0	38,465	64,409	102,874		102,874
Account 218K total cost	**0**	**490,862**	**270,660**	**761,522**	**0**	**761,522**
Technical support center						
Excavation work	0	0	0	0		0
Substructure concrete	0	86,254	72,766	159,019		159,019
Superstructure	0	1,037,227	482,686	1,519,913		1,519,913
Building services	124,610	70,097	21,029	215,736		215,736
Account 218L total cost	**124,610**	**1,193,578**	**576,480**	**1,894,668**	**0**	**1,894,668**
Containment equipment hatch and missile shield						
Substructure concrete	0	0	0	0		0
Superstructure	0	402,192	125,635	527,827		527,827
Account 218P total cost	**0**	**402,192**	**125,635**	**527,827**	**0**	**527,827**
Waste water treatment						
Waste water treatment building:						
Excavation work	0	12,593	4,502	17,095		17,095
Substructure concrete	0	160,296	54,007	214,303		214,303
Superstructure	0	100,961	165,372	266,333		266,333
Plumbing and drains	0	8,791	6,614	15,406		15,406
Heating, ventilation, air conditioning	19,937	17,525	1,752	39,214		39,214
Lighting and service power	0	40,795	18,384	59,179		59,179
Waste water holding basins:						
Excavation work	0	121,320	48,353	169,673		169,673
Substructure concrete	0	698,779	361,519	1,060,298		1,060,298
Account 218S total cost	**19,937**	**1,161,060**	**660,504**	**1,841,501**		**1,841,501**
Control room emergency air intake structure						
Excavation work	0	39,672	18,170	57,842		57,842
Substructure concrete	0	106,260	49,817	156,077		156,077
Superstructure	0	0	0	0		0
Building services	0	0	0	0		0
Account 218V total cost	**0**	**145,932**	**67,987**	**213,919**	**0**	**213,919**
Total cost, other structures	**308,304**	**6,057,322**	**3,175,558**	**9,541,183**	**0**	**9,541,183**

Summary of Account 21 Cost

The net reduction of the structures and improvements account is $31.5 million, leaving a total cost of $450 million. This value represents only an initial, cursory screening of cost for applicability to the AHTR. Significant additional changes are likely as the development of the AHTR concept progresses.

8.2.3 Reactor Plant Equipment—Account 22

Accounts 221 through 228 cover reactor plant equipment, including the reactor equipment itself, main heat transfer systems, reactor safety (safeguards) equipment, radioactive waste processing systems, fuel handling and storage systems, reactor instrumentation and control hardware, and other reactor plant equipment. Reactor plant equipment comprises 21% of the overall plant capital cost and 34% of the direct capital cost.

The costs for reactor plant equipment are dominated by the nuclear steam supply system (NSSS) vendor cost, quoted as a single procurement. The remaining 41% of the reactor plant equipment cost is largely site material and labor cost, including supports and installation of NSSS equipment. A fairly detailed breakdown of the site cost is provided in the EEDB data sets, but the single cost for NSSS procurement obscures this detail.

To make the PWR12 data sets more useable, the escalated NSSS procurement cost has been distributed into the various three-digit accounts. For interim use, this was done by listing the appropriate accounts and items within those accounts and using a simple set of percentages. First, the entire NSSS cost is allocated at the three-digit account level, then those allocations are distributed to line items with a secondary set of percentages. The result is shown in Table 20.

Table 20. Reactor vendor PWR12 BE NSSS cost allocations (2011 dollars)

Title	Initial distribution	Cost	Secondary distribution	Cost
Reactor equipment	40.0%	172,166,400		
Vessel structure			40.0%	68,866,560
Vessel internals:				
Lower internals			15.0%	25,824,960
Upper internals			15.0%	25,824,960
Control rod system:				
Control rods			15.0%	25,824,960
Control rod drives			15.0%	25,824,960
Main heat transfer/transport system	30.0%	129,124,800		
Main coolant pumps			30.0%	38,737,440
Reactor coolant piping			15.0%	19,368,720
Steam generators			40.0%	51,649,920
Pressurizer			10.0%	12,912,480
Pressurizer relief tank			5.0%	6,456,240

Table 20. Reactor vendor PWR12 BE NSSS cost allocations (2011 dollars) (continued)

Title	Initial distribution	Cost	Secondary distribution	Cost
Safeguards system	15.0%	64,562,400		
Residual heat removal system:				
Residual heat removal pumps and drives			20.0%	12,912,480
Residual heat removal heat exchanger			20.0%	12,912,480
Safety injection system:				
Safety injection pumps and drives			20.0%	12,912,480
Accumulator tank			10.0%	6,456,240
Boron injection tank			10.0%	6,456,240
Boron injection surge tank			10.0%	6,456,240
Boron injection recirculating pump and drive			10.0%	6,456,240
Fuel handling and storage	5.0%	21,520,800		
Fuel handling tools			50.0%	10,760,400
Fuel storage racks			50.0%	10,760,400
Other equipment	5.0%	21,520,800		
Coolant treatment and recovery equipment:				
Rotating machinery (pumps and motors)			25.0%	5,380,200
Heat transfer equipment			25.0%	5,380,200
Tanks and pressure vessels			15.0%	3,228,120
Purification and filtration equipment			25.0%	5,380,200
Maintenance equipment			10.0%	2,152,080
Instrumentation and control	5.0%	21,520,800		
Standard NSSS valve package			100.0%	21,520,800
Nuclear steam supply (NSSS) total vendor cost	**100.0%**	**430,416,000**		**430,416,000**

This NSSS distribution approach obviously reduces the fidelity of the PWR12 BE data set for the reactor plant equipment accounts. However, the reactor equipment accounts also represent the equipment most different for an AHTR compared to a PWR. Many of the functions remain applicable, but the comparative estimating technique is likely less accurate for this important segment of the total cost than for segments such as the turbine-generator, electrical or other plant systems, or site and buildings. Obtaining improved methods of estimating cost for reactor equipment should be a high priority for future work.

Account 221—Reactor Equipment

The combined reactor data set, including NSSS allocations and field cost taken directly from the PWR12 BE data set, is shown in Table 21. There are numerous differences between the PWR equipment and the AHTR components. The PWR operates at high pressure to avoid boiling; the AHTR salt coolant boils at temperatures far above potential fuel temperature and operates with only static and dynamic pressure loads. Thus, the AHTR has much thinner walls. The PWR vessel is a single forging and is transported to the site intact; the AHTR vessel is very large and may be completed on-site. The AHTR systems in contact with fluoride salt must be constructed of alloys such as the nickel-based Alloy N, whereas the water-cooled systems use more common steel alloys. However, Busby[29] shows that the use of advanced alloys does not necessarily mean higher cost. There are no lower penetrations in the AHTR, but the upper penetrations may be somewhat more complex to allow fuel handling at operating temperature. There are more control rods in the AHTR than in a typical PWR.

Table 21. Reactor equipment—account 221 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Reactor supports (field cost)	1,951,807	1,219,680	121,968	3,293,455		3,293,455
Reactor vessel structure (NSSS allocation)	68,866,560	0	0	68,866,560		68,866,560
Reactor vessel structure (field cost), including vessel body and attachments, studs, fasteners, seals, gaskets, and insulation	0	5,388,667	538,867	5,927,534		5,927,534
Lower internals (NSSS allocation)	25,824,960	0	0	25,824,960		25,824,960
Lower internals (field cost)	0	794,119	79,411	873,530		873,530
Upper internals (NSSS allocation)	25,824,960	0	0	25,824,960		25,824,960
Upper internals (field cost)	0	510,506	51,050	561,557		561,557
Transport to site	0	0	13,292,400	13,292,400		13,292,400
Control rods (NSSS allocation)	25,824,960	0	0	25,824,960		25,824,960
Control rod drives (NSSS allocation)	25,824,960	0	0	25,824,960		25,824,960
Control rod drives (field cost)	0	969,960	96,996	1,066,956		1,066,956
Control rod drive missile shield (field cost)	0	110,880	11,088	121,968		121,968
CRDM seismic supports (field cost)	60,420	38,808	3,881	103,109		103,109
Account 221 total cost	**174,178,627**	**9,032,621**	**14,195,662**	**197,406,910**	**0**	**197,406,910**

Until more specific information on the AHTR reactor equipment becomes available, only broad generalizations can be made about the cost of reactor equipment. The vessel cost shown in Table 21 is about $69 million, plus an additional $6 million incurred as field cost. The reduction in wall thickness and lack of bottom penetrations could easily lead to a reduction on the order of $20 million. The larger size could offset $10 million of this savings. The impact on cost of using Alloy N instead of the more common steels is another factor that must be considered.

Of equal concern is the fidelity of the PWR12 BE estimate for the vessel. The factors used to distribute NSSS cost are only judgments and are not supported by actual estimates. As further details on the AHTR reactor design become available, techniques such as comparing the weight and unit mass cost for the two vessels can lead to better assessments of both relative cost between the PWR and the AHTR, and ultimately an actual cost estimate for the AHTR. Such techniques were used in both the Busby paper[29] and in ORNL-4541.[25]

Even less detail is available on design of AHTR internals, including control rods and instrumentation. Likewise, the distribution of NSSS cost impacts the base PWR12 BE estimate in the same manner as with the vessel. Rather than adjusting cost in Table 21 at this time, a more detailed review of the reactor vessel and other reactor assembly equipment cost is highlighted as a key recommendation for further work in Section 8.7 of this chapter.

The scope of this account has not been increased to account for preheating the reactor system prior to nuclear operation. Preheat of the entire salt system will be treated as a unit in account 228.

There is no significant difference between the PWR12 BE and ME data sets for reactor equipment. The difference between the PWR12 BE and the improved PWR12 data sets is modest, with most of the difference in the NSSS package.

Account 222—Main Heat Transport System

The heat transport systems for the AHTR and the reference PWR12 differ in several key respects. The most obvious is that the AHTR operates at a higher temperature, using alloys that are compatible with fluoride salts such as Alloy N, but is not pressurized. The AHTR also transfers heat first to an intermediate liquid salt circuit, then to the supercritical water power system. The PWR uses water as a heat transport fluid but must maintain pressure to avoid boiling in the core or flashing to steam in the rest of the system. The PWR uses more common iron-based alloys but has thick walls. The PWR uses a single heat transfer circuit to move heat from the reactor fuel to the steam generators, whereas the AHTR has two circuits.

A series of adjustments to the PWR BE data set is documented in Table 22. A difference in cost of the main coolant pumps is not assessed at this time, but the number of pumps is reduced from four to three. Similarly, the use of high-temperature alloys in AHTR primary circuit piping is assumed to offset the cost of thicker pipe walls of the PWR primary system, but the number of circuits is reduced from four to three. Flow velocity in the AHTR is significantly lower than the PWR BE (under 4 m/s, compared to about 10 m/s), which would tend to make the AHTR primary pumps less expensive.

Table 22. Primary and intermediate heat transfer equipment—account 222 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Main coolant pumps (NSSS allocation, 4 PWR, 3 AHTR)	38,737,440	0	0	38,737,440	–10,000,000	28,737,440
Fluid circulation drive (field cost)	3,184,526	3,684,240	368,424	7,237,190	–2,000,000	5,237,190
Reactor coolant piping (NSSS allocation)	19,368,720	0	0	19,368,720	–5,000,000	14,368,720
Reactor coolant piping (field cost)	3,701,275	9,586,488	942,602	14,230,366	–3,000,000	11,230,366

Table 22. Primary and intermediate heat transfer equipment—account 222 (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Primary to intermediate heat exchangers (3 units)					24,000,000	24,000,000
Intermediate salt pumps (3 units)					24,000,000	24,000,000
Intermediate salt piping					18,000,000	18,000,000
Intermediate salt mixing plenum					5,000,000	5,000,000
Intermediate to steam cycle heat exchanger body (2 units)					10,000,000	10,000,000
Supercritical fluid tube bundles					14,000,000	14,000,000
Steam reaheat tube bundles					8,000,000	8,000,000
Steam generators (NSSS allocation)	51,649,920	0	0	51,649,920	–51,649,920	0
Steam generator equipment (field cost)	63,290	1,774,080	177,408	2,014,778	–2,014,778	0
Pressurizer (NSSS allocation)	12,912,480	0	0	12,912,480	–12,912,480	0
Pressurizing system (field cost)	12,658	237,468	23,746	273,871	–273,871	0
Pressurizer relief tank (NSSS allocation)	6,456,240	0	0	6,456,240	–6,456,240	0
Account 222 total cost	**136,086,550**	**15,282,276**	**1,512,180**	**152,881,006**	**9,692,710**	**162,573,716**

A new set of entries is provided for three primary to intermediate heat exchangers, three intermediate circuit pumps and drives, and piping between the reactor building and the heat transfer bay adjacent to the turbine hall. Initial cost entries, reflecting similar cost as other reactor system components and assuming the primary to intermediate heat exchangers are relatively simple shell-and-tube components, are included. These values are based on engineering judgment only rather than specifications and vendor quotes.

Similarly, a mixing chamber and two salt-to-water heat exchanger bodies are added to the list. Each has a supercritical fluid tube bundle and steam reheat tube bundle in a configuration that loosely resembles the tube bundles in the flue gas of a fossil plant.

With the salt to supercritical fluid/reheat steam equipment added, the traditional steam generator cost is deleted. Similarly, the costs associated with pressurizers are deleted since the AHTR reactor is not pressurized.

As with the reactor assembly, preheating of the system is not addressed in this account but will be covered as a unit in account 228.

Because of the extent of differences in the AHTR and PWR systems, comparisons to the PWR12 ME and improved PWR data sets is not considered useful.

Account 223—Safety Systems

Safety systems are significantly different for the AHTR compared to traditional PWRs. DRACS are used to transfer heat directly from the reactor vessel coolant to the atmosphere. The DRACS system is completely separate from the ex-vessel primary circuit, with heat exchangers immersed in primary salt inside the reactor vessel. A second heat exchanger is located in a chimney that is part of the reactor building structure. Heat transport is accomplished by natural circulation; backflow and loss of heat to the DRACS during normal operation are restricted by the use of flow diodes inside the reactor vessel.

The DRACS replaces the safety function of the traditional residual heat removal system, and all costs associated with safety-related residual heat removal are deleted. Data for the DRACS components is entered in new lines, based on early engineering judgment. The AHTR reactor circuit is not pressurized, and safety injection systems are not required. Cost for an accumulator tank is retained to represent possible cost for a primary salt accumulator tank.

Safety-related boron injection and removal systems are replaced by lines for injection of a neutron poison salt into the primary salt. The AHTR does not use a containment spray system, and because containment is inerted, cost for a combustible gas control system is deleted (the AHTR does not use zirconium clad fuel, which is the major potential source of combustible gas in LWR containments). These adjustments are summarized in Table 23.

Table 23. Safety systems—account 223 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Residual heat removal pumps and drives (NSSS allocation)	12,912,480	0	0	12,912,480	–12,912,480	0
Residual heat removal heat exchanger (NSSS allocation)	12,912,480	0	0	12,912,480	–12,912,480	0
Residual heat removal (field cost)	2,501,501	2,954,268	280,370	5,736,139	–5,736,139	0
DRACS in-vessel heat exchangers					18,000,000	18,000,000
DRACS chimney heat exchangers					18,000,000	18,000,000
DRACS interconnecting piping and flow diodes					9,000,000	9,000,000
Safety injection pumps and drives (NSSS allocation)	12,912,480	0	0	12,912,480	–12,912,480	0
Safety injection system (field cost)	3,152,678	4,790,530	802,349	8,745,557	–8,745,557	0
Accumulator tank (NSSS allocation)	6,456,240	0	0	6,456,240		6,456,240
Boron injection tank (NSSS allocation)	6,456,240	0	0	6,456,240	–6,456,240	0
Boron injection surge tank (NSSS allocation)	6,456,240	0	0	6,456,240	–6,456,240	0

Table 23. Safety systems—account 223 (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Boron injection recirculating pump and drive (NSSS allocation)	6,456,240	0	0	6,456,240	–6,456,240	0
Neutron poison salt injection system					5,000,000	5,000,000
Neutron poison salt supply system					5,000,000	5,000,000
Containment spray system	7,294,414	4,933,253	495,446	12,723,113	–12,723,113	0
Combustible gas control system	2,071,618	475,798	46,800	2,594,215	–2,594,215	0
Account 223 total cost	**79,582,610**	**13,153,848**	**1,624,966**	**94,361,424**	**–32,905,184**	**61,456,240**

Again, these changes are so significant that comparisons to the PWR12 ME and improved PWR data sets are not warranted.

Account 224—Radioactive Waste Processing Systems

This account covers the cost equipment used to collect, process, package, store, and ship radioactive waste from liquid and solid sources. It also provides systems to treat gas streams that may contain radioactive materials, including tritium.

Radioactive waste processing systems address wastes associated with coolant treatment systems, as well as wastes associated with the general operation of the plant. The scope of this account covers disposal of waste produced by coolant treatment systems, not the treatment systems themselves.

Adjustments to the PWR12 BE data set include a significant reduction in cost associated with traditional aqueous waste streams produced by coolant treatment systems. Some liquid waste cost is retained to handle turbine system wastes, decontamination wastes, and other potential sources of contaminated water. Because there is no boron regeneration system, the regenerated chemical waste train waste equipment is deleted. Other miscellaneous waste streams associated with PWRs are relatively minor and left in the data set.

Allocations for waste treatment systems that process waste from the primary and intermediate salt treatment systems are added. An allocation of $25 million for a tritium control system is also added to the gaseous waste system. These allocations are not yet based on system design information.

These adjustments are shown in Table 24.

Table 24. Radioactive waste systems—account 224 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Salt waste system:						
Primary salt waste system					5,000,000	5,000,000
Intermediate salt waste system					5,000,000	5,000,000
Liquid waste system:						
Equipment drain train	6,721,666	5,050,356	879,876	12,651,898	–6,000,000	6,651,898
Miscellaneous waste train	4,348,298	477,910	47,794	4,874,002	–2,000,000	2,874,002
Detergent waste train	1,199,126	54,838	5,486	1,259,450		1,259,450
Chemical waste train	22,027	5,741	576	28,344		28,344
Steam generator blowdown	2,245,994	1,859,491	191,450	4,296,936		4,296,936
Regenerated chemical waste train	2,732,954	562,764	454,855	3,750,574	–3,750,574	0
Miscellaneous radwaste equipment	59,921	17,028	1,704	78,653		78,653
Instrumentation and control	292,073	80,940	8,095	381,108		381,108
Radioactive gaseous waste system	3,196,042	417,506	49,771	3,663,319		3,663,319
Tritium control system					25,000,000	25,000,000
Solid waste system:						
Dry active waste volume reduction	431,957	40,891	4,090	476,938		476,938
Volume reduction and solids system	17,535,204	1,063,464	201,888	18,800,556		18,800,556
Account 224 total cost	**38,785,262**	**9,630,929**	**1,845,586**	**50,261,777**	**23,249,426**	**73,511,203**

Tritium control costs could be even higher than $25 million. A review of tritium control technologies is identified in Section 8.7 as one of the recommendations for further study. This review could be based in part on experience with existing heavy water reactors, such as the Canadian CANDU power reactors, and research reactors, such as the High Flux Reactor at Institut Laue-Langevin in Grenoble, France, that are cooled and reflected with heavy water. Studies addressing tritium control for the MSBR could also provide a basis for improved estimates.

In the PWR12 ME data set, a $21 million increase in labor cost is shown, along with about $3 million in added material costs. This may reflect changes in waste management practices during construction, along with longer construction schedules. There is a relatively small $3 million decrease in the improved PWR12 data set.

Account 225—Fuel Handling Systems

The AHTR uses solid fuel assemblies, but they are much longer and are made of different materials than the assemblies used in PWRs. The refueling approach used in the AHTR is significantly different from the PWR refueling approach, with fuel removed in partial reloads at operating temperature. Handling fuel at temperature is necessary because the salt must be liquid; since the reactor is unpressurized, fuel can be handled immediately after shutdown. In-vessel fuel handling is performed using a remotely operated fuel handling system. Fuel is transferred from a lobe on the reactor vessel to a poisoned salt pool under a high-purity cover gas, and after cooling it is transferred to dry cask storage.

Costs (allocated from the NSSS vendor procurement) for fuel handling tools are deleted, and new lines are added for the remote in-vessel fuel handling system and for transfer equipment to move fuel elements between the primary salt and the intermediate salt pool. Costs for other more typical fuel handling tools and equipment, including equipment for fresh fuel receipt and inspection, are left unchanged. Adjustments are summarized in Table 25.

Table 25. Fuel handing systems—account 225 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Fuel handling tools (NSSS allocation)	10,760,400	0	0	10,760,400	–10,760,400	0
Fuel storage racks (NSSS allocation)	10,760,400	0	0	10,760,400		10,760,400
Remote in-vessel fuel handling system					25,000,000	25,000,000
Fuel transfer pool hardware					8,000,000	8,000,000
Fuel handling tools and equipment	2,370,106	927,991	92,801	3,390,898		3,390,898
Service platforms	245,698	73,130	7,313	326,141		326,141
Fuel storage, cleaning and inspection equipment	2,672,585	1,057,817	153,744	3,884,146		3,884,146
Account 225 total cost	**26,809,188**	**2,058,938**	**253,858**	**29,121,984**	**22,239,600**	**51,361,584**

There is no significant change in cost for fuel handling systems in the improved PWR data set and only a $2.6 million increase in the PWR12 ME data set. Designs for fuel handling were likely provided by the reactor vendor, and field changes were not significant.

Account 226—Other Reactor Plant Equipment

The scope of account 226 includes inert gas systems, coolant storage and treatment systems, and component cooling.

The existing cost for PWR12 inert gas systems has been deleted. New lines are added for a high-purity salt cover gas system and for a large reactor building inert atmosphere system. Similarly, the reactor water makeup system line is replaced with allocation of cost for primary and intermediate salt drain and storage systems (salt itself is included in account 27, special materials).

The reactor coolant treatment systems, including the NSSS cost allocation, the chemical and volume control system, and the boron recycle system, are replaced with new cost items for primary and intermediate salt chemical processing. These rather large allocations should be a priority for improved definition in future years.

The traditional component cooling water system is replaced by a gas-cooling system, avoiding the use of water to cool reactor components inside containment. A nonsafety service water system is retained to accept heat from the gas component cooling system, and a small portion of the water cooling system cost is retained for special applications yet to be defined.

The resulting adjustments are summarized in Table 26.

Table 26. Other reactor plant equipment—account 226 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Inert gas system - PWR12	1,733,719	1,130,772	111,631	2,976,122	–2,976,122	0
Inert gas system - primary salt cover gas					20,000,000	20,000,000
Inert gas system - reactor building					5,000,000	5,000,000
Reactor makeup water system	1,915,795	1,317,314	349,087	3,582,197	–3,582,197	0
Primary salt drain and storage system					8,000,000	8,000,000
Intermediate/DRACS salt drain and storage system					8,000,000	8,000,000
Coolant treatment systems (NSSS allocation)	19,368,720	0	0	19,368,720	–19,368,720	0
Primary salt treatment system					50,000,000	50,000,000
Intermediate/DRACS salt treatment system					30,000,000	30,000,000
Chemical and volume control system	7,970,465	11,967,763	1,377,298	21,315,526	–21,315,526	0
Boron recycle system	8,406,223	3,716,875	901,730	13,024,829	–13,024,829	0
Fluid leak detection system	372,715	40,471	2,023	415,210		415,210
Nuclear service water system	12,544,956	13,047,182	1,257,266	26,849,405	–10,000,000	16,849,405
Primary component cooling water	11,189,940	7,694,474	758,558	19,642,973	–15,000,000	4,642,973
Primary component cooling gas						
Maintenance equipment (NSSS allocation and field cost)	2,152,080	163,560	1,110,473	3,426,113		3,426,113
Sampling equipment	874,382	603,192	64,958	1,542,533		1,542,533
Account 226 total cost	**66,528,996**	**39,681,605**	**5,933,026**	**112,143,626**	**35,732,606**	**147,876,233**

An exceptionally large ($71 million) increase is seen in the PWR12 ME data set, mostly attributed to additional field labor cost. This may be the result of incomplete design and protracted construction schedules.

The improved PWR 12 data set shows a net decrease of $10 million, with a shift of $14 million from field to factory cost. This reflects increased use of modular fabrication and skid installation techniques.

Account 227—Reactor Instrumentation and Control

At a fundamental level, the scope of reactor instrumentation and control is essentially the same for the AHTR as in any similar power plant. Detailed instrument counts are beyond the scope of this initial report.

The main adjustment made here is the modernization of control systems, with increased use of distributed, digital control systems. The improved PWR data set identified this as a cost reduction but shows only a $500,000 reduction.

As an initial adjustment, an overall 25% reduction is made to this account. This is shown on a separate, added line in Table 27.

Table 27. Reactor instrumentation and control—account 227 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
NSS control board	2,463,067	867,245	43,363	3,373,675		3,373,675
Remote shutdown panels						
HVAC panels	200,249	132,977	6,648	339,874		339,874
Radwaste panels and racks	837,043	520,346	26,018	1,383,408		1,383,408
Logic panels and cabinets	800,998	520,346	26,018	1,347,362		1,347,362
Instrument racks	1,057,318	404,714	20,237	1,482,269		1,482,269
Alarm system	570,158	144,542	7,226	721,927		721,927
Process computer	6,897,221	828,576	82,858	7,808,654		7,808,654
Radiological monitoring and data management	2,284,109	578,162	28,908	2,891,179		2,891,179
Neutron monitoring system	2,602,723	809,426	40,471	3,452,621		3,452,621
Instrumentation for monitoring course of an accident	314,530	86,726	4,337	405,593		405,593
Reactor diagnostic system	1,034,014	289,082	14,455	1,337,551		1,337,551
Containment atmosphere monitoring	471,792	289,082	14,455	775,330		775,330
Containment leak monitor	235,896	144,542	14,455	394,894		394,894
Failed fuel detection	212,306	132,977	13,298	358,582		358,582
Reactor power control	1,965,804	578,162	57,816	2,601,782		2,601,782
Reactor protection system	2,358,965	722,705	72,271	3,153,941		3,153,941
Engineered safety feature actuation system	1,376,062	462,530	46,253	1,884,845		1,884,845
Standard NSSS valve package (NSSS allocation)	21,520,800	0	0	21,520,800		21,520,800
Reactor plant I&C tubing and fittings	461,100	8,094,274	809,426	9,364,800		9,364,800

Table 27. Reactor instrumentation and control—account 227 (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
TMI instrumentation	5,474,467	2,890,812	289,082	8,654,362		8,654,362
Modernization allocation					–18,000,000	–18,000,000
Account 227 total cost	**53,138,621**	**18,497,230**	**1,617,598**	**73,253,448**	**–18,000,000**	**55,253,448**

Account 228—Reactor Plant Miscellaneous Items

In the PWR12 data sets, this account includes a few miscellaneous cost items such as field painting and insulation.

For the AHTR, this account is used to track preheat and insulation systems used for all salt-containing vessels, pools, and piping. Values are not yet based on designs and should not be regarded as quantitative estimates.

The addition of salt system preheating equipment and insulation to the scope of this account replaces the traditional NSSS insulation costs. Other miscellaneous cost items are retained, as shown in Table 28.

Table 28. Reactor plant miscellaneous items—account 228 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Field painting	0	1,190,592	387,050	1,577,642		1,577,642
Qualification of welders	0	6,079,200	910,733	6,989,933		6,989,933
Pipe insulation	0	1,552,512	2,509,666	4,062,178	–4,062,178	0
Equipment insulation	0	298,560	919,250	1,217,810	–1,217,810	0
NSSS insulation	0	1,134,528	2,903,369	4,037,897	–4,037,897	0
Reactor assembly preheat and insulation systems					30,000,000	30,000,000
Intermediate circuit preheat and insulation systems					15,000,000	15,000,000
DRACS preheat and insulation systems					10,000,000	10,000,000
Fuel transfer pool preheat and insulation systems					5,000,000	5,000,000
Account 228 total cost	**0**	**10,255,392**	**7,630,068**	**17,885,460**	**50,682,115**	**68,567,575**

Because this account covers mostly new AHTR cost, comparisons to other data sets are not warranted.

Summary of Account 22 Cost

The net increase in the reactor equipment account is about \$75 million, giving a total cost of \$803 million. Most of the changes are based only on preliminary engineering judgment and should not be considered quantitative.

Some of the more significant changes for which development and design tasks should be considered are

- replacement of a single high-pressure water coolant system with low-pressure, high-temperature primary and intermediate salt heat transfer circuits;
- replacement of traditional residual heat removal and safety injection systems with a DRACS system;
- changes in radioactive waste systems to reflect wastes produced by salt chemical purification systems and by the addition of a tritium control system for gaseous wastes;
- inclusion of a remote in-vessel fuel handling system and equipment to move fuel through an intermediate salt transfer pool;
- replacement of traditional coolant chemical and volume control and boron recycle systems with salt drain and storage systems and salt chemical treatment systems;
- addition of high purity cover gas over salt systems; and
- addition of salt system preheat and insulation systems.

Significant changes in projected cost should be anticipated as these systems become more defined and better cost data is available.

8.2.4 Turbine-Generator Equipment—Account 23

Accounts 231 through 237 cover the turbine-generator equipment, beginning with supercritical fluid or steam from steam generators (PWR) or salt-to-water heat transfer equipment (AHTR) and ending with electricity at the generator outputs. All steam and feedwater piping and equipment are included, as is support equipment for the turbine-generators such as hydrogen coolant for the generators, lubricating oil systems, and instrumentation and controls. These accounts add up to \$537 million in the PWR BE data set, representing 15% of the total capital cost and 25% of the direct capital cost.

The AHTR design is based on a traditional supercritical Rankine power cycle commonly implemented in pulverized-coal power plants, although the operating temperature is somewhat higher to maximize thermal efficiency consistent with the high temperature reactor. This allows comparisons with coal-fired power plant systems, which have been constructed in far greater numbers than nuclear power plants. Data from the report *Market-Based Advanced Coal Power Systems*[17] is combined with data from the PWR12 BE data set in Table 29. Reactor plant data is escalated to January 1998, the cost year used in the fossil plant study. The top portion of Table 29 lists the operating parameters for each type of plant. The three coal-fired plants all operate at about 425 MW gross electrical output; the PWR12 plant is larger with gross electrical output of 1192 MW. Efficiencies range from 33.5% for the nuclear plant to 41.4% for the ultra-supercritical coal-fired plant.

Table 29. Comparison of turbine-generator parameters and cost[a]

Pulverized coal plant parameters and cost	PWR12	Subcritical	Supercritical	Ultra-Super
Throttle pressure, psig	975	2,400	3,500	4,500
Throttle temperature, °F	542	1,000	1,050	1,100
Reheat outlet temperature, °F	519	1,000	1,050	1,100
Second reheat outlet temperature, °F				1,100
Gross power at generator, kW(e)	1,192,000	422,224	427,100	425,000
Net power, kW(e)	1,144,000	397,482	401,823	399,661
Ratio to subcritical gross power	2.823	1.000	1.012	1.007
Cycle efficiency	33.5%	37.6%	39.9%	41.4%
Calculated total thermal power, kW(e) (based on net power output)	3,416,965	1,057,133	1,007,075	965,365
Turbine rating	1192 MW TC6F43	550 MW TC4F30	435 MW TC4F30	435 MW
Costs, based on January 1998 dollars, in thousands				
Steam turbine-generator				
Equipment	162,640	30,684	33,394	34,999
Material	607	0	0	0
Labor, direct	5,950	5,055	5,502	5,766
Labor, indirect		354	385	404
Subtotal, bare erected cost	169,197	36,093	39,281	41,169
Ratio to subcritical system cost	4.688	1.000	1.088	1.141
Turbine plant auxiliaries and steam piping				
Equipment	14,795	11,740	11,839	11,797
Material	1,594	358	361	359
Labor, direct	13,159	6,439	6,493	6,470
Labor, indirect		451	455	453
Subtotal, bare erected cost	29,549	18,988	19,148	19,079
Ratio to subcritical system cost	1.556	1.000	1.008	1.005
Feedwater and balance of plant systems				
Equipment	20,846	15,953	16,550	16,924
Material	940	0	0	0
Labor, direct	9,438	6,963	7,175	7,397
Labor, indirect		487	502	518
Subtotal, bare erected cost	31,224	23,403	24,227	24,839
Ratio to subcritical system cost	1.334	1.000	1.035	1.061
Overall T-G, steam and feedwater cost	229,970	78,484	82,656	85,087
Ratio to subcritical system cost	2.930	1.000	1.053	1.084

[a] PWR12 costs escalated from 1987 to 1998 using COE power plant factor of 1.324.
PWR 12 costs for feedwater may not include cost for other BOP systems as with fossil plants.
Scope of PWR 12 turbine-generator set may be larger than scope of coal units.

One observation is the level of consistency between two completely independent data sets. The overall cost for the turbine-generator, steam, and feedwater systems from the PWR12 BE data set is 2.9 times that of the subcritical coal data set. This is very similar to the ratio of turbine ratings (2.8), although the method of using exponential factors to adjust for differences in equipment sizes would suggest that the PWR12 BE cost would be lower. The purchase cost for the turbine-generator set appears high relative to the coal units; the supporting system costs might be slightly low considering the relative size of the systems. Table 29 also shows that the cost differential between subcritical and supercritical units is not large.

The relatively high cost of the nuclear turbine-generator set may also be a factor of the low steam pressure and temperature, relative to the coal-fired units. One of the advantages of the AHTR is the improvement of steam conditions entering the turbines.

The current basis for the AHTR is two turbine-generator sets. At an efficiency of about 45%, each would have a rated electrical output of 825 MW. Using Corps of Engineers escalation factors for power plants between the 1998 basis of the fossil plant data and January 2011, and a power exponent of 0.50 to adjust from 435 to 825 MW (Ref. 19), the ultra-supercritical plant identified in Table 29 would have a vendor cost of about $73 million. Two units would cost about $149 million. This is significantly less than the $294 million in the escalated PWR12 BE estimate.

Similar ratios (just over 2) could be used to compare the steam piping, feedwater system, and auxiliaries cost. These parameters will be considered in adjusting the PWR12 BE cost basis for each three-digit account.

Account 231—Turbine Generator(s)

Based on the analysis above, two ultra-supercritical AHTR turbine-generator sets would cost $149 million, rather than $295 million. The AHTR does, however, operate at a higher temperature. As a conservative approach, the PWR12 BE data will be reduced by $100 million to account for improved turbine operating conditions and better reflect the fossil plant experience.

Moisture separators are not needed with the AHTR power cycle, and the reheater has already been covered in account 222. Thus, costs for the reheater/moisture separator are dropped. Because of the large adjustment in the turbine-generator purchase cost, the other smaller accounts are left unadjusted. The results of these adjustments are shown in Table 30.

Table 30. Turbine generators—account 231 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Turbine-generator purchase	294,887,040	0	0	294,887,040	–100,000,000	194,887,040
Other turbine-generator cost	0	10,454,659	1,045,440	11,500,099		11,500,099
Associated piping	0	333,545	55,090	388,634		388,634
Turbine generator pedestal	0	3,966,427	1,739,904	5,706,331		5,706,331
Reheater/moisture separator supports	1,027,848	498,960	49,896	1,576,704	–1,576,704	0

Table 30. Turbine generators—account 231 (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Lubricating oil system	689,402	414,370	213,151	1,316,923		1,316,923
Hydrogen storage system	437,885	481,692	48,168	967,745		967,745
Carbon dioxide storage system	284,998	311,522	31,152	627,672		627,672
Moisture separator/reheater drain system	2,551,207	1,855,171	184,728	4,591,106	–4,591,106	0
Account 231 total cost	**299,878,380**	**18,316,346**	**3,367,529**	**321,562,255**	**–106,167,810**	**215,394,445**

Because the cost basis has shifted toward the fossil plant studies, comparisons to the PWR12 ME and improved PWR12 data sets are not relevant.

Account 233—Condensing Systems

The AHTR condensing systems are expected to be fairly conventional, condensing steam from the low-pressure turbines using water from a cooling tower. Because of the higher thermal efficiency, the amount of heat carried in the condensing equipment is slightly less than with the PWR12 system. Using a 0.50 exponent on the ratio of discharged heat would lead to a factor of 0.92, indicating that there might be a $6 million reduction in cost. However, there are also more components since two turbine-generator sets are being serviced. At this time, it is assumed that the effects of the reduced heat load and the extra components roughly offset, and no adjustments are made to the PWR12 BE data set, shown in Table 31.

Table 31. Condensing systems—account 233 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Condenser equipment	26,640,000	4,650,530	465,053	31,755,583		31,755,583
Condensate system	13,264,188	13,473,247	2,176,198	28,913,633		28,913,633
Gas removal system	1,704,341	868,114	84,485	2,656,939		2,656,939
Turbine bypass system	578,916	0	0	578,916		578,916
Condensate polishing	5,266,169	350,479	35,047	5,651,695		5,651,695
Account 233 total cost	**47,453,614**	**19,342,370**	**2,760,782**	**69,556,766**	**0**	**69,556,766**

The PWR12 ME data set shows a $22 million increase, mostly in site labor. The improved PWR12 data set shows an $8 million reduction, with $4 million of cost shifted to factory fabrication.

Account 234—Feed Heating Systems

The output of the two turbine-generator sets in the AHTR is greater than that of the PWR12, but the larger temperature differential means that less feedwater is circulated and equipment should be smaller. There are two systems in the AHTR that would tend to increase cost. The AHTR feedwater system operates at higher pressure, tending to increase cost. The PWR12 BE feedwater heating system cost seems low in the comparison shown in Table 29, suggesting that an upward cost adjustment might be warranted. However, without more specific design data, the lower amount of water circulated is assumed to offset the other factors and no adjustment to the cost data in Table 32 is made at this time.

Table 32. Feedwater heating system—account 234 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Feedwater heaters	10,131,226	1,437,926	143,791	11,712,943		11,712,943
Feedwater system	21,572,832	11,249,796	1,121,590	33,944,218		33,944,218
Extraction steam system	2,008,750	1,927,802	191,098	4,127,650		4,127,650
Feedwater heater vent and drain system	4,083,943	2,497,392	246,977	6,828,312		6,828,312
Account 234 total cost	**37,796,750**	**17,112,917**	**1,703,455**	**56,613,122**	**0**	**56,613,122**

The PWR12 ME data set shows the usual trend in higher labor cost, likely due to longer construction times. The improved PWR data set moves more cost to factory materials with an overall reduction of about $9 million.

Account 235—Other Turbine Plant Equipment

The largest cost element in this account is the main vapor (steam and supercritical fluid) piping system. The AHTR will have higher pressure piping with more pipe segments (with two turbine-generator sets). However, the piping will be smaller. At this time, the two factors are considered offsetting, and no adjustment is made.

There is no clear basis for adjusting the turbine cooling water system cost, and no adjustment is made to that line. Costs for chemical treatment and neutralization equipment are small and not addressed further. The PWR12 BE data set is shown in Table 33.

Table 33. Other turbine plant equipment—account 235 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Main vapor piping system	15,071,777	15,848,429	1,604,179	32,524,385		32,524,385
Turbine auxiliaries	17,506	40,440	6,679	64,625		64,625
Turbine closed cooling water system	6,491,184	4,811,592	480,396	11,783,172		11,783,172
Demineralized water makeup system	4,227,739	2,343,967	673,260	7,244,966		7,244,966
Chemical treatment system	159,763	65,926	12,823	238,512		238,512
Neutralization system	857,604	748,805	113,597	1,720,006		1,720,006
Account 235 total cost	**26,825,573**	**23,859,158**	**2,890,934**	**53,575,666**	**0**	**53,575,666**

The PWR12 ME data set shows a large $43 million increase, mostly in labor cost but also in factory and site materials. The improved PWR data set moves $5 million to factory materials, with an overall reduction of about $9 million.

Account 236—Instrumentation and Control

The cost reduction from the use of modern instrumentation and control equipment is offset by the increased instrument counts arising from the use of two turbine-generator sets. No adjustments are made to Table 34 at this time.

Table 34. Turbine plant instrumentation and control—account 236 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Process instrumentation and control equipment	4,017,370	2,636,424	108,696	6,762,490		6,762,490
Turbine plant instrumentation and control tubing	465,926	8,383,356	838,337	9,687,619		9,687,619
Account 236 total cost	**4,483,296**	**11,019,780**	**947,033**	**16,450,109**	**0**	**16,450,109**

There is a $3 million increase in the PWR12 ME data set and a $1.5 million decrease in the improved PWR data set.

Account 237—Turbine Plant Miscellaneous Items

Because there are two turbine-generator sets, an increase in painting and insulation might arise. However, the units are likely to be physically smaller, and thus no adjustments are made in Table 35.

Table 35. Turbine plan miscellaneous items—account 237 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Field painting	0	2,515,968	664,932	3,180,900		3,180,900
Qualification of welders	0	3,647,520	546,439	4,193,959		4,193,959
Turbine plant insulation	0	4,896,384	7,038,917	11,935,301		11,935,301
Account 237 total cost	**0**	**11,059,872**	**8,250,288**	**19,310,160**	**0**	**19,310,160**

There is an increase of $3 million in labor hours in the PWR12 ME data set and almost no change in the improved PWR12 data set.

Summary of Account 23 Cost

A major adjustment to the cost for turbine-generator equipment is the procurement of two supercritical water turbine-generator sets as opposed to a single low-pressure, low-temperature turbine-generator set typical of light-water reactors. Costs for the large reheater/moisture separators found in PWRs are also removed as the steam reheater is built into the salt-to-water heat exchanger set. There are offsetting cost drivers for most other 23 series accounts. The net reduction in cost for turbine-generator equipment is $106 million, bringing the total cost of this account down from $537 million to $431 million.

As always, this is a cursory analysis and the cost adjustments should not be considered quantitative.

8.2.5 Electrical Equipment—Account 24

This account includes switchgear, station service equipment, switchboards, protective equipment, electrical raceways, conduit, and wiring. It represents 6% of total capital cost and 9% of direct capital cost.

Because the AHTR is not dependent on active systems for reactor safety, there are no class 1E electrical requirements. Costs for such systems are reduced by about 25% to reflect standard construction. Specific lines are added as appropriate to address salt system heater power. No estimates of overall station loads have yet been developed, so other loads and costs are assumed to be similar to the PWR BE.

Account 241—Switchgear

Costs for class 1E electrical systems are reduced by 25% to reflect typical construction methods. An allocation of $4 million is added to cover the additional loads for salt system electrical heaters. Other entries are left unadjusted, as seen in Table 36.

Table 36. Switchgear—account 241 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Generator equipment switchgear:						
Generator load break switch	3,084,000	73,097	7,310	3,164,407		3,164,407
Generator neutral grounding equipment	0	80,578	16,198	96,775		96,775
Generator Current and potential transformer	0	46,044	63,559	109,603		109,603
Station service switchgear:						
Non-class 1E 13.8 kV	7,863,060	184,178	18,418	8,065,656		8,065,656
Non-class 1E 4.16 kV	4,019,153	115,111	11,510	4,145,774		4,145,774
Class 1E 4.16 kV	7,958,693	184,178	18,418	8,161,289	–2,000,000	6,161,289
Diesel generator sequence logic panels	613,440	75,396	7,541	696,377		696,377
Additional switchgear for salt system heaters					4,000,000	4,000,000
Non-class 1E 480V motor control centers	1,842,070	345,331	34,534	2,221,934		2,221,934
Class 1E 480V motor control centers	1,629,398	345,331	34,534	2,009,263	–500,000	1,509,263
Account 241 total cost	**27,009,814**	**1,449,245**	**212,021**	**28,671,079**	**1,500,000**	**30,171,079**

Little change is seen in the PWR12 ME data set, and a $2 million decrease is seen in the improved PWR12 data set (possibly as a reduction of class 1E requirements).

Account 242—Station Service Equipment

Cost for class 1E load centers, transformers, and battery systems are reduced by 25%. Costs for diesel generators are reduced by $10 million, as emergency power is not a safety-related function. Additional lines are added for switchgear and transformers to power salt system heaters. Data is summarized in Table 37.

Table 37. Station service equipment—account 242 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Station service and startup transformer	5,161,553	605,174	184,666	5,951,393		5,951,393
Non-class 1E load center switchgear	3,659,210	656,131	65,614	4,380,955		4,380,955
Class 1E load center switchgear	2,322,578	368,354	36,835	2,727,768	–700,000	2,027,768
Salt system heating equipment load center switchgear					2,000,000	2,000,000
Nonclass 1E load center transformers	1,012,320	49,217	4,922	1,066,459		1,066,459
Class 1E load center transformers	604,171	25,325	2,532	632,028	–150,000	482,028
Salt heater load center transformers					500,000	500,000
Miscellaneous transformers	63,914	74,822	7,483	146,220		146,220
Non-class 1E batteries	241,954	74,249	7,426	323,628		323,628
Class 1E batteries	283,195	148,493	14,849	446,537	–100,000	346,537
Non-class 1E charger	128,206	43,166	4,318	175,690		175,690
Class 1E charger	208,063	71,947	7,195	287,206	–100,000	187,206
Emergency diesel generator systems	28,849,234	1,321,272	349,183	30,519,689	–10,000,000	20,519,689
TMI emergency power supply	962,489	287,777	28,778	1,279,044		1,279,044
Non-class 1E inverters	206,510	6,329	634	213,473		213,473
Class 1E inverters	228,113	12,662	1,267	242,042	–50,000	192,042
Account 242 total cost	**43,931,510**	**3,744,919**	**715,702**	**48,392,131**	**–8,600,000**	**39,792,131**

Little change is seen in the PWR12 ME data set, and a $2.6 million reduction is seen in the improved PWR data set. The latter may be the result of reduced class 1E requirements.

Account 243—Switchboards

Additional AC distribution panels are included for salt system heating equipment. No DC power is expected for salt heating systems. Class 1E equipment cost is reduced by 25%. The results are shown in Table 38.

Table 38. Switchboards—account 243 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Generator and auxiliary power systems control panel	932,935	287,777	28,778	1,249,490		1,249,490
Generator protective relay panel	701,962	218,710	21,871	942,542		942,542
TSC and OSC system control panels	1,625,678	86,335	8,633	1,720,646		1,720,646
Non-class 1E AC distribution panels	32,446	18,415	1,841	52,702		52,702
Class 1E AC distribution panels	69,240	29,928	2,993	102,161	–50,000	52,161
Salt system heating power distribution panels					50,000	50,000
Non-class 1E DC distribution panels	97,421	20,143	2,014	119,578		119,578
Class 1E DC distribution panels	311,746	80,578	8,057	400,380	–100,000	300,380
Miscellaneous pushbuttons, panels and fuses	0	104,902	224,954	329,856		329,856
Account 243 total cost	**3,771,427**	**846,787**	**299,141**	**4,917,355**	**–100,000**	**4,817,355**

Little change is seen in either the PWR12 ME or the improved PWR12 data sets.

Account 244—Protective Service Equipment

At present, no basis is seen for adjusting the protective service equipment account. Costs for protective service equipment are shown in Table 39.

Table 39. Protective equipment—account 244 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
General station grounding system	0	4,353,456	1,636,433	5,989,889		5,989,889
Lightning protection	0	177,751	175,642	353,393		353,393
Cathodic protection	0	868,358	824,083	1,692,442		1,692,442
Heat tracing and freeze protection	0	582,792	1,608,811	2,191,603		2,191,603
Account 244 total cost	**0**	**5,982,358**	**4,244,969**	**10,227,326**	**0**	**10,227,326**

Only a small cost increase is seen in the PWR12 ME data set, and there is essentially no change in the improved PWR12 data set.

Account 245—Electrical Raceway Systems

Cost for class 1E underground duct banks are reduced by 25%. No adjustment is made for additional salt heating power wiring. Cost for this account is shown in Table 40.

Table 40. Electric power structure and conduit—account 245 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Nonclass 1E underground duct banks	0	1,665,319	692,244	2,357,563		2,357,563
Class 1E underground duct banks	0	5,739,550	2,346,962	8,086,512	–2,000,000	6,086,512
Cable tray	0	7,479,554	3,093,552	10,573,106		10,573,106
Conduit	0	28,271,242	4,235,616	32,506,858		32,506,858
Account 245 total cost	**0**	**43,155,665**	**10,368,374**	**53,524,039**	**–2,000,000**	**51,524,039**

The PWR12 ME data set shows over double the cost of the BE set, almost entirely in field labor. This may have been influenced by rework as fire protection standards changed.

A substantial reduction of nearly $24 million is seen in the improved PWR data set. Reasoning for this should be considered for adoption in the AHTR concept.

Account 246—Power and Control Cables and Wiring

An entry is added for salt system heater power wiring. It is assumed that modernization of control systems more than offset any increase from salt system heater controls, and costs for control cable and instrument wiring are reduced. Cost for containment penetrations is unchanged. The results are seen in Table 41.

Table 41. Power and control wiring—account 246 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Generator circuits wiring	2,120,784	1,317,110	131,712	3,569,606		3,569,606
Station service power wiring	0	3,518,755	2,969,208	6,487,963		6,487,963
Salt heater power wiring					2,000,000	2,000,000
Control cable	0	11,839,421	7,904,208	19,743,629	-9,000,000	10,743,629
Instrument wire	0	10,650,526	6,393,240	17,043,766	-7,000,000	10,043,766
Containment penetrations	1,678,668	835,430	83,544	2,597,642		2,597,642
Account 246 total cost	**3,799,452**	**28,161,242**	**17,481,912**	**49,442,606**	**-14,000,000**	**35,442,606**

The PWR12 ME data set is about $30 million higher, with almost all the change in field labor. This may have been influenced by rework as fire protection standards changed. A significant reduction of cost is seen in the improved PWR data set. Reasoning for this reduction should be explored and considered for the AHTR.

Summary of Account 24 Cost

The net sum of changes, mostly reclassifying equipment from class 1E to nonclass 1E and addition of salt heating system power, leads to a net change of $7 million, reducing the total cost for electrical equipment from $195 million to $188 million.

8.2.6 Heat Rejection Equipment—Account 25

Heat rejection equipment is in account 25 in the GenIV cost code of accounts. It is account 26 in the EEDB data base. The two are essentially swapped; the content under the heading is the same in both systems.

Heat rejection equipment represents 3.4% of all capital cost and 5.4% of direct capital cost. It is dominated by the cost of the large, natural draft cooling towers. Other costs cover structures and equipment associated with the main circulating cooling water system that removes heat from the turbines.

Account 251—Structures

Changes in the amount of heat rejected in the AHTR, as compared to the PWR12, are not sufficiently large to affect the structures identified in Table 42. No adjustments are made.

Table 42. Main heat rejection systems structures—account 251 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Makeup water intake structure	18,970	1,537,085	892,793	2,448,847		2,448,847
Circulating water pump house structure	0	3,182,513	1,335,557	4,518,070		4,518,070
Circulating water pump house services	238,054	201,338	63,588	502,980		502,980
Makeup water pretreatment building	0	1,237,781	1,171,546	2,409,326		2,409,326
Makeup water pretreatment building services	163,224	278,510	77,570	519,305		519,305
Account 251 total cost	**420,247**	**6,437,227**	**3,541,054**	**10,398,528**	**0**	**10,398,528**

The PWR12 ME data set shows an additional $3 million, mostly in site labor. There is very little change in the improved PWR12 data set.

Account 252—Mechanical Equipment

Because of the higher thermal efficiency of the AHTR, the amount of heat rejected is reduced from about 2250 MW to 1870 MW. Using a power exponent of 0.50, this leads to an extrapolation factor of just under 0.92. These reductions are applied to the circulating water equipment and the cooling towers themselves. Other items shown in Table 43 are assumed to be unaffected by the modest change in load.

Table 43. Main heat rejection mechanical equipment—account 252 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Water intake equipment	857,244	229,886	26,098	1,113,228		1,113,228
Circulating water system	19,965,254	11,699,902	1,813,106	33,478,262	–2,778,696	30,699,567
Cooling towers	49,510,414	17,792,028	1,776,600	69,079,042	–5,733,560	63,345,481
Cooling tower basins	0	98,791	97,524	196,315		196,315
Main cooling tower makeup and blowdown system	2,788,774	414,406	85,762	3,288,941		3,288,941
Account 252 total cost	**73,121,686**	**30,235,013**	**3,799,090**	**107,155,788**	**–8,512,256**	**98,643,532**

The PWR12 ME data set shows an additional $15 million, mostly in site labor. There is very little change in the improved PWR12 data set, relative to the total cost of this account.

Summary of Account 25 Cost

Because of the higher AHTR thermal efficiency and the lower amount of heat discharged, cost for the main heat rejection equipment is reduced by $9 million, from $118 million to $109 million.

8.2.7 Miscellaneous Equipment—Account 26

Miscellaneous equipment represents 3.2% of total capital cost, 5.2% of direct capital cost. The largest cost subaccount covers air, water, and steam service systems. Other accounts cover lift equipment, communications equipment, fixtures and furnishings, and wastewater processing. Only one minor adjustment is made to the miscellaneous equipment accounts. Miscellaneous equipment is numbered as the 25 series of accounts in the EEDB; the EMWG code of accounts is used here.

Account 261—Transportation and Lift Equipment

The main scope of transportation and lift equipment consists of overhead cranes. One crane is added to serve the supercritical fluid and steam reheat equipment in the new bay attached to the turbine building. Cost is shown in Table 44.

Table 44. Transportation and lifting equipment—account 261 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Turbine building overhead crane	3,054,000	350,479	35,047	3,439,526		3,439,526
Heater bay crane	1,221,600	146,038	14,604	1,382,242		1,382,242
Supercritical steam bay crane					1,000,000	1,000,000
Reactor containment building crane	6,108,000	993,024	99,302	7,200,326		7,200,326
Misc. cranes, hoists and monorails	732,960	467,304	46,730	1,246,994		1,246,994
Diesel building cranes	1,026,144	81,780	8,179	1,116,103		1,116,103
Account 261 total cost	**12,142,704**	**2,038,625**	**203,863**	**14,385,192**	**1,000,000**	**15,385,192**

Account 262—Air, Water, Plant Fuel Oil, and Steam Service Systems

The scope and cost of service systems is hard to assess until further definition of the systems being served is completed. These costs are carried unadjusted at this time as seen in Table 45.

Table 45. Service systems—account 262 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Compressed air system	1,054,615	3,205,862	494,124	4,754,602		4,754,602
Containment building instrument air system	2,601,626	6,138,972	245,131	8,985,730		8,985,730
Service water system	4,625,760	4,668,218	467,508	9,761,486		9,761,486
Fire protection system	5,979,662	17,653,512	8,548,306	32,181,480		32,181,480
Potable water system	1,236,874	1,150,006	154,056	2,540,935		2,540,935
Auxiliary boiler system	2,762,270	1,656,883	210,830	4,629,984		4,629,984
Auxiliary boiler feedwater system	160,044	54,319	5,774	220,138		220,138
Auxiliary fuel oil system	26,782	30,151	4,390	61,322		61,322
Auxiliary deaerator and makeup system	149,316	58,718	5,873	213,907		213,907
Auxiliary chemical feed system	47,035	26,729	4,894	78,658		78,658
Auxiliary steam and condensate return	1,922,794	2,304,238	231,384	4,458,415		4,458,415
Auxiliary boiler blowdown	39,919	9,192	1,147	50,258		50,258
Auxiliary steam system complete I&C	340,454	202,358	10,118	552,931		552,931
Plant fuel oil system	0	214,315	237,408	451,723		451,723
Account 262 total cost	**20,947,152**	**37,373,474**	**10,620,943**	**68,941,570**	**0**	**68,941,570**

Account 263—Communications Equipment

Cost for personnel communications might be reduced to account for modern technology, but this would be offset by addition of a broadband system. The bulk of the cost in this account relates to the fire detection and alarm system, and the security system. Cost for security systems may have increased in recent years in response to new requirements, but no adjustment is made here. The unadjusted cost set is shown in Table 46.

Table 46. Communications equipment—account 263 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
General purpose telephone system	0	262,258	157,975	420,233		420,233
Public address and intercom system	0	1,165,584	478,711	1,644,295		1,644,295
Fire detection system	1,077,120	2,622,564	262,258	3,961,942		3,961,942
Security system	3,600,000	5,245,128	524,513	9,369,641		9,369,641
Account 263 total cost	**4,677,120**	**9,295,534**	**1,423,457**	**15,396,110**	**0**	**15,396,110**

Account 264—Furnishings and Fixtures

No meaningful basis for adjustments to the furnishings and fixtures account, shown in Table 47, exists at this time.

Table 47. Furnishings and fixtures—account 264 (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Safety equipment	0	16,272	34,320	50,592		50,592
Chemical laboratory shop	2,567,940	421,963	42,197	3,032,100		3,032,100
Office equipment and furnishings	315,300	9,348	936	325,584		325,584
Change room equipment	360,658	50,856	5,086	416,599		416,599
Environmental monitoring equipment	1,525,800	656,798	65,678	2,248,277		2,248,277
Dining facilities	437,268	50,856	5,086	493,210		493,210
Account 264 total cost	**5,206,966**	**1,206,094**	**153,302**	**6,566,362**	**0**	**6,566,362**

Account 265—Wastewater Treatment Equipment

The EEDB data set shows $1.8 million in factory cost, $4.5 million in site labor cost, and just under $0.5 million site material cost for a total of $6.8 million. No further breakdown is presented; no adjustment is made at this time.

Summary of Account 26 Cost

The only adjustment to the miscellaneous equipment accounts is the addition of an overhead crane to serve the supercritical fluid/steam heating bay. This brings the total from $112 million to $113 million.

The only interesting comparison to the PWR12 ME and improved PWR12 data sets is for the air, water, steam, and other service systems. In the PWR12 ME case, an additional $53 million is shown, mostly in site labor. This likely follows trends for an overall increase in construction time and possibly system rework. In the improved PWR12 case, a $5 million decrease is shown with just over $3 million shifted to factory materials. This would reflect increased use of prefabricated equipment modules.

8.2.8 Special Materials—Account 27

This cost code is to be used for special materials cost. For the AHTR, the most costly special material is the primary salt, especially the beryllium and ^{7}Li in the 2LiF-BeF$_2$ primary salt.

An early estimate based on the volume of the primary system (assuming the total volume is twice the volume of the reactor) shows that about 2,950 metric tons of salt will be needed. Of this, about 268 ton is beryllium and 417 ton is ^{7}Li of high isotopic purity. The ^{7}Li is used because the ^{6}Li isotope absorbs neutrons and forms undesirable tritium.

Various assessments have been made of the cost of salt components.[5,30] A 1971 review, documented in ORNL/CF-71-8-10,[30] gives a price of $120/kg for 99.995% ^{7}Li in the form of LiF. Using the U.S. Bureau of Labor Statistics Producer Price Index (PPI), this would be equivalent to $558/kg in 2011 dollars. Current prices for laboratory quantities of ^{7}Li are as high as $2.5/g. Lithium-7 enrichment technology development is an active area of research, especially by the fusion energy community. The efficiency and cost of new technologies, based on electromigration characteristics of lithium isotopes in various media, shows promise for reducing the cost of ^{7}Li enrichment.

Beryllium is also an expensive commodity. The U.S. Geological Survey's *Minerals Commodity Summaries 2011*[31] evaluates overall beryllium metal production and consumption and provides data that indicates the cost of beryllium, as metal, would be about $500/kg. Table 48 summarizes the potential cost of the key primary salt components needed for a single AHTR.

Table 48. Cost of AHTR primary salt components

Salt material	Mass (kg)	Price ($/kg)	Cost (2011 $)
Be	210,094	500	105,047,183
^{7}Li	327,124	558	182,535,356
Subtotal			287,582,539
Other salt components			10,000,000
Total primary salt cost			**297,582,539**

The cost for salt materials, especially isotopically pure ^{7}Li, are not derived from technologies tailored to markets of this scale. Construction of new ^{7}Li isotope enrichment facilities may lead to a significantly reduced production cost. With sales approaching the prices shown in Table 48, capital costs for an enrichment facility might be recovered after supplying the first few AHTRs with salt. The $298 million shown in Table 48 is used as a reference cost in this study; parametric evaluations showing the impact of salt cost ranging from $100 million up to $900 million are included at the end of this chapter.

8.2.9 Simulator—Account 28

A plant simulator and operator training facility is not explicitly included in the EEDB PWR12 data sets. This account has been added in the Gen IV cost code of accounts.

A simulator and training facility may serve a single plant or may serve a group of identical plants. Because the approach toward training and simulators has not yet been established, cost for this account will not be included in the initial AHTR economic evaluation. A reactor upper assembly mockup may be useful for checkout of remote systems for maintenance and refueling; such a mockup could also be addressed in the future under this account.

8.2.10 Contingency on Direct Cost

Contingency is added to a project budget to account for unanticipated cost (not scope) encountered as the project advances. Because the EEDB was developed from allocations of cost from a number of completed projects, contingency was not pertinent.

Contingency is usually established through an evaluation of technical and construction risk associated with a project. This type of evaluation has not yet been performed for the AHTR. In order to provide a consistent comparison to the PWR12 BE case, contingency is not included at this time. The need to add contingency is noted in the conclusions.

8.2.11 Summary 20-Series Data for G4-ECONS

Table 49 summarizes the adjustments made throughout this section. This data (at the two-digit level) forms the input into G4-ECONS. Because more definition is needed to establish a basis, reactor equipment adjustments are not yet shown. Salt costs, simulator and training facility costs, and contingency are also not included in the table. Cost is listed in the Gen IV code of accounts, which differs slightly from the EEDB accounts. Cost for the initial core is calculated separately, and the direct cost listed here is not dependent on the fuel cycle or enrichment paramaters.

Table 49. Total adjusted direct costs for input into G4-ECONS (2011 dollars)[a]

Account	Account Description	PWR12 BE Total cost	AHTR adjustment	AHTR cost
211	Yardwork	59,982,046	2,000,000	61,982,046
212	Reactor containment building	155,606,498	–25,000,000	130,606,498
213	Turbine room and heater bay	55,565,592	7,500,000	63,065,592
214	Security building	3,268,692		3,268,692
215	Primary auxiliary building and tunnels	44,333,148		44,333,148
216	Waste processing building	34,481,563		34,481,563
217	Fuel storage building	23,709,847	6,000,000	29,709,847
218	Other structures	104,838,449	–22,028,084	82,810,365
21	*Structures and improvements subtotal*	*481,785,835*	*–31,528,084*	*450,257,751*
221	Reactor equipment	197,406,910		197,406,910
222	Main heat transfer transport system	152,881,006	9,692,710	162,573,716
223	Safeguards system	94,361,424	–32,905,184	61,456,240
224	Radwaste processing	50,261,777	23,249,426	73,511,203
225	Fuel handling and storage	29,121,984	22,239,600	51,361,584
226	Other reactor plant equipment	112,143,626	35,732,606	147,876,233
227	Reactor instrumentation and control	73,253,448	–18,000,000	55,253,448
228	Reactor plant miscellaneous items	17,885,460	50,682,115	68,567,575
22	*Reactor plant equipment*	*727,315,634*	*90,691,274*	*818,006,909*
231	Turbine generator	321,562,255	–106,167,810	215,394,445
233	Condensing systems	69,556,766	0	69,556,766
234	Feedwater heating system	56,613,122	0	56,613,122
235	Other turbine plant equipment	53,575,666	0	53,575,666
236	Instrumentation and control	16,450,109	0	16,450,109
237	Turbine plant miscellaneous items	19,310,160	0	19,310,160
23	*Turbine plant equipment*	*537,068,078*	*–106,167,810*	*430,900,268*

Table 49. Total adjusted direct costs for input into G4-ECONS (2011 dollars)[a] (continued)

Account	Account Description	PWR12 BE Total cost	AHTR adjustment	AHTR cost
241	Switchgear	28,671,079	1,500,000	30,171,079
242	Station service equipment	48,392,131	–8,600,000	39,792,131
243	Switchboards	4,917,355	–100,000	4,817,355
244	Protective equipment	10,227,326	0	10,227,326
245	Electric structure and wiring	53,524,039	–2,000,000	51,524,039
246	Power and control wiring	49,442,606	-14,000,000	35,442,606
24	*Electric plant equipment*	*195,174,538*	*–23,200,000*	*171,974,538*
251	Structures	10,398,528		10,398,528
252	Mechanical equipment	107,155,788	–8,512,256	98,643,532
25	*Main condenser heat rejection system*	*117,554,316*	*–8,512,256*	*109,042,060*
261	Transportation and lifting equipment	14,385,192	1,000,000	15,385,192
262	Air, water and steam service systems	68,941,570	0	68,941,570
263	Communications equipment	15,396,110	0	15,396,110
264	Furnishings and fixtures	6,566,362	0	6,566,362
265	Waste water treatment equipment	6,795,322	0	6,795,322
26	*Miscellaneous plant equipment subtotal*	*112,084,555*	*1,000,000*	*113,084,555*
27	*Special materials (primary salt components)*	*0*	*297,582,539*	*297,582,539*
	Total direct costs	**2,170,982,957**	**219,865,663**	**2,390,848,620**

[a] Changes to reactor equipment (account 221) not yet established.
Simulator and training facility costs (account 28) not included.
Contingency (account 29) not included.

The adjustments shown in the table should not be considered quantitative evaluations, and the final total does not represent a credible cost estimate for an AHTR. The table does show that there is about an even split between items for which cost is reduced and items for which cost is increased. Again, extraneous digits are retained to facilitate data checking. The addition of contingency and simulator/training facility cost would increase values for both the PWR and AHTR cases. Cost for the initial core is calculated separately; there is no difference in direct cost for the 19.75% and 9% enriched uranium AHTR cases.

8.3 INDIRECT CAPITAL COST EVALUATION

Indirect capital cost addresses design, quality assurance, project management, and construction management and supervision both at the architect-engineer’s home office and on the construction site. It also includes all of the temporary facilities needed to support the construction personnel, laydown and storage areas for materials and equipment, and tools. Indirect cost includes insurance, taxes, local permits, and other costs associated with the construction site. Because the number of personnel on the site during construction is much larger than the operating staff, the extent of construction support facilities is also large.

The Gen IV cost code of accounts for indirect costs differs significantly from the EEDB accounts. To enter data into G4-ECONS in the Gen IV accounts (accounts 31 through 38), the EEDB accounts 91, 92, and 93 are mapped into the Gen IV accounts. Account 31 contains data from EEDB account 921. Account 32 consists of EEDB accounts 922 and 923. No EEDB data appears to map into account 33. Account 34 contains data from EEDB account 933, and account 35 contains EEDB data from account 932. Account 36, field indirect costs, has data from EEDB accounts 911, 912, 913, 924, and 931. Account 37 contains EEDB account 934. There is no data for account 38 demonstration run (this account may be used for fuel cycle facilities). The resulting indirect cost data is shown, unadjusted, in Table 50.

Table 50. Indirect cost summary—30 series accounts (2011 dollars)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Design services at A/E home office—account 31						
Home office services	**482,090,400**	**0**	**0**	**482,090,400**	**0**	**482,090,400**
PM/CM services at A/E home office—account 32						
Home office construction mgmt.	11,181,600	0	0	11,181,600		11,181,600
Home office quality assurance	17,308,800	0	0	17,308,800		17,308,800
Home office design services total	**28,490,400**	**0**	**0**	**28,490,400**	**0**	**28,490,400**
Design services at plant site (field office)— account 33 (no data associated with this account)						
PM/CM services at plant site (field office)—account 34						
Field quality assurance and control	**14,625,600**	**5,320,800**	**0**	**19,946,400**	**0**	**19,946,400**
Construction supervision at plant site (field supervision— account 35						
Field job supervision	**175,005,600**	**16,281,600**	**0**	**191,287,200**	**0**	**191,287,200**
Field indirect costs (rentals, temp facilities, etc)—account 36						
Temporary construction facilities:						
Temporary buildings	0	63,724,800	10,226,400	73,951,200		73,951,200
Temporary facilities	0	133,845,600	36,957,600	170,803,200		170,803,200
Construction tools and equipment:						
Major equipment	0	17,664,000	69,175,200	86,839,200		86,839,200
Purchase of small tools	0	571,200	15,292,800	15,864,000		15,864,000
Expendable supplies	0	0	19,327,200	19,327,200		19,327,200
Safety equipment—inspection	0	571,200	823,200	1,394,400		1,394,400
Permits, insurance and local taxes	0	0	27,156,000	27,156,000		27,156,000
Field office expenses	0	1,456,800	27,628,800	29,085,600		29,085,600

Table 50. Indirect cost summary—30 series accounts (2011 dollars) (continued)

	Factory cost	Site labor cost	Site material cost	PWR12 BE cost	AHTR adjustment	AHTR cost
Payroll insurance and taxes	149,260,800	0	0	149,260,800		149,260,800
Construction supervision subtotal	**149,260,800**	**217,833,600**	**206,587,200**	**573,681,600**	**0**	**573,681,600**
Plant commissioning services—account 37						
Plant startup and test	**27,040,800**	**0**	**0**	**27,040,800**	**0**	**27,040,800**
Plant operation-demonstration run—account 38 (no data associated with this account)						
Total indirect cost (30 series accounts)	**876,513,600**	**239,436,000**	**206,587,200**	**1,322,536,800**	**0**	**1,322,536,800**

When preparing budgets, indirect cost is often estimated as a percentage of direct cost. Indirect cost varies considerably in the PWR12 BE, PWR12 ME, and improved PWR12 data sets. A comparison of the data for each of the indirect accounts, as a percentage of direct cost, is shown in Table 51. It is assumed that the PWR12 BE costs represent the costs of successful projects, such as one might use as a basis for future planning. Thus, the PWR12 ME indirect cost data is compared to the PWR12 BE direct cost, as though planners would have estimated direct cost at the better experience level. In the case of the improved PWR12, the direct cost reported is a new estimate, corresponding to changes in design and construction techniques. Thus, the improved PWR12 indirect cost is compared to its own direct cost.

Table 51. Indirect costs as percentage of PWR12 BE or improved PWR direct cost[a]

Account	PWR12 better experience	PWR12 median experience	Improved PWR12
Design services at A/E home office—account 31	*22.2%*	*51.4%*	*10.0%*
PM/CM services at A/E home office—account 32	*1.3%*	*2.5%*	*0.6%*
Home office construction management	0.5%	0.8%	0.2%
Home office quality assurance	0.8%	1.7%	0.4%
PM/CM services at plant site (field office)—account 34	*0.9%*	*3.5%*	*0.7%*
Construction field supervision at plant site—account 35	*8.8%*	*41.4%*	*6.6%*

Table 51. Indirect costs as percentage of PWR12 BE or improved PWR direct cost[a] (continued)

Account	PWR12 better experience	PWR12 median experience	Improved PWR12
Field indirect costs (rentals, temp facilities, etc.)—account 36	*26.4%*	*47.6%*	*22.9%*
Temporary construction facilities	11.3%	21.6%	9.3%
Construction tools and equipment	5.7%	9.3%	5.4%
Permits, insurance and local taxes	1.3%	1.8%	1.2%
Field office expenses	1.3%	2.2%	1.1%
Payroll insurance and taxes	6.9%	12.7%	5.8%
Plant commissioning services—account 37	1.2%	2.0%	0.9%
Total indirect cost (30 series accounts)	**60.9%**	**148.4%**	**41.7%**

[a] PWR 12 BE and ME data compared to PWR BE direct cost.
Improved PWR12 data compared to improved PWR12 direct cost.

The table shows that actual indirect cost in the median experience exceeds what planners might have expected by more than a factor of 2. This follows the general trend in comparing the data sets, where field labor cost show the greatest increase.

The biggest difference between the better experience and improved data sets is in design services at the architect-engineer's home site. The better experience shows a design cost that is just over 22% of indirect cost, whereas the improved PWR12 data set is based on an assumption that construction can be completed at a design cost that is 10% of direct cost. The basis for this rather low design estimate is that the plant is sufficiently standardized that most design information comes with the reactor procurement, and relatively little design is needed by the constructor. Other indirect costs for the improved case are generally slightly lower than the better experience case; some reduction in temporary construction facilities is likely associated with the greater use of prefabricated assemblies.

The selection of percentages of indirect cost is more important for developing a quantitative budget estimate than for comparing concepts. At this time, no adjustments are made, and the data shown in Table 50 is used for the G4-ECONS input sheet.

As with direct cost, contingency is not included in this evaluation. There is no difference in the indirect cost for the 19.75% and 9% enriched uranium AHTR cases.

8.4 OTHER CAPITALIZED COSTS

Most other categories of capitalized cost are not used in this analysis. A few exceptions are noted here; most cost is inferred by escalating cost for the existing example cases provided with the G4-ECONS package, especially from the System 80+ example in G4-ECONS case 1, presented in 2001 dollars.

8.4.1 Capitalized Preconstruction Cost (10 series accounts)

Capitalized preconstruction costs include such items as land, site permits, plant licensing and plant permits, studies, and reports. Of these, the example cases in the G4-ECONS model typically only use land cost. An allocation of $6 million is added to account 11 for both the PWR12 BE and the AHTR case entries, reflecting values used in the other cases.

8.4.2 Capitalized Owner's Cost (40 series accounts)

Capitalized owner's cost includes several categories of cost incurred prior to commercial operation but not covered in the direct or indirect cost categories. These include staff recruitment, training, housing, and other staff-related costs. Based on data entries for the other G4-ECONS example cases, an allocation of $300 million is added to account 46 for both the PWR12 BE and the AHTR to cover all capitalized owner's cost.

8.4.3 Capitalized Supplemental Costs (50 series accounts)

Capitalized supplemental cost covers various shipping and transportation costs, spare parts and supplies, taxes, insurance, or similar cost not addressed in the direct or indirect cost. None of the other example cases show cost in these accounts, and no cost is added to the PWR12 BE and AHTR cases.

Capitalized supplemental cost may also be used to directly enter the cost of the initial core, if a key in G4-ECONS is not set to calculate first core costs in the model. The model will be used to calculate first core costs for the PWR12 BE and AHTR cases, and no entry is made to account 56.

8.5 ANNUAL OPERATING COST EVALUATION

8.5.1 Operating and Maintenance Parameters

Data input to G4-ECONS falls into two categories. The first are the basic operating parameters that define electricity production of the plant. The second are the cost categories associated with operating staff, subcontracts, materials and consumables, other maintenance activities, and capital equipment replacement (expressed as a percentage of direct capital cost). Some of the data entries are based on the AHTR design, some are based on external references, and, for some entries, an initial allocation was made by reviewing entries for the sample cases in G4-ECONS. A summary of key operations and maintenance input data is shown in Table 52. Data are shown for a baseline sample case in G4-ECONS (a System 80+ reactor plant, expressed in 2001 dollars), the PWR12 BE plant, and the AHTR plant (both fuel enrichment cases are treated the same).

Table 52. Operations and maintenance data input to G4-ECONS (millions of 2011 dollars)

Reactor system **Year of estimate** **G4-ECONS case number**	**System 80+** **2001** **1**	**PWR12 BE** **2011** **8**	**AHTR** **2011** **9, 14**
Reactor net electrical capacity	1300	1144	1530
Reactor average capacity factor over life	0.90	0.90	0.92
Thermodynamic efficiency (net electric)	33.0%	33.5%	45.0%
Plant economic and operational life	40	40	40
Years to construct	6	6	6
On-site staffing cost	23.53	30.83	30.83
Pensions and benefits	6.29	8.23	8.23
Consumables	18.64	24.41	24.41
Repair costs	4.56	5.97	5.97
Purchased services and subcontracts	6.38	8.35	8.35
Insurance premiums and taxes	7.04	9.22	9.22
Regulatory fees	4.08	5.34	5.34
Radioactive waste management	0.00	0.00	0.00
Other general and administrative cost	7.97	10.43	10.43
Capital replacement as percent of direct capital	0.0%	0.5%	0.5%

The reactor net electrical capacity for the AHTR is based on a thermal power of 3400 MW and a net thermal efficiency of 45.0%, as discussed earlier in this report. Data for the PWR12 BE plant comes from the Technical Reference Book, and the System 80+ reference case is simply the data from the existing G4-ECONS worksheets.

Operation of commercial power reactors has improved in recent years to the extent that many plants achieve or exceed 90% availability. This basis was used in the System 80+ example and is similarly applied to the PWR12 BE case. The AHTR is designed to be refueled at temperature (as it must, since the salt must be liquid when the fuel is withdrawn from the core), and thus the time required to cool and depressurize a light-water power reactor is not a factor in AHTR refueling outages. This offers a reduced refueling outage time, with a tradeoff in the increased cost for remote fuel handling systems. An early assessment of a refueling option for the AHTR suggests that half the core can be changed out in a 3-day cycle. This would result in only 2% loss of availability due to refueling. Pending more detailed assessment of AHTR maintenance requirements that cannot be accomplished during scheduled refueling outages, a capacity factor of 92% is used.

The G4-ECONS supporting documentation warns that for many plants the early capacity factor is much lower than the eventual factor; since this is lifetime capacity factor, a reduction might be made for all the cases. This was not done for the example cases, however, and is not done in this assessment.

The plant construction time is taken to be 6 years, as was used for most of the example cases. For a truly NOAK plant, this may be shortened as a result of experience and optimization of plant construction techniques. The useful lifetime is set to 40 years, consistent with NRC licensing practice, although many LWRs are now having their licenses extended for an additional 20 years. This too mimics the example cases.

Permanent plant staff, including operators, maintenance personnel, security personnel, and administrative staff, is listed in the entries covering on-site staffing cost and pensions and benefits. Consumables, repair costs, and purchased services and subcontracts (which may cover maintenance and outage support, or may address other general administrative activities) are also listed. Other entries cover insurance premiums, taxes, and regulatory fees, and a final entry provides space for other general and administrative costs.

Several good references for operation and maintenance cost are available, especially for identifying typical LWR staff size and consumables cost. Two particular ORNL references were developed as part of the same effort as developed the EEDB.[32,33] A more recent analysis was performed by the DOE Energy Information Administration.[34] Other assessments have been made by organizations such as the Nuclear Energy Institute and the EUCG Nuclear Committee.

At this time, operation and maintenance cost was simply based on the data from the System 80+ example case, escalated from 2001 to 2011 using the producer price index for finished goods. The same data set was entered in both the PWR12 BE and the AHTR case input spreadsheet.

This approach toward staff and operating costs addresses security costs as incurred in the mid-1980s. Security costs may have increased in recent years. A further assessment of security cost recommended in Section 8.7.

Capital equipment replacement cost (addressing topics such as steam generator replacements that have proven necessary in existing PWRs) are set at 0.5% of total direct cost, consistent with some of the other examples (no entry was made for the System 80+ base case).

No cost is entered for charges on working capital or radioactive waste management, following the trends of other example cases in G4-ECONS. Contingency is also not included, consistent with other data sets used in this report. No difference in the operation and maintenance cost is projected for the 19.75% and 9% enriched uranium AHTR cases.

8.5.2 Fuel Cycle Cost

The uranium fuel cycle begins with mining and milling of ore, with a product of natural uranium oxide. This oxide is then converted to UF_6 and fed into an enrichment plant. The unit in which the cost of enriching uranium is expressed is the separative work unit (SWU). The tails, depleted in ^{235}U, are then converted back to oxide, stored for an interim period, and then shipped to a geologic disposal site. The enriched ^{235}U product is converted to oxide and used to fabricate fuel elements.

After there is no longer enough ^{235}U or other fissile isotopes to sustain fission, the “spent” or “used” fuel is removed from the reactor, held in storage pools, and eventually transferred out of the storage pools into some type of long-term, on-site storage (usually dry storage casks). A fee is paid to the U.S. government for the eventual geologic disposal of the used fuel.

Fuel cycle cost input for the PWR12 BE and AHTR reactors are shown in Table 53. Entries include the basic parameters that define the fuel cycle, including the type of fuel, number of assemblies, refueling parameters, and enrichment levels. The table also includes entries for typical enrichment plant operating parameters and unit costs for various fuel cycle activities.

Table 53. Fuel cycle data input to G4-ECONS (millions of 2011 dollars)[a]

Reactor system	**PWR12 BE**	**AHTR 19.75%**	**AHTR 9%**
G4-ECONS case number	**8**	**9**	**14**
Fuel assembly type	UO_X–PWR	UO_2 TRISO	UO_2 TRISO
Heavy metal mass in a fuel assembly, MT	0.423	0.1306	0.0659
Number of fuel assemblies in a full core	193	252	252
Number of fuel assemblies replaced in each refueling	86	252	126
Average time between refueling operations, years	1.5	2	0.5
Tails assay for uranium enrichment	0.30%	0.30%	0.30%
Enrichment level of uranium feed to enrichment plant	0.71%	0.71%	0.71%
Enrichment level of uranium fuel (initial core)	3.00%	19.75%	9.00%
Enrichment level of uranium fuel (reload average)	3.00%	19.75%	9.00%
Uranium ore (mining and milling), \$/lb U_3O_8	50	50	50
Oxide to UF_6 conversion, \$/kg U	10	10	10
Enrichment for non-reprocessed UF_6, \$/SWU	135	135	135
Fabrication of virgin enriched uranium fuel, \$/kg U	240	777	1541
Spent fuel storage external to reactor building, \$/kg HM	100	324	642
Depleted UF_6 conversion, storage, and geologic disposal as impure U_3O_8 (enrichment plant DUF_6 tails), \$/kg DU	6	6	6
Geological repository disposition of spent fuel (waste fee in mills/KWh)	1	1	1

[a] Fuel fabrication and spent fuel storage rates adjusted to give constant values on assembly basis.

Fuel parameters, such as number and type of fuel elements and mass of heavy metal in each element, were taken from tables presented in this report and the accompanying reactor core and refueling design studies report[6] (AHTR) or the Technical Reference Book[23] (PWR12 BE). Feed and tails ^{235}U isotopic percentages are typical values for natural uranium and enrichment plant operation, taken from the other G4-ECONS example cases.

Enrichment needs and the refueling cycle for the reference AHTR core (entire core reload every 2 years) were taken from the reactor core design report base case. An alternate case uses 9% enriched fuel and replaces half the fuel elements in the core every 6 months. The PWR12 BE data used is simply 3%, although actual practice and the Technical Reference Book both give a range of values bracketing 3%. The PWR12 BE data represents practices from the 1970s and 1980s and does not reflect the higher fuel enrichment and burnup typically encountered with PWRs today. No change is made for initial core, compared to reload fuel, in either the AHTR or PWR12 BE case.

Various internet sources show the spot market cost for uranium ore is about $50 per pound oxide, as of September 2011.

A discussion of enrichment cost in the G4-ECONS documentation[20] gives the historical cost range as between $80 and $150 per SWU. A paper from Stanford University[35] identifies a 2008 market price of $135/SWU, and that value is shown in Table 53. No penalty is entered at this time for enrichment beyond the typical 5% limit associated with current LWRs.

Fabrication cost for AHTR fuel assemblies has not yet been established. AHTR fuel is significantly different than PWR fuel. At this time, however, the example cost given in the G4-ECONS spreadsheet for System 80+ fuel assemblies has been escalated using the producer price index and is used as the basis for both the PWR12 BE and AHTR cases. Because data is entered into G4-ECONS as dollars per kilogram of uranium, the fabrication cost rate is adjusted by the ratio of uranium in a single assembly, giving a constant fabrication cost per assembly. Developing a more credible estimate for fabrication of AHTR fuel, which uses TRISO fuel in a graphite matrix that is entirely different from the pelletized uranium oxide used in LWRs, is a priority task to be performed in future years.

Costs for conversion of mined oxide to UF_6, conversion of depleted UF_6 back to oxide, disposal of depleted uranium oxide, and spent fuel storage beyond near-term storage in the spent fuel pool (presumably using dry cask storage) are based on System 80+ base case data escalated using the producer price index. Interim site storage rates were adjusted in a manner similar to the fuel assembly fabrication cost to provide a constant cost per fuel assembly. In accordance with the Nuclear Waste Policy Act, utilities pay 1 mill/kWh generated into the Nuclear Waste Fund.

8.6 ECONOMIC MODEL

8.6.1 Financial Parameters

The objective of this economic model is to compare the impact of the AHTR concept in terms of the cost of generating electricity and to evaluate the impact of AHTR design and fuel cycle alternatives on the LUEC. The G4-ECONS model used for this evaluation incorporates several simplifications into its financial model that streamline data entry and minimize the impacts of specific financial environments. It is not intended as a tool for optimizing the financial structure of a project. All data are manipulated in constant dollars, and one real (inflation-free) discount (interest) rate is used for all construction financing, capital amortization, and decontamination and decommissioning escrow fund calculations. Taxes are not directly addressed in the model but may be indirectly included by increasing the discount rate.

The model includes a flag that represents the risk of the project. For this evaluation, the traditional economic model of a regulated utility with a guaranteed market for the power generated is used. This model generally calls for a moderate discount rate and no taxes. A discount rate of 5% is used in the study. This rate reflects a moderate-risk project, has been used in many of the other ECONS example cases, and seems consistent with current financial conditions. The same financial parameters are used for all cases developed for this report, and should not impact the comparative evaluation.

8.6.2 G4-ECONS Model for AHTR and PWR12 BE

The Excel-based G4-ECONS software presents an integrated economic model for assessing the levelized unit electricity cost (LEUC) for advanced energy systems. It consists of a reactor model and a fuel cycle model. The version used is marked Version 2.0 Beta 2 and was retrieved as the file G4EconsVer_2-0_P_04Mar2008.xls. Data was entered into pre-existing empty columns for cases 8 (PWR12 BE), 9, and 14 (AHTR at 19.75% and 9% enrichment, respectively). Other existing cases were kept for purposes of comparison. In particular, the base System 80+ (case 1) and variants of that case were used to assess whether the output for the new cases 8 and 9 were reasonable. Several additional new cases were created to evaluate impacts of various changes in the input data.

Direct capital cost for both cases was entered as documented in Table 49, and indirect capital cost was entered as documented in Table 50. Indirect cost summary—30 series accounts (2011 dollars). Select other capital costs were entered as discussed in Section 6.4. Basic reactor parameters and nonfuel operating and maintenance data documented in Table 52 were used, and fuel cycle data was taken from Table 53.

Various switches and flags were set to establish the use of an open fuel cycle (repository disposition without processing of used fuel) and to establish electricity as the sole product. A flag was set to use the economic model for a regulated utility, as represented by a lower discount rate and no taxes. The discount rate was set at 5%. The revised file is documented as G4EconsVer_2-0_P_04Sep2011_PWR12_BE_ and_AHTR_options.xls. The data output for the two new cases, along with the example case 1, are shown in Table 54.

Table 54. Levelized unit cost output from G4-ECONS (mills/kWh)

Reactor system	**System 80+**	**PWR12 BE**	**AHTR 19.75%**	**AHTR 9%**
Year of estimate	**2001**	**2011**	**2011**	**2011**
G4-ECONS case	**1**	**8**	**9**	**14**
Capital cost recovery	17.40	29.66	24.47	22.77
Operation and maintenance	8.61	12.60	9.31	9.31
Fuel cycle costs	4.28	5.60	17.54	10.74
Decommissioning fund	0.27	0.32	0.23	0.23
Levelized unit cost of electricity	**30.56**	**48.18**	**51.55**	**43.05**
Total capital investment cost, $/kW(e)	**2092**	**4012**	**3384**	**3149**

It is again stressed that this effort 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).

In a general sense, the new PWR12 BE and AHTR cases seem reasonable in the context of the G4-ECONS example case 1 and the other cases in the G4-ECONS spreadsheet. A comparison of the AHTR case to the PWR12 BE case does show several trends. Several elements of the LUEC for the AHTR are lower because more electricity is generated. As the models have been constructed, identical annual input was used for categories such as operation and maintenance and input to the decommissioning fund calculation. Although the two operate at essentially the same thermal power, the higher thermal efficiency of the AHTR reduces the LUEC.

As noted at the end of Section 8.2, direct capital cost was not particularly different; there were about an equal number of reasons to adjust cost downward for the AHTR, compared to the PWR12 BE, as there were to adjust cost upward. A summary of the capitalized investment cost is shown in Table 55, showing the components of total capital cost and the impact of the higher efficiency of the AHTR on the specific TCIC (the largest component of the LUEC).

Table 55. Total capitalized investment cost (millions of 2011 dollars)

Capital cost, in millions of 2011 dollars	PWR12 BE	AHTR 19.75%	AHTR 9.00%
Capitalized preconstruction costs (accounts 11–19)	6	6	6
Capitalized direct costs (accounts 21–29)	2,171	2,391	2,391
Capitalized support services (accounts 31–39)	1,323	1,323	1,323
Capitalized operations costs (accounts 41–49)	300	300	300
Overnight cost without initial fuel load	3,800	4,019	4,019
Initial fuel load	135	419	111
Total overnight cost with initial fuel load	3,935	4,438	4,130
Interest during construction (calculated)	655	739	688
Total Capitalized Investment Cost (TCIC)	4,590	5,177	4,818
Reactor net electrical capacity (MW)	1,144	1,530	1,530
Specific TCIC ($/kWe)	4,012	3,384	3,149

The most significant difference between the AHTR cases and the PWR12 case is the relatively high fuel cycle cost. This is especially significant for the AHTR fueled with 19.75% enriched uranium. A summary of fuel cycle cost is shown in Table 56. Again, the results should be considered as qualitative examples and should not be regarded as quantitative results. In particular, the basis for fuel fabrication and out-of-reactor storage of used fuel is taken from example cases in the ECONS spreadsheet and may not be applicable to AHTR fuel. The model may also underestimate the cost of enrichment above a 5% ^{235}U level.

The impact of the relatively high enrichment used in the AHTR, compared to existing LWRs, is seen in the table. The enrichment cost shows up not only as direct enrichment cost, expressed as separative work units, but also in the cost of the additional ore that is mined, milled, converted, and sent to a disposal site. The 9% enriched AHTR case offers a reduction both the enrichment needed for the uranium and in the amount of uranium used in the core, at the expense of more frequent refueling and shorter assembly life in the core. The magnitude of the fuel fabrication and the used fuel storage costs is not large compared to the overall fuel cycle cost, diminishing the lack of a good model for these cases. Used fuel disposal is estimated using the current payment rate to the nuclear waste fund and so long as that model continues as a basis for ultimate fuel disposition, should be valid for both systems.

Improved modeling of the AHTR fuel cycle, including an evaluation of whether the G4-ECONS fuel cycle model is appropriate for the enrichment levels encountered with AHTR fuel, is recommended as a future task.

Table 56. Fuel cycle cost (in 2011 dollars)

	PWR12 BE ($ millions)	AHTR 19.75% ($ millions)	AHTR 9.00% ($ millions)	PWR12 BE (mills/kWh)	AHTR 19.75% (mills/kWh)	AHTR 9.00% (mills/kWh)
Annual average ore cost	20.20	95.74	45.13	2.24	7.76	3.66
Annual average conversion cost	1.55	7.36	3.47	0.17	0.60	0.28
Annual average enrichment cost	10.93	79.37	33.71	1.21	6.44	2.73
Annual average fuel fabrication cost	5.67	12.10	25.27	0.63	0.98	2.05
Annual average enrichment tails disposal cost	0.79	4.33	1.98	0.09	0.35	0.16
Total front end fuel cycle cost	39.15	198.90	109.57	4.34	16.13	8.89
Spent fuel storage outside pool and prior to shipment (including packaging)	2.36	5.04	10.53	0.26	0.41	0.85
Disposal in repository (payment to nuclear waste fund)	9.02	12.33	12.33	1.00	1.00	1.00
Total back end fuel cycle cost	11.38	17.37	22.86	1.26	1.41	1.85
Total fuel cycle cost	**50.53**	**216.27**	**132.43**	**5.60**	**17.54**	**10.74**

8.6.3 Parametric Evaluations

A major advantage of using G4-ECONS for economic modeling is the ease with which additional optional cases can be evaluated. A number of option cases were prepared and are documented as additional cases in the file as G4EconsVer_2-0_P_04Sep2011 _PWR12_BE_and_AHTR_options.xls. These optional cases are compared to the LUEC calculated for the reference 19.75% enriched AHTR model (case 9) unless indicated otherwise.

Section 8.2.8 includes a discussion of the basis for estimating the cost of the key primary salt components. A total value of $367 million was entered into account 28, special materials, to cover the salt cost. There is considerable uncertainty in this basis, especially for the production of enriched ^{7}Li. Two cases were run to examine the impact of salt cost on the LUEC. In case 15, a reduced allocation of $100 million is entered in account 27, assuming technology developments can lower salt production cost to roughly a third of the base case. The result is a decrease of 1.2 mills/kWh in the LUEC. Case 16 roughly triples the salt cost, entering $900 million in account 27. This change adds 3.6 mills/kWh to the LUEC.

Fuel cycle cost represents a relatively large fraction of the overall AHTR LUEC, primarily as a result of the relatively high enrichment. Case 14 evaluates a lower enrichment along with more frequent refueling; the enrichment is dropped to 9%, but half the core is replaced every 6 months. The uranium loading is also reduced to 16.6 MT total. As shown in Section 8.6.1, the reduced enrichment and uranium loadings drastically reduce the fuel cycle cost, reducing the LUEC by over 8 mills/kWh. This includes a small reduction in the capital cost, as the cost of the initial core loading is also reduced.

The applicability of the current G4-ECONS model for fuel enrichments above 5% is another area that will be investigated in the future. In particular, enrichment cost in dollars per SWU for fuels above 5% is likely to be higher than for common LWR enrichment levels. Case 18 considers a doubled enrichment cost, from $135/SWU to $270/SWU, and finds an increase in the LUEC of 7 mills/kWh.

Costs for the PWR 12 BE reactor equipment were based on an assumed distribution of reactor vendor NSSS cost. Offsetting considerations were identified in comparing the AHTR reactor equipment to a traditional PWR, and no adjustments were made to the direct cost used in this evaluation. In case 12, the impact of doubling the $197 million under reactor equipment (account 221) is evaluated by raising the overall input to account 22 from $818 million to $1,000 million. An increase in the LUEC of 1.1 mills/kWh is observed.

No contingency is included in the comparative estimate, as there is no contingency in the PWR 12 BE case. If $524 million contingency (25% of the total direct cost) is added, the LUEC rises by 3 mills/kWh.

High efficiency and capacity factors are crucial in bringing the LUEC down. If the efficiency were to drop from 45.0% to 41.5%, as is seen with existing supercritical coal-fired plants, the LUEC would increase by 4.3 mills/kWh. With two 3-day refueling outages scheduled each year, scheduled refueling outages impact availability by only 2%. Pending further work on defining maintenance outage times, there is a real possibility that the availability could reach 95%.

The potential impacts identified here are generally independent of each other, and a cumulative impact may ultimately be observed. For example, future evaluations may incorporate the impacts of moving to the 9% enriched, 6-month refueling cycle along with added reactor equipment cost and the addition of contingency.

8.6.4 Infrastructure

In addition to the impacts on direct cost or fuel cycle cost discussed above, there are several infrastructure elements that would be needed to support implementation of AHTRs. Construction of a large-scale lithium enrichment facility is necessary to supply sufficient ^{7}Li for multiple AHTRs, as well as to bring down the cost of enriched lithium. Similarly, expanded beryllium production capabilities may be needed to assure supply of raw materials for the primary salt and possibly reduce the salt price.

Commercial uranium enrichment facilities are typically licensed to handle material up to 5% enriched. Expansion of the enrichment infrastructure, both equipment and license, will be needed before the fuel described in this report can be fabricated. This may be easier for the 9%, 6-month, half-core refueling cycle than the base case using 19.75% enriched uranium with full core replacement every 2 years.

High-nickel Alloy N, the alloy originally developed at ORNL for fluoride-salt reactors, is currently not available as a normal commercial product; custom mill runs can be made, but at considerable cost. Establishing commercial levels of Alloy N is needed to support AHTR implementation.

A supply chain for qualified reactor or plant systems components unique to the AHTR will be required. This will not be experienced as a singular event, but rather as incremental infrastructure appearing at a wide range of industrial sites. Similarly, a cadre of trained engineers, operators, and maintenance staff will have to be developed, focusing on the unique skills needed to operate AHTRs.

Most of these infrastructure improvements would likely be implemented as commercial investments, with the investment cost recovered in the pricing of the commodities or equipment as they are sold. This would especially be true if the investment cost is low; for example, production of Alloy N would utilize the same mill equipment and ingredients as are used for other alloys now in production. In some cases, such as increasing the capabilities of uranium enrichment facilities, separate funding sources might be required.

8.7 RECOMMENDATIONS FOR FURTHER STUDY

8.7.1 Recommended Studies

Primary coolant salt studies

The first recommended study is the technology needed for large-scale production of the primary FLiBe salt, especially the cost and technology needed for ^{7}Li enrichment and the prospects for enhanced beryllium production (in terms of both production rate and cost). The ^{7}Li portion of this study could build on efforts initiated by the fusion energy community, which is investigating lithium enrichment technologies that are based on electro-migration of lithium isotopes in various media. As seen in Table 48, the production cost for salt in this evaluation is about \$300 million, treated as direct capital cost. This is based on an escalation of values used in the 1970s, when the last major production runs of FLiBe salt were conducted for the MSBR program. However, the current price for small quantities of ^{7}Li is about five times the cost used here, which could lead to salt costs approaching \$1 billion. Beryllium cost is based on an overall evaluation of current production levels and sales. The beryllium production effort should explore to what extent current production rates and cost is driven by the current market, and whether production expansion, improvement in mining and recovery methods, and economy of scale could reduce that cost. An initial goal would be to reduce the cost of primary coolant salt production to below \$100 million per AHTR unit, at which point it would have a marginal impact on the capital cost recovery element of the LUEC.

Fuel cycle studies

The fuel cycle cost associated with the AHTR may be a larger portion of the LUEC than is traditionally experienced with other reactors, especially if uranium enrichments up to 19.75% are needed. A comprehensive review of the AHTR uranium fuel cycle is needed, addressing not only enrichment SWU cost but also the cost of uranium mining, milling, conversion, and tails disposal. This study should be integrated with the AHTR reactor core development task, ensuring that the core optimization reflects not only nuclear physics and operational concerns but fuel cost as well. A review of the G4-ECONS modeling techniques is needed to determine its applicability at enrichments up to 19.75%. The possibility of partially or completely closed fuel cycles may also be considered to determine whether reuse of used but still enriched uranium can have a significant impact on the overall fuel cycle cost.

A review of enrichment facilities should accompany the fuel cycle study. The present capability and additional needs of enrichment facilities to produce uranium ranging from 9% up to 19.75% should be identified. This review of enrichment infrastructure may be performed in tandem with the review of the applicability of the G4-ECONS model for this range of fuel enrichments.

For this initial study, fuel fabrication costs have been set so that G4-ECONS assigns a cost that is equivalent, on an assembly basis, to fuel fabrication cost for an example PWR case. In fact, AHTR fuel, based on TRISO technology, is significantly different than PWR fuel. A review of costs for fabrication of AHTR fuel would provide an improved basis for the fuel fabrication portion of the fuel cycle cost. This review should include preparation of the TRISO particles, fabrication of the carbon fuel planks, and bundling of the planks into a finished fuel assembly.

Reactor systems studies

An improved model of the AHTR reactor systems cost is needed. The EEDB PWR12 BE model itself, used as the basis for comparative estimating, is not as well documented for reactor equipment as it is for most other areas. This is because a large fraction of the cost is covered in a single NSSS vendor cost quote. Further, the EEDB documentation notes that since no new reactor orders had taken place for some time prior to the ninth update in 1987, even the NSSS quote may have been outdated. In any case, significant design differences between the PWR12 and the AHTR make the comparative estimating technique more questionable.

Evolution of the AHTR design may improve the basis for comparative estimates relative to the EEDB PWR12 BE data set. Other reactor systems, should detailed cost data be identified, may provide alternate bases for comparative estimates. These include sodium-cooled reactors, which share many of the structural aspects (low pressure, thinner vessel walls, relatively high-temperature operation, need for preheat) as the AHTR. Gas-cooled reactors may also serve as a basis for some comparative estimates, as the TRISO fuel used in the AHTR was originally developed for use in gas-cooled reactors.

As the design matures, more direct methods of estimating the cost of reactor systems may become practical. This includes the use of component weights as an estimating guide, as well as the possibility of obtaining vendor quotes for equipment that is similar to components sold for use in other applications. These techniques were demonstrated in the 1971 comparison between the MSBR[25] and a typical PWR, and the more recent paper by Busby.[29] The reactor equipment study should address not only the vessel but also core internals, control blades and drives, instrumentation, and other reactor assembly components.

Salt pumps and heat exchangers

Design and costs for pumps and heat exchangers in all salt systems, especially the primary-to-intermediate heat exchangers and the heat transfer system between the intermediate salt and the supercritical fluid and reheat steam fluids, are key technological needs that also support improved cost estimates.

Definition of the intermediate salt-to-water system heat exchangers also leads to a better definition of the space required for these systems, now portrayed as an additional heat exchanger bay on one end of the turbine building.

Advanced materials

Various advanced materials are used in the AHTR. These range from high-nickel alloys similar to materials already in widespread use to SiC/SiC and carbon composite materials for which limited experience exists in reactor systems. The use of advanced materials introduces not only new technical issues, but also adds uncertainties into the cost estimate. Further work is needed to confirm the technical for advanced materials in the AHTR and to develop cost estimating techniques consistent with AHTR performance and quality requirements.

Improved definition and cost estimates for all salt systems

In the present model, only rough allocations have been included for many of the salt systems, modeled loosely after existing cost for similar water systems. A set of allocations, totaling $60 million, replaced traditional insulation cost in account 228 to cover the preheat and insulation requirements for salt systems, a net increase of about $40 million was made to account 226 to cover anticipated higher costs for salt processing systems (compared to traditional water filters and demineralizers), and a general assumption is made that the thinner walls of piping systems is roughly offset by the higher cost of material and the enhanced fabrication rigor and component cost for high-temperature systems.

Improved salt system design, covering the primary and intermediate heat transfer circuits, the DRACS system, the fuel transfer pools, and processing systems for both primary and secondary salts, will help refine the estimates for salt systems. A flowsheet for salt processing is a key element for improved salt system definition, as are methods for accommodating thermal expansion and incorporation of layout and drain considerations. Key components, such as pumps, control valves, and containment isolation valves should also be addressed.

Tritium control

Tritium can be very difficult to control, especially if distributed into water or other hydrogenous material. Tritium can be produced in salt-cooled reactors, especially by irradiation of residual ^{6}Li. Definition of tritium control systems that remove tritium from salt cover gas systems, before mixing with water or other hydrogenous material, is key to assessing the cost of cover gas and tritium recovery systems. Studies conducted in the 1960s and 1970s as part of the MSBR development should form an initial basis for this task. Work performed by the fusion energy community may also prove valuable, as would experience with existing heavy water reactors, such as the Canadian CANDU power reactors or the heavy-water-cooled and the Institut Laue-Langevin research reactor in Grenoble, France.

Neutron poison salt injection and recovery system

Salt injection, containing a neutron poison, will be provided as a fallback reactivity control system. Definition of the system, including salt injection system components and the means to remove the neutron poison and any unwanted salt components from the primary coolant, is needed before these costs can be assessed.

Reactor building optimization

As the reactor, fuel handling systems, primary salt systems, and other components located in the reactor building are defined, the building itself can be optimized. Optimization can include basic factors such as building shape (rectangular or cylindrical), depth, and the amount of base and support concrete or structural steel required. Methods for supplying preheat to the reactor and primary circuit components (local heaters and insulation or a complete heated and insulated structural chamber) influence the building structure. This task also includes improved definition of the containment boundaries and the necessary containment barriers and components. Another key interface in optimizing the reactor building is its interface with the DRACS, including the transition of the DRACS salt piping out of containment and ultimately to the heat exchangers in the chimneys outside of the reactor building. Optimization of the building allows better estimates of building cost.

Turbine-generator optimization

Based on comparisons and costs reported for fossil energy systems, the cost of a high-temperature turbine generator set is estimated to be lower than for the large, cool, and wet turbine turbine-generator sets used in LWRs. Further review of turbine-generator systems should confirm this. The review should also investigate the impact of temperature increases (compared to existing fossil plants) up to 600°C (1200°F).

The selection of two 825 MW rated turbine-generator sets, instead of a single set rated at 1,700 MW, should also be reviewed.

Alternate heat rejection systems

The efficiency and capital cost impacts of the use of heat rejection systems other than large, natural draft, evaporative cooling towers should be investigated. The use of wet–dry hybrid systems or water-to-air heat exchangers may extend the applicability of AHTR technology to locations where traditional cooling towers may not be practical (such as dry climate locations that are not near a large water source). Cost considerations include changes in overall plant efficiency, additional "house loads" that reduce power placed on the grid, and the relative cost of the cooling system equipment compared to cooling tower systems.

Alternate component cooling systems

It is desired to limit the use of cooling water systems for reactor component cooling applications, to reduce the possibility of producing steam and pressure should water come in contact with high-temperature equipment. A presumed cost for enhanced gas-based component cooling is included as one of the AHTR cost adjustments. Better definition of component cooling requirements and equipment would allow improvement of the cost allocations for these systems, whether based on gas cooling or other types of coolants.

Modernization of control and electrical systems

Modernization of control, communications, and electrical systems forms a basis for reduction of cost in several of the accounts. A comprehensive review of digital and distributed control and monitoring systems may bring better focus, and ultimately better estimates of cost, for these systems. Power cabling may not change as much, but improved power control systems may reduce the size and cost of key electrical system components. In performing this review, it should be kept in mind that initial control and monitoring devices are often included in the scope of the system they serve.

Cost impacts may include simplification of building layouts and reductions in space and ventilation requirements, as well as the obvious impacts to control, communication, and power systems.

Plant efficiency and availability review

Most of the gains in LUEC arise from the high net plant efficiency, supported by a high availability. Coal-fired supercritical plants do realize net efficiencies above 41%, after allowing for substantial internal power loads associated with flue gas handling and treatment operations and coal handling operations. The AHTR internal power loads are mainly associated with salt and feedwater pumping loads; ventilation loads; salt and feedwater handling and treatment systems; instrumentation and controls; and services such as lighting, heating, and air conditioning. The reduction of internal power loads easily supports use of a 43% net efficiency. The AHTR offers the potential for higher temperatures at the turbine inlets, and the resulting change in Carnot efficiency is used to project an efficiency of about 45%. At present, the impact of heat losses through the DRACS is considered minor, and the efficiency is not reduced to account for such losses. Because the high efficiency is critical to establish the economic attractiveness of the AHTR, additional work should be performed to confirm, or even increase, the efficiency used in this report.

Current LWRs already operate at availabilities that often exceed 90%. When LWRs are refueled, significant time is required to cool and depressurize the system and initiate refueling operations. With the AHTR, refueling must be performed at temperature (with the salt liquid), and there is no operating pressure, so refueling can begin earlier. Initial motion studies suggest that a partial core reload can be accomplished in as little as 3 days, or about 1% of a year. Two partial refueling outages a year result in the potential for operation 98% of the year. Maintenance activities, including unplanned shutdowns and maintenance, would likely reduce the availability below this amount. This report is based on an overall 92% availability. As the design progresses, improved estimates of maintenance activities and the downtime required to accomplish these activities will help substantiate the overall estimate of plant availability.

Security, operating staff, and other operating and maintenance costs

At this time, operation and maintenance cost is drawn from the EEDB data base, escalated to 2011, but not adjusted in any other way. The resulting annual cost appears to have a relatively small impact on LUEC.

Security practices and costs have changed since the early 1980s, with significant upward pressure on cost. A review on security operations cost should be a focal area as reviews of operating costs are performed.

Several sources of operating cost data have been identified, some of which are slightly dated.[32,33,34] These can serve as an initial basis for a review of operating cost, including staff (by functional area), consumables, and materials. A search for more recent data should be undertaken to update or supplant these resources.

Simulator and mockup costs

Most plant sites today have a control room simulator located at the site. The simulator is used for operator training, and is a valuable tool for maintaining the proficiency of the operating staff. Multiunit sites may have one simulator facility serving operators for several identical reactors at the site. Cost for a modern LWR simulator may be found in the literature.

A mockup of at least the upper portion of the reactor assembly may be necessary for checkout and maintenance of remote handling systems used in reactor maintenance and refueling activities. The high plant availability goal, and the fact that the operations are always performed in a high-quality inert atmosphere over hot salt and radioactive material would make in-situ maintenance and checkout activities difficult. Cost for a mockup could be established as a fraction of the relevant reactor equipment cost.

Improvements to the EEDB and G4-ECONS models

A general improvement of the tools used for this evaluation could support the development of economic models for the AHTR. The PWR12 base estimate used in the comparative development of AHTR costs is based on 1987 data, escalated using a single extrapolation factor. Escalation rates vary significantly between the sources consulted; the extrapolation factor used in this study is a compromise between several sources.

Improved escalation methods could include separate factors for different aspects of construction; the escalation factor for buildings could differ significantly from the extrapolation factor used for reactor equipment. Ultimately, other more direct means could be used to confirm estimates. This includes utilizing material lists and labor man-hour estimates, along with current equipment quotes and labor rates, to develop a revised estimate based on EEDB data. This might be done selectively for areas of high importance.

Continued work on the G4-ECONS model could improve its applicability to the AHTR, especially in modeling the cost of the uranium fuel cycle. A revised PWR fuel cycle model, reflecting the high burnup fuel and higher fuel enrichment used in most PWRs today, could provide an improved reference for fuel cycle cost. Coordination with the EMWG should continue, so any new revisions or other modeling developments can be incorporated into the AHTR economic model.

8.7.2 Other Cost Data or Methods

A general review of cost estimating techniques, including top-down, bottom-up, and comparative techniques, can be found in the EMWG cost estimating guidelines.[19]

A modified approach to comparative estimating, performed during the development of the MSBR concept in the late 1960s and early 1970s, is documented in ORNL-4541.[25] Approaches to compare estimates for a reactor vessel and other major components, at a slightly more advanced level of MSBR design than presently exists for the AHTR, are shown. As with this document, the ORNL-4541 approach builds on a comparison of MSBR costs to a definition of a typical PWR, with a cost data base as understood around 1970. This approach was used to update a capital cost for a molten-salt-fueled reactor by ORNL in August 2010.[26]

An approach to evaluating the cost and benefits of the use of advanced materials has been documented in a report by Busby.[29] Targeted to liquid-metal reactor designs, and focusing on the possible reduction in wall thickness resulting from better-performing alloys, it offers techniques that can be useful in the development of better estimates for AHTR components.

Sections 8.1.6 through 8.1.9 discuss other reactor and fossil power plant designs for which cost data may be available. Some of this is proprietary; not all have detailed data available for public use. Summary cost data for these systems may be used to confirm other techniques. Partial details may prove more useful to compare AHTR cost for select systems than the EEDB PWR data. Even EEDB data for other systems (generally only available at a summary level) may be useful.

Ultimately, bottom-up data prepared from drawings and piping diagrams, supported by traditional bills of material and vendor estimates, is needed to establish a firm estimate. Such data may not be available for some time, but might be developed for select, high-impact systems or structures on an accelerated schedule.

8.8 ECONOMIC EVALUATION CONCLUSION

Chapter 8 describes the development of a transparent and flexible tool for evaluating the cost and economics of the AHTR, using the detailed EEDB as a basis for comparative estimating and the G4-ECONS model for economic modeling. The evaluation is based on a set of preliminary adjustments to the EEDB data base and should not be considered as a quantitative cost estimate. The evaluation does show likely trends in comparing the economics of the AHTR to the economics of traditional LWRs.

The evaluation shows the potential for cost-effective electricity, compared to existing LWRs. It is seen that the factors affecting capital cost pull in both directions; preliminary evaluations show little net difference between the AHTR and an LWR. The high-thermal efficiency and availability projected for the AHTR can significantly reduce the LUEC associated with the capital cost.

Fuel cycle costs for the current base AHTR design are higher than encountered in LWRs, primarily due to the relatively high enrichment cost but also due to the number of fuel elements used in a given time period. The impacts of higher fuel cycle costs roughly balance against the reduction in LUEC observed as a result of the high efficiency and the overall LUEC for the two reactor types appear similar.

Several important uncertainties exist, ranging from the very early level of AHTR design to costs for commodities such as primary coolant salt with enriched ^{7}Li. This evaluation can be used to prioritize a set of recommended studies to reduce the uncertainties, based on the impact on LUEC.

9. AHTR PRECONCEPTUAL SYSTEM DEVELOPMENT PLANS

The AHTR system design effort over the next year will focus on describing and defining the major AHTR plant systems (outside the core) and evaluating the overall plant dynamical response to transients. The objective of this effort is to identify and describe all major plant subsystems and components and to complete an end-to-end transient performance model of the power plant and associated safety systems.

Identification and description of all reactor subsystems to a preconceptual level of detail will be a major outcome of this system design activity. Design effort will be focused on identifying existing reactor or industrial process analogs that can be used to better understand power and component requirements for the subsystems and to provide as accurate as possible cost models of those subsystems. A more detailed and complete plant layout and increased fidelity plant systems and economic models will be the end product of the effort. Included in this activity is the initial definition and placement of sensors within the system. The plant system model will be used to evaluate the transient plant response to upset scenarios to enable better understanding of the effectiveness of the passive safety systems to mitigate accident consequences. This task will also identify areas where more uncertainty exists in subsystem design and cost due to the lack of good analogs and will help direct future technology development efforts.

10. 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. The objective of the AHTR design is to be a low-cost producer of electricity. Additionally, the AHTR can deliver high-quality heat to industrial processes at near atmospheric pressure and over a narrower temperature range than gas-cooled reactors.

The features of an AHTR systems transient model were identified, and an initial static model was developed. Further work will be necessary to model reactor transient behavior and incorporate the passive safety features related to decay heat removal into the model. An economic model of the AHTR was also developed, and areas where larger amounts of cost uncertainty exist have been identified. Significant work remains to develop the AHTR constituent technologies sufficiently to increase the model fidelity sufficiently to provide a low-uncertainty system cost estimate. Further AHTR systems work is required to define the components to hold, handle, pump, and transfer heat from the reactor coolant salt to the power conversion system. FHR specific functions that have no direct analog in light-water reactor technology require more fundamental analysis as part of the system definition.

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.

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