Goals, Requirements, and Design Implications for the Advanced High-Temperature Reactor

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ABSTRACT

The Advanced High-Temperature Reactor (AHTR), also called the liquid-salt-cooled Very High-Temperature Reactor (LS-VHTR), is a new reactor concept that has been under development for several years. The AHTR combines four existing technologies to create a new reactor option: graphite-matrix, coated-particle fuels (the same fuel as used in high-temperature gas-cooled reactors); a liquid-fluoride-salt coolant with a boiling point near 1400°C; plant designs and decay-heat-removal safety systems similar to those in sodium-cooled fast reactors; and a helium or nitrogen Brayton power cycle. This paper describes the basis for the selection of goals and requirements, the preliminary goals and requirements, and some of the design implications.

For electricity production, the draft AHTR goals include peak coolant temperatures between 700 and 800°C and a maximum power output of about 4000 MW(t), for an electrical output of ~2000 MW(e). The electrical output matches that expected for a large advanced light-water reactor (ALWR) built in 2025. Plant capital cost per kilowatt electric is to be at least one-third less than those for ALWRs with the long-term potential to significantly exceed this goal. For hydrogen production, the peak temperatures may be as high as 950°C, with a power output of 2400 MW(t). The safety goals are to equal or surpass those of the modular high-temperature gas-cooled reactor with a beyond-design-basis accident capability to withstand large system and structural failures (vessel failure, etc.) without significant fuel failure or off-site radionuclide releases. These safety goals may eliminate the technical need for evacuation zones and reduce security requirements and significantly exceed the safety goals of ALWRs. The plant design should enable economic dry cooling to make possible wider nuclear-power-plant siting options. Uranium consumption is to be less than that for a LWR, with major improvements in repository performance and nonproliferation characteristics.

INTRODUCTION

The Advanced High-Temperature Reactor (AHTR) is a new reactor concept with three design goals: (1) high reactor-coolant exit temperatures (700 to 950°C) to enable the efficient production of hydrogen or electricity, (2) passive safety systems equivalent to those of modular high-temperature gas-cooled reactors (MHTGRs) for public acceptance and reduced costs, and (3) competitive economics. Within the U.S. Department of Energy (DOE) Generation IV (GenIV) Program, the AHTR is being developed as a liquid-salt-cooled Very High-Temperature Reactor (LS-VHTR). The LS-VHTR is the high-temperature variant of the AHTR that is required for hydrogen production. A preconceptual point design has been developed [1]. A series of studies are under way to evaluate alternative core designs [2], salt coolants [3, 4], decay heat removal systems [5], and other critical plant features.

To systematically evaluate alternative system designs, several inputs are required.

- *Top-level reactor design goals.* Goals must be defined before alternative reactor structures, systems, and components can be evaluated to determine the preferred options. Top-level goals include defining the missions as well as the goals for safety and economics.

- *Functional safety requirements*. Reactors have multiple functional safety requirements. These requisites must be defined to ensure all safety requirements are met and that specific plant features will not impact safety.

Because the AHTR is a new concept, these top-level inputs have not been systematically assembled, assessed, and reviewed. This paper provides initial goals and functional safety requirements as a starting point for development of a formal set of goals and functional safety requirements for the development of the AHTR.

The AHTR goals are defined in terms of hydrogen or electricity production in major markets such as the continental United States, Europe, Japan, and East China. The economic requirements for small markets, where the size of the nuclear power plant is limited by electrical grid constraints or other such considerations, are not considered herein. There are differences in emphasis between the goals of the reactor vendors and national goals. The emphasis of the reactor vendors is electricity production. This focus reflects the existence of a large near-term market for electric power plants and the shorter time frame of investment associated with private companies. The federal government's primary interest in high-temperature reactors is hydrogen production to reduce environmental impacts from energy production and to decrease the dependence on foreign oil to meet transport needs.

Two potential specialized AHTR applications have been identified and are dependent upon other specific characteristics of the AHTR. These applications have significantly different goals and requirements and thus are briefly described but are not further considered herein.

- *Shale oil*. New processes are being developed for in situ shale-oil recovery that require heating the rock to high temperatures. The current technology uses electrical heaters. Direct heating would reduce the inefficiencies in converting heat to electricity and back to heat. One alternative source of heat is the high-temperature reactor [6]. Liquid-salt-cooled reactors operate with much smaller temperature drops across their cores (50 to 100°C) than do gas-cooled reactors (~350°C). This characteristic, which allows a liquid-salt-cooled reactor to deliver heat over a small temperature range, may match the specific requirements for insitu oil recovery.

- *Small reactors*. Russia [7] has been examining a small pebble-bed-cooled AHTR for electricity generation at remote sites. The reactor provides high-temperature heat to a gas turbine operating on air. With this configuration, there is no need to build cooling systems onsite. Heat rejection is directly to the atmosphere.

A systematic basis for defining goals is required. In cooperation with other countries, DOE (8) developed GenIV goals, criteria, and metrics for development of future reactors. This structure is used as a basis to discuss goals and criteria. Table 1 lists the GenIV goals, criteria, and metrics. The goals are broken into four categories: economics; sustainability; safety and reliability; and proliferation resistance and physical protection.

The paper has six sections: the baseline description of the AHTR, the four goals, and safety requirements. For each goal, the goal, the basis for that goal, and current understanding of the potential of the AHTR to meet that goal is described. The goals are described relative to ALWRs and MHTGRs.

AHTR DESCRIPTION, BASELINE

The preconceptual baseline AHTR is described herein to (1) provide an understanding of the concept and (2) provide examples in which the choice of goals will strongly impact the design. Studies are under way to evaluate alternative designs. Figure 1 is a schematic of the AHTR plant [1, 9, and 10], showing how the facility may be used for the production of either electricity or hydrogen production, or both. The AHTR uses graphite-matrix coated-particle fuels and a liquid-fluoride-salt coolant. The fuel is the same type that has been successfully used in high-temperature gas-cooled reactors such as the Fort St. Vrain. The optically transparent liquid salt coolant is a mixture of fluoride salts with freezing points near 400°C and atmospheric boiling points of ~1400°C. Several different salts can be used as the primary coolant, including lithium-beryllium and sodium-zirconium fluoride salts. The reactor operates at near-atmospheric pressure, and at operating conditions, the liquid-salt heat-transfer properties are similar to those of water.

Heat is transferred from the reactor core by the primary liquid-salt coolant to an intermediate heat-transfer loop. The intermediate heat-transfer loop uses a secondary liquid-salt coolant to move the heat to a thermochemical hydrogen production facility or to a turbine hall to produce electricity. If electricity is produced, a multi-reheat nitrogen or helium Brayton power cycle (with or without a bottoming steam cycle) is used.

The baseline reactor layout for a 2400-MW(t) version of the AHTR is similar to the S-PRISM sodium-cooled 1000 MW(t) fast reactor designed by General Electric. Both reactors operate at low coolant pressure and high temperature; thus, they have similar design constraints. The 9.2-m-diam. vessel is the same size as that used by the S-PRISM design. The AHTR also uses a passive reactor vessel auxiliary cooling system (RVACS) similar to that developed for decay heat removal in the General Electric sodium-cooled S-PRISM. The reactor vessel in its silo layout is shown in Fig. 2, with the preconceptual baseline design parameters shown in Table 2.

Because the AHTR uses the same basic fuel type and the liquid salt coolant has a low neutron-absorption cross section, the reactor core physics and fuel cycle options are generally similar to those for helium-cooled high-temperature reactors. Reactor power is limited by a negative temperature coefficient, control rods, and other emergency shutdown systems.

Several liquid fluoride salts with different molar compositions [^{7}LiBe (67–33), NaBe (57–43), ^{7}LiNaZr (26–37–37), NaZr (59.5–40.5), and NaRbZr (33–23.5–43.5)] but somewhat similar properties are being evaluated to determine the optimum coolant salt [3, 4]. In the 1950s and 1960s, several programs examined and built two molten salt reactors in which the fuel was dissolved in the coolant [11]. These programs provide the technical foundation for the AHTR coolant technology. Economic assessments indicate that the salt costs will not be a major contributor to the capital costs.

TABLE 1. GENIV REACTOR GOALS

Goal Areas	Goals	Criteria	Metrics
Economics	EC1 Life Cycle Cost	EC1-1 Overnight construction costs	• Overnight construction costs
		EC1-2 Production costs	• Production costs
		EC1-3 Construction duration	• Construction duration
	EC2 Risk to Capital	EC2-1 Overnight construction costs	• Overnight construction costs
		EC2-2 Construction duration	• Construction duration
Sustainability	SU1 Resource Utilization	SU1-1 Fuel utilization	• Use of fuel resources
	SU2 Waste Minimization and Management	SU2-1 Waste minimization	• Waste mass • Volume • Heat load • Radiotoxicity
		SU2-2 Environmental impact of waste management and disposal	• Environmental impact
Safety and Reliability	SR1 Operational Safety and Reliability	SR1-1 Reliability	• Forced outage rate
		SR1-2 Worker/public – routine exposure	• Routine exposures
		SR1-3 Worker/public – accident exposure	• Accident exposures
	SR2 Core Damage	SR2-1 Robust safety features	• Reliable reactivity control • Reliable decay heat removal
		SR2-2 Well-characterized models	• Dominant phenomena – low uncertainty • Long fuel thermal response time • Integral experiments scalability
	SR3 Offsite Emergency Response	SR3-1 Well-characterized source term/energy	• Source term • Mechanisms for energy release
		SR3-2 Robust mitigation features	• Long system time constants • Long and effective holdup
Proliferation Resistance and Physical Protection	PR1 Proliferation Resistance and Physical Protection	PR1-1 Susceptibility to diversion or undeclared production	• Separated materials • Spent fuel characteristics
		PR1-2 Vulnerability of installations	• Passive safety features

TABLE 2. CONCEPTUAL BASELINE AHTR PLANT DESIGN PARAMETERS

Parameter	Value	Parameter	Value
Total power output	2400 MW(t)	Power cycle	3-Stage Brayton Multireheat
Core inlet/outlet temperature (options)	900°C/1000°C 700°C/800°C 670°C/705°C	Electricity (output at different peak coolant temperatures)	1357 MW(e) at 1000ºC 1235 MW(e) at 800ºC 1151 MW(e) at 705ºC
Vessel diameter	9.2 m	Power cycle working fluid	Nitrogen or helium
Vessel height	19.5	Core geometry	Cylinder
Decay heat system	Air cooled	Discharge burnup	~150 GWd/t
Coolant salt	^{2}LiF-BeF$_2$	Fuel cycle length	≥18 months
^{7}Li isotopic concentration	99.995%	Fuel element height	79.3 cm
Outlet coolant temperature	950°C	Fuel element diameter (across flats)	36.0 cm
Inlet coolant temperature	≥850°C	^{235}U enrichment	~15%
Fuel form	Prismatic	Power density	10.0 MW/m^3
Particle packing fraction	≤25 vol %	Number of fuel columns	265
Particle type	Triso	Number of fuel blocks/column	10

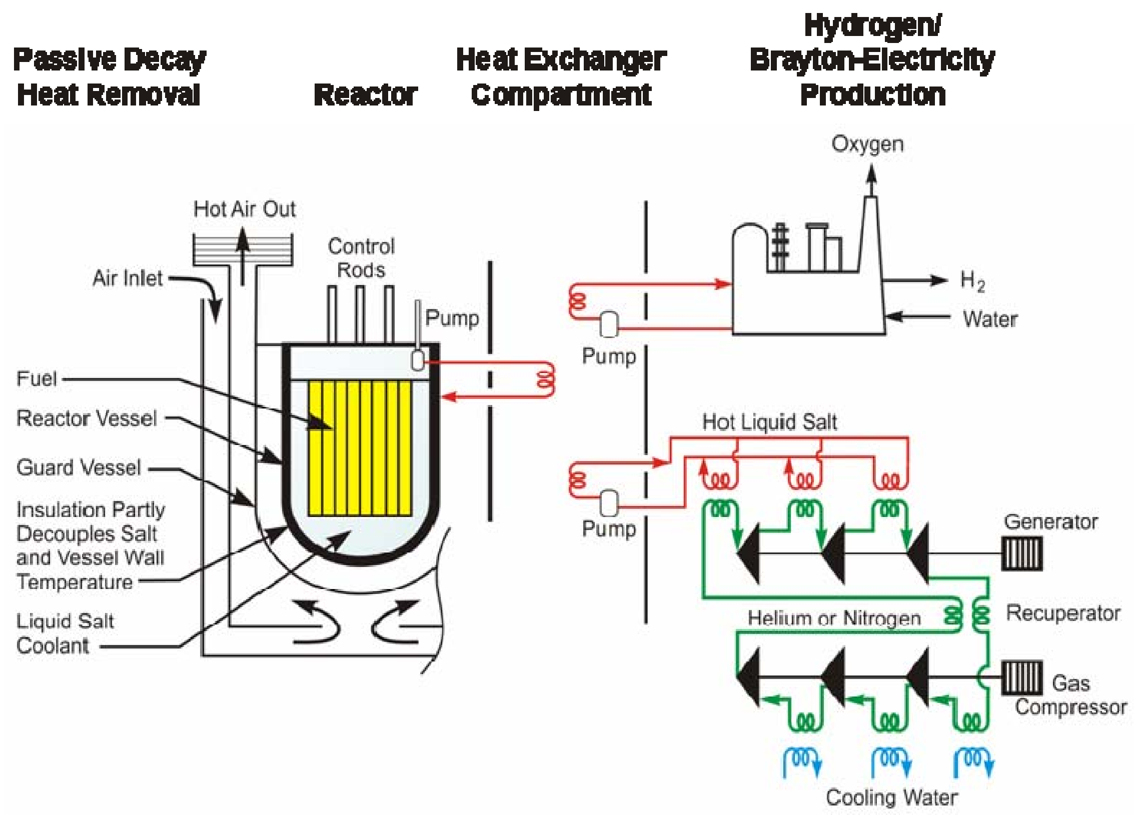

FIG. 1. SCHEMATIC OF THE AHTR PLANT

The reactor and decay-heat-cooling system are located in a below-grade silo. In the AHTR, RVACS decay heat is (1) transferred from the reactor core to the reactor vessel graphite reflector by natural circulation of the liquid salts, (2) conducted through the graphite reflector and reactor vessel wall, (3) transferred across an argon gap by radiation to a guard vessel, (4) conducted through the guard vessel, and then (5) removed from outside the guard vessel by natural circulation of ambient air.

The rate of heat removal is controlled primarily by the radiative heat transfer through the argon gas from the reactor vessel to the guard vessel. Radiative heat transfer increases by the temperature to the fourth power (T^4); thus, a small rise in the reactor vessel temperature (as would occur upon the loss of normal decay-heat-removal systems) greatly increases heat transfer out of the system. Under accident conditions such as a loss-of-forced-cooling accident, natural circulation flow of liquid salt up the hot fuel channels in the core and down the edge of the core rapidly results in a nearly isothermal core with about a 50°C temperature difference between the top and bottom plenums.

Three alternative decay-heat-removal systems are being investigated [5]. RVACS has many advantages; however, heat rejection is dependent upon the surface area of the reactor vessel. That characteristic limits the rate of decay heat removal and thus the maximum size of a reactor with RVACS. The goals, as defined in the maximum desired size of the reactor, may determine whether RVACS is viable for a large AHTR or whether an alternative passive decay heat removal system is required [5, 12].

In terms of passive decay-heat-removal systems, major differences exist between the *liquid-cooled* AHTR and *gas-cooled* reactors. The AHTR can be built in large sizes [>2400 MW(t)] because the liquid coolant with natural circulation can move large quantities of decay heat from the hottest fuel to the vessel wall with a small coolant temperature difference. Unfortunately, in a gas-cooled reactor—under accident conditions when the reactor is depressurized—the natural circulation of gases can not efficiently transport heat from the fuel to the reactor vessel. The heat must be conducted through the fuel to the vessel wall. This inefficient heat transport process limits the size of the reactor to ~600 MW(t) to ensure that the fuel in the hottest location in the reactor core does not overheat and fail under accident conditions. This technical difference enables the AHTR to achieve the goals of (1) being a large reactor with the potential economics of scale and (2) using passive safety systems. This difference in capabilities is what separates the potential markets and goals of the AHTR from modular gas-cooled reactors.

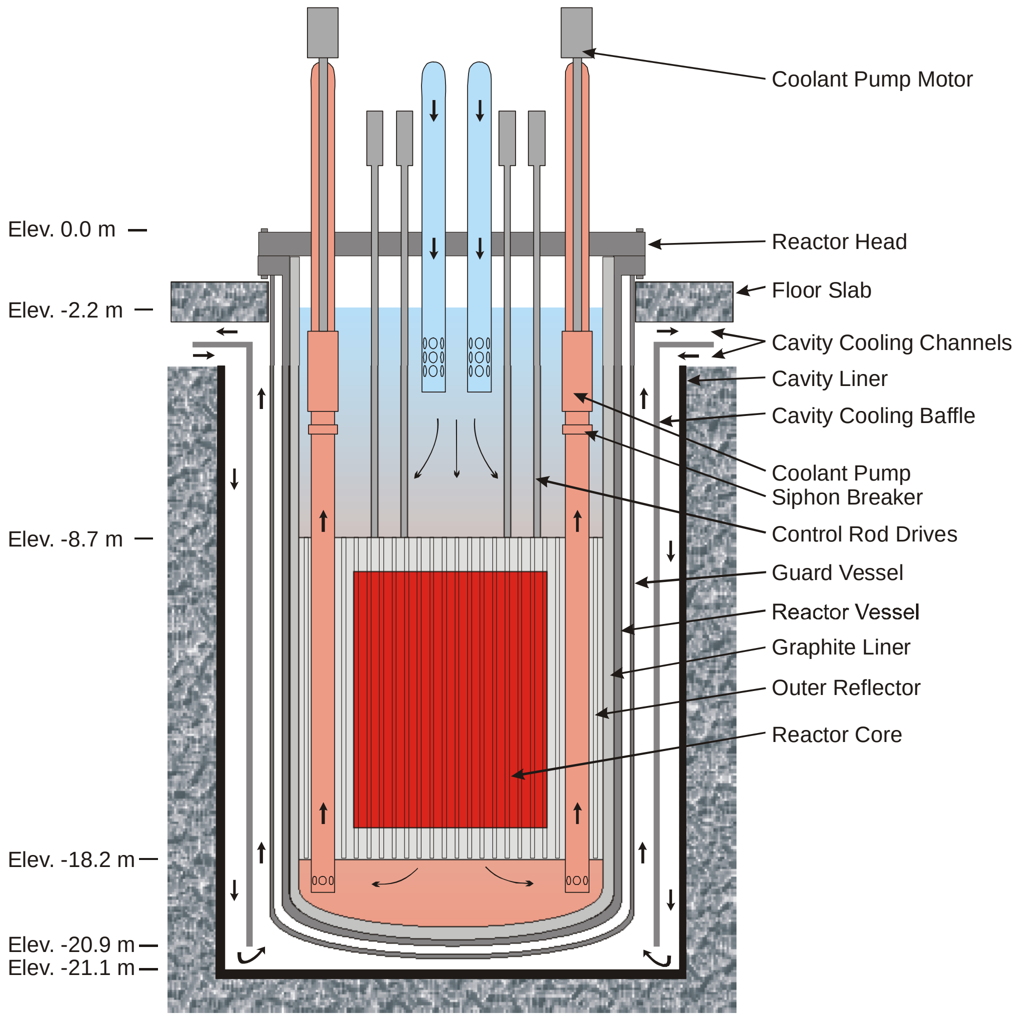

FIG. 2. ELEVATION VIEW OF BASELINE AHTR

In a beyond-design-basis accident [equivalent to core melt accidents in light-water reactors (LWRs)], it is assumed that the air-cooled passive decay-heat-cooling system and structural failures (vessel failure, guard vessel failure, etc.) have occurred. Decay heat continues to heat the reactor core but decreases with time. To avoid the potential for catastrophic accidents (accidents with significant release of radionuclides), the temperature of the fuel must be kept below that of fuel failure. This is accomplished by the capability to move decay heat to the silo wall and the ground by design features that convert the silo into an efficient radiator to the ground [13].

- *Heat transfer to silo wall*. Liquid salt coolant from the reactor vessel fills the bottom of the silo. The reactor vessel contains sufficient salt to keep the reactor core flooded. The circulating liquid salt between the reactor vessel and silo efficiently transfers heat from the reactor vessel to the silo wall.

- *Silo-wall heat conduction*. The silo wall contains thick, low-cost steel rings that are similar to those used in the mining industry to line deep mine shafts and prevent their collapse. Following vessel failure, the rings conduct heat up the silo wall and distribute it above the coolant salt layer to increase the surface area for heat transfer to the soil and aid heat transfer upward ultimately to the atmosphere.

- *Secondary-salt melting (optional)*. Near the top of the silo is an annular ring of a secondary solidified liquid salt. As the temperature of the secondary salt increases, the secondary salt melts, flows into the silo, and floods the silo to a higher level. The melting, heating, and boiling of the secondary salt can provide a significant source of thermal inertia and aids transport of heat to the soil. The secondary salt composition is different than the primary salt and is chosen to maximize its performance in this mission.

The ability to avoid significant radionuclide releases in a beyond-design-basis accident is aided by several other system characteristics. The fuel failure temperature is ~1650°C, which provides a large temperature drop to drive heat to the ground. Most fission products (including cesium and iodine) and all actinides that escape the solid AHTR fuel are soluble in the salt and will remain in the liquid salt at very high temperatures. The chemical inertness and low pressure of the liquid salt coolant eliminate the potential for damage to the confinement structure by rapid chemical energy releases (e.g., sodium) or coolant vaporization (e.g., water). The liquid salt and silo configuration exclude access of air to the solid fuel, thus avoiding concerns about graphite fuel oxidation and preventing direct transfer of radionuclides from fuel to air.

The goal for a beyond-design-basis accident is to eliminate the potential for catastrophic accidents initiated from internal events. However, that goal imposes a set of requirements on the system design, such as the requirement during a serious accident to flood the bottom of the silo with salt while the core remains covered with salt. This goal limits the choice of decay-heat-removal and other systems.

ECONOMIC GOALS

The first commercial consideration is economics, which is defined relative to competing methods to produce electricity or hydrogen in 2025—the approximate time frame for initial deployment of an AHTR. Because technologies advance, it is not sufficient to match the economics of today's nuclear reactors. A new reactor concept must have significantly superior economics to ensure a competitive machine in 2025. Three methods have been used to develop initial cost estimates based on a 2400-MW(t) reactor.

- *Sodium and gas-cooled reactor comparisons.* Costs were derived relative to the S-PRISM and the MHTGR, based on scaling factors on a system-by-system basis [10]. The capital costs of the AHTR were estimated to be between 50 and 60% of those for the previous two reactors per kilowatt (electric). Both the S-PRISM and the MHTGR are modular reactors; thus, the 2400-MW(t) AHTR has the benefits of large economics of scale. Figure 3 [12] shows a scale drawing of the nuclear systems for a 600-MW(t) gas turbine modular high-temperature reactor (GT-MHR) versus a 2400-MW(t) AHTR to provide a perspective on the scale of the different reactors.

- *LWR comparisons.* Figure 4 provides an economic comparison of various current and future LWRs [14] based on the quantities of materials required for their construction. All quantities are relative to that required to build a standard pressurized-water reactor (PWR) in 1970. The oldest reactors are on the left, and the most advanced concepts are on the right. The first-generation reactors used relatively small quantities of materials. Following the Three Mile Island accident and the added safety requirements that resulted, a significant increase in the quantities of material per unit power output occurred, as is seen in the GE Advanced Boiling Water Reactor (ABWR) and the Areva NP Economic Pressurized-Water Reactor (EPR). However, as technology progressed, the quantities of materials lessened as seen in the projected quantities of materials for the GE Economic Simplified Boiling-Water Reactor (ESBWR) that is now being licensed in the United States. The analysis indicates potentially highly competitive economics for the AHTR. A more detailed economic comparison with the Areva EPR [12] shows similar results for the AHTR.

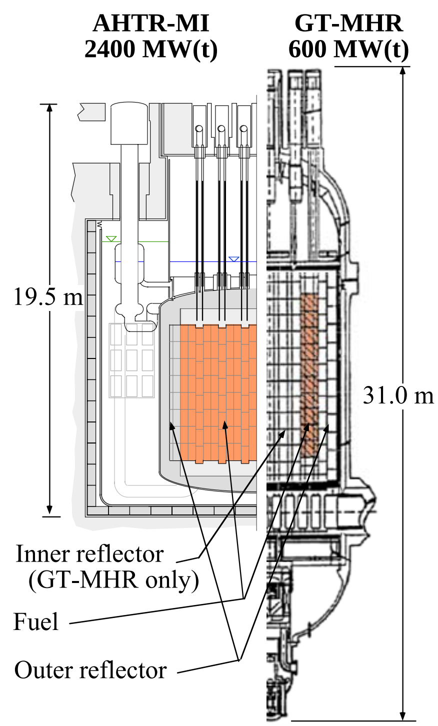

FIG. 3. SCALED COMPARISON OF THE 600-MW(t) GT MHR AND THE 2400-MW(t) AHTR WITH METALLIC INTERNALS (AHTR-MI)

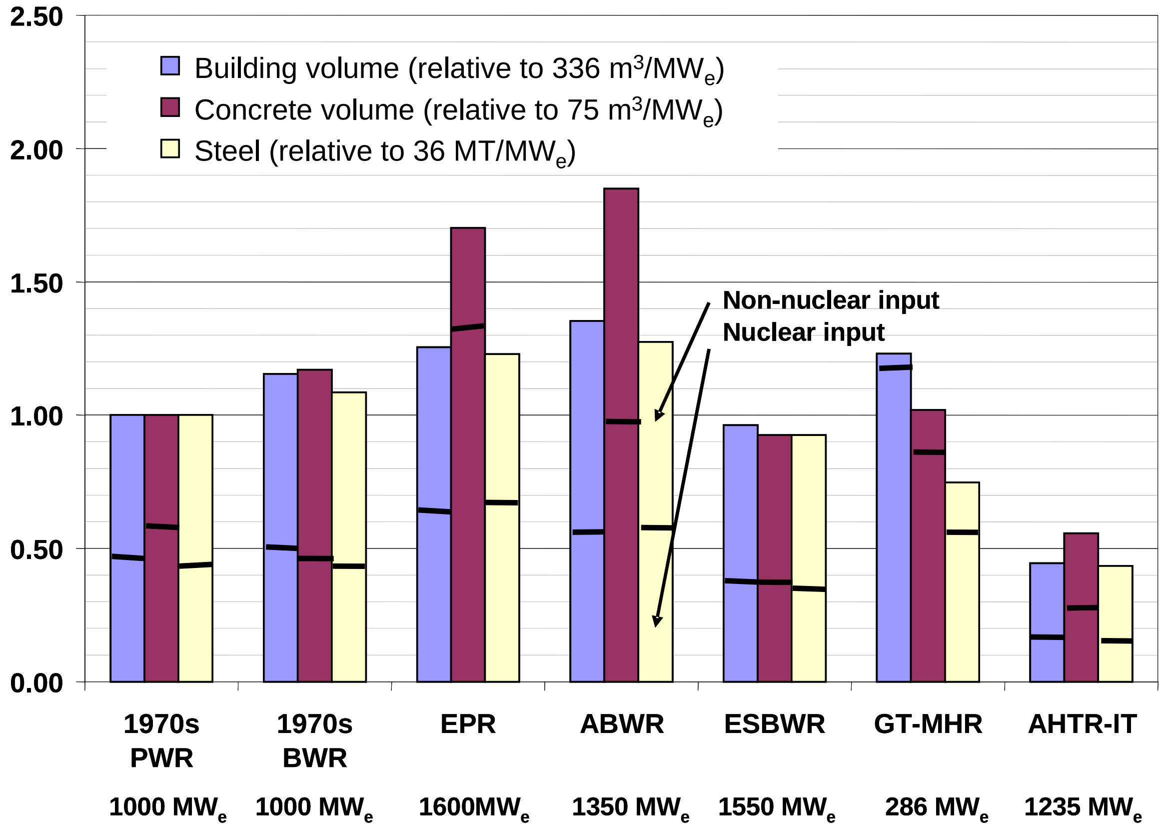

FIG. 4. RELATIVE QUANTITIES OF MATERIALS PER UNIT POWER OUTPUT REQUIRED TO CONSTRUCT VARIOUS TYPES OF REACTORS.

The potential for excellent economics reflects several factors: the AHTR can be a large reactor with the associated economics of scale; the high efficiency reduces capital costs (decay-heat-removal systems, power system heat rejection, cooling towers, etc.); closed Brayton power cycles have lower capital costs compared with traditional steam cycles; and the high heat capacity of liquid salts reduces the size (and hence the costs) of pumps, valves, and heat exchangers. As with all new reactor concepts, there are significant uncertainties. These alternative estimates support an economic capital cost goal per kilowatt (electric) that is one-third less than that for the best ALWRs for similar sized large plants. There is the longer-term potential that this goal can be significantly exceeded; however, this will likely require significant experience from operating AHTRs.

Electricity Production

From a commercial perspective, a top-level economic requirement for electricity production is to produce electricity at significantly lower costs than the estimated cost of electricity from large LWRs in 2025. Because of the capital-intensive characteristics of nuclear energy, this usually translates into minimizing the capital cost per kilowatt (electric) of electrical-generating capacity. Experience with other liquid-cooled reactors (LWRs and sodium-cooled reactors) has shown significant economics of scale. Because the AHTR is also a liquid-cooled reactor, the same economics-of-scale should be applicable.

In the specific case of LWRs, the gains from economics of scale have resulted in increasing the size of LWRs over four decades to ~1650 MW(e). The newest steam turbines being designed for LWRs have maximum ratings of ~1800 MW(e), an indication that the vendors expect continued growth in the size of these reactors. The expectation is that by 2025 large LWRs will have power outputs approaching 2000 MW(e). If an AHTR is ultimately a replacement for the LWR to produce electricity and if economics of scale apply, the expectation is that the power output of an AHTR should roughly match that of a large LWR. In other words, the general plant design and major system designs allow the plant to be built in sizes up to an electrical power output for an AHTR of ~2000 MW(e) or a thermal output of ~4000 MW(t), assuming an efficiency of ~50%. The actual size will depend upon the specific customer requirements. While this electrical output is larger than that for existing LWRs, the thermal power of such an AHTR would be less than that for large existing LWRs that have thermal power outputs of ~4500 MW(t).

The choice of peak reactor coolant temperature is a trade-off between the material challenges of operating at high temperatures and the efficiency gains from such operations.

For electricity production, preliminary assessments indicate peak nominal operating coolant temperatures between 700 and 800°C, based on several considerations.

- *Salt freezing points*. The candidate liquid salts [3, 4] have freezing points between 350 and 500°C; thus, salt coolant temperatures should be several hundred degrees above the freezing points to improve salt properties (low viscosity) and to provide a margin between operating conditions and the freeze point.

- *Material limits*. Existing alloys for liquid-salt service have been nuclear-code-qualified to 750°C. A wide variety of alloys are potentially viable for operations to ~850°C but require additional testing and qualification. Beyond this temperature, the material choices decrease, the uncertainties in performance, and costs increase rapidly. Day to day operational temperatures must be significantly below peak allowable temperatures for short durations.

- *Brayton power cycles*. Brayton power cycles (helium or nitrogen) have major advantages over Rankine (steam) cycles: higher efficiency, lower capital costs, and an inert coolant. However, the minimum temperature for closed Brayton power cycles is ~700°C.

- *Efficiency gains*. The primary incentive for higher temperatures is higher plant efficiency. However, the gains in power plant efficiency (per degree rise in peak reactor coolant temperature) decrease with increasing temperatures (Table 2).

- *Dry cooling*. The temperature is sufficiently high to boost plant efficiency and enable economic dry cooling.

Dry cooling is an important longer-term consideration for an expanded nuclear energy economy. Because of siting constraints, strong incentives exist for a nuclear reactor with the capability to use dry cooling for heat rejection. In the last decade in the United States, several major proposed fossil power stations were ultimately canceled because the companies could not obtain sufficient water rights to ensure an adequate supply of cooling water. For nuclear plants, strong licensing, public acceptance, and safety benefits are associated with siting nuclear power plants some distance from major populations. However, most power plant sites are relatively close to large populations because (1) reactors with conventional cooling systems need large quantities of water and (2) the population of the United States is located primarily along the rivers and coast because of the domestic and industrial need for water. If the water requirement is eliminated, the nuclear plant siting options dramatically increase. For example, the west coast of the United States near the Pacific Ocean has a high population density. Only 150 km inland to the desert (a short distance for electrical transmission) are low population densities and relatively short electrical transmission distances; however, there is no water at these locations.

Although dry cooling is expensive, about 30,000 MW(e) of fossil plants worldwide have such systems. Dry cooling systems have not been used with nuclear power plants because the lower efficiency of LWRs (~33%) relative to fossil plants (~40%) implies larger cooling systems. Increasing the efficiency of the nuclear power plant from ~33% (LWR) to ~50% (AHTR) reduces the heat rejection per kilowatt of electricity by a factor of 2. This reduction is sufficient to make dry cooling a potentially viable cooling option under a wide variety of circumstances. To obtain efficiencies of ~50%, the peak reactor coolant temperatures must be above 700°C.

Hydrogen Production

Hydrogen production, potentially the second large market for nuclear energy, has the long-term potential to approach the size of the electricity market [15−18], regardless of whether hydrogen-fueled cars are ever deployed. Hydrogen is the primary input in converting carbon feedstocks (heavy oil, tar sands, shale oil, coal, etc.) into liquid transport fuels and in the longer term may be used for peak electricity production. Currently about 5% of the natural gas in the United States is used to produce hydrogen by steam reforming.

The energy from nuclear reactors can convert water to hydrogen and oxygen. The existing technology is electrolysis, the room-temperature process that converts electricity and water to hydrogen and oxygen. Three other classes of technologies, which use less electricity and more heat to convert water to hydrogen and oxygen, are being developed [19]. Because heat is less expensive than electricity, these technologies have the long-term potential to produce hydrogen at lower costs. The energy inputs to high-temperature electrolysis are electricity and heat to convert water to steam. For hybrid cycles, the energy inputs are electricity and high-temperature heat to drive chemical reactions, while thermochemical cycles require high-temperature heat to drive a series of chemical reactions.

Various studies [20, 21] project the cost of hydrogen production via the thermochemical processes to be as low as 60% of those for electrolysis, with long-term potential heat-to-hydrogen efficiencies in excess of 60% (which represents the potential for major improvements over time).

Hydrogen demand is growing rapidly today because of the need to upgrade heavy crude oil to liquid fuels (gasoline, diesel, and jet fuel) and to improve liquid fuel quality by removal of sulfur compounds. Almost all hydrogen today is made by steam reforming of fossil fuels. The size of the hydrogen production unit is controlled by the market need, with multiple hydrogen production units typically located at a single facility [22] to ensure a continuous supply of hydrogen. Ten years ago, a typical single-train hydrogen plant produced 1.4×10^6 m^3/d (50×10^6 ft^3/d). Today there are almost three dozen units with production capacities exceeding 2.8×10^6 m^3/d, new units coming online with capacities of 3.7×10^6 m^3/d, and plans for single-train units twice that size.

The growth in plant size is driven by the economics of scale and the existence of markets sufficiently large to consume the hydrogen produced by these facilities. Miller and Duffy [23] have estimated the scaling factor for hydrogen plants operating on natural gas to be 0.66. This implies that if the plant size is increased by 4, the capital cost increases by only a factor of 2.5; that is, the capital cost of the larger facility is only 62% of that for the smaller facility per unit of capacity. For larger-scale hydrogen applications—such as coal liquefaction [24], production of peak electricity [17], or hydrogen-fueled vehicles—the economic optimum hydrogen plant size would be larger.

To provide perspective on the current scale of industrial hydrogen operations, the largest hydrogen production complex now under construction [25] to support oil refinery operations will have four parallel trains producing hydrogen from natural gas. Each train will produce 3.9×10^6 m^3/d of hydrogen, with a total facility output is 15.6×10^6 m^3/d of hydrogen. The power equivalent of that rate of hydrogen production is about 2300 MW. Thus, if electrolysis were used with typical efficiencies, approximately three 1000-MW(e) nuclear plants would be required to provide the electricity to produce that hydrogen assuming typical plant availability factors. If a single high-temperature nuclear reactor with 50% efficiency produced that quantity of hydrogen, the reactor output would be 4600 MW(t). Significant expansions have also been required in hydrogen production for other uses. For example, in China 18 large hydrogen production systems using coal are expected to start up between 2005 and 2007. Ten of these are for ammonia, five are for methanol, and one is for coal liquefaction.

If we assume that a nuclear thermochemical process (when commercially deployed in 15 to 20 years) is to produce 8.5×10^6 m^3/d of hydrogen (twice the size of current plants and about the size of the largest conventional single-train hydrogen plants being considered for future plants), the nuclear reactor or reactors must deliver ~2400 MW(t) of high-temperature heat to the process. This assumes that the process is 50% efficient in converting heat and water to hydrogen. If applications such as coal liquefaction become important, the plant size would likely be larger. In the 1970s, Westinghouse began development of a high-temperature gas-cooled reactor for nuclear hydrogen production [21] with a nuclear plant size in excess of 3000 MW(t).

For nuclear hydrogen production, there are several other specific considerations.

- *Capital versus operating costs*. The cost of hydrogen produced by steam reforming of fossil fuels is dominated by the operating cost, primarily the cost of the fossil fuel. If the demand for hydrogen changes, production rates are altered by reducing or increasing the output of a single unit or shutting down or starting up one of several parallel hydrogen production trains. Nuclear hydrogen production costs are dominated by the capital costs. The variable operating costs are small. Variable hydrogen demand [26] can be met via large production units and hydrogen storage in underground caverns using the same technology as is used for utility-scale natural gas storage. Hydrogen storage caverns have operated for decades in the United States and the United Kingdom. This consideration favors building a few large nuclear hydrogen production plants with associated economics of scale versus construction of multiple smaller units. Hydrogen demand during nuclear plant refueling operations or variable demand is met by hydrogen from storage. Instead of four smaller units [1200 MW(t)] each, the economics would likely dictate two units of 2400 MW(t).

- *Hydrogen process economics of scale*. There are strong economics of scale, independent of the production method. Different studies have identified scaling factors that vary from about 0.5 to 0.85. Many of the DOE hydrogen studies have used a scale factor of 0.75; however, other factors indicate larger scaling factors (lower numbers). A scaling factor of 0.7 implies that doubling the hydrogen output capacity of the production facility decreases the capital cost per unit of hydrogen to 81% of that for the smaller facility. The scaling factor for the nuclear hybrid thermochemical process [27] was estimated at 0.54; that is, the capital cost of the larger facility (which is 4 times the size of the smaller facility) is only 53% that of the smaller facility per unit of capacity. The economics of chemical plants require that thermochemical nuclear hydrogen facilities be large to achieve good economics.

For the hybrid and thermochemical processes, the required peak *chemical-process temperatures* are near 850°C; however, ongoing research may potentially lower these temperatures by 100 to 150°C. Because of temperature loses across heat exchangers and safety requirements that an intermediate heat transport loop be used to separate the nuclear reactor from the hydrogen production plant, the peak reactor coolant temperatures will be higher than the hydrogen process plant temperatures. The peak reactor coolant temperature may be as high as 950°C. The peak reactor coolant temperature will be less than that required for gas-cooled high-temperature reactors because liquid-cooled reactors have smaller temperature drops across heat exchangers than gas-cooled reactors [28]. Significant uncertainty is associated with the goals and requirements for hydrogen production.

SUSTAINABILITY GOALS

The GenIV sustainability goals address the availability of uranium resources and the impacts on repositories. With the AHTR, uranium consumption is less per kilowatt electricity [29] than for LWRs. This is partly due to the higher thermal-to-electricity efficiency of the AHTR (50%) relative to that for LWRs (33%). Relative to the MHTGR, the AHTR has lower uranium consumption and higher spent nuclear fuel (SNF) burnup. This difference occurs because the AHTR is a large reactor with a large reactor core and low neutron leakage whereas an MHTGR with its annular core has high neutron leakage. This allows the AHTR to have significantly higher SNF burnup relative to the MHTGR for the same initial fresh-fuel enrichment.

With respect to repository impacts, the AHTR SNF toxicity and SNF decay-heat load in the repository are less per kilowatt electricity [29] than for LWRs. This is primarily because of the higher thermal-to-electricity efficiency of the AHTR (50%) relative to that for LWRs (33%) that implies fewer fissions per unit of electricity produced. The reduced decay heat per unit of electricity produced implies greater repository capacity per unit of electricity. The repository performance of graphite-matrix SNF is potentially several orders of magnitude better than that of LWR SNF [29].

There is the long-term option of recycling the SNF. Recent research [30] has identified new methods for front-end processing technologies that are potentially major improvements over the historical technologies for processing carbon-matrix SNFs. The technologies integrate front-end SNF processing and the waste treatment operations to use the carbon in the SNF to produce a very high-performance high-level-waste form. The one restriction is that the equipment and technologies may require facilities with large throughputs.

SAFETY AND RELIABILITY GOALS

As specified earlier, the design goals for the AHTR are to match or exceed those of the MHTGR. This implies no major radionuclide releases *from the fuel* in beyond-design-basis accidents versus add-on containment systems to contain core melt accidents in LWRs. This goal substantially exceeds the safety goals of ALWRs. While current LWRs meet all safety requirements, there are potentially large economic, safety, and institutional advantages if these more aggressive goals can be achieved.

The primary emphasis of the U.S. GenIV program has been development of the very high-temperature reactor (VHTR) based on two considerations: (1) the ability to produce high-temperature heat for the production of hydrogen and (2) the unique safety characteristics of the VHTR. The emphasis for hydrogen production is based on the Presidential hydrogen initiative. The capabilities of the VHTR to meet the GenIV goals are a consequence of the remarkable performance capabilities of graphite-matrix, coated-particle fuel. Earlier assessments by the U.S. Nuclear Regulatory Commission [31] indicated that the MHTGR has the potential capability to withstand accidents involving non-mechanistic failures of all the decay-heat-removal systems. Under such conditions, the plant is destroyed (in terms of its capability to produce electricity), but no major releases of radioactivity occur. The decay heat is conducted to the earth through the silo. The transient also shuts down the reactor. These safety capabilities are a consequence of the very high temperature capabilities of the fuel and a system design that allows sufficient decay heat to ground in severe accidents to avoid exceeding the temperature limits that result in catastrophic fuel failure. The AHTR is to retain these same goals and capabilities.

To achieve these safety goals requires the use of inherent and passive safety systems. As defined by the International Atomic Energy Agency [32, 33], inherent safety is “safety achieved by the elimination of a specified hazard by means of the choice of material and design concept.” Passive safety is “either a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation.” Two examples of inherent safety that are unique to the AHTR as a high-temperature reactor are: (1) a low-pressure coolant that eliminates pressure as a driving force to move radionuclides to the environment and (2) a coolant that dissolves and holds most fission products (including iodine and cesium) and actinides if these materials escape from the fuel.

This potential capability has major implications in terms of GenIV safety and reliability goals. In terms of safety, reactors with the graphite-matrix, coated-particle fuel have better performance than other GenIV reactors that are being developed. From a technical perspective, the safety capabilities eliminate the need for off-site emergency responses. This has potentially major economic benefits in terms of factors that are tied to the accident potential of the plant: reduced emergency off-site preparation, increased public acceptance, and less-stringent security requirements.

PROLIFERATION RESISTANCE AND PHSICAL PROTECTION GOALS

In terms of meeting the GenIV goals in this area, the AHTR characteristics are approximately equal to those of the MHTGR because the two reactors use similar fuels. The MHTGR SNF has the highest resistance to proliferation (Criteria PR1-1) of all reactor fuels because (1) the fissile material is diluted compared with other types of reactor fuels and (2) the fuel is in a relatively inert matrix. These characteristics complicate recovery of fissile materials on a small scale, as might be attempted by a proliferator. Equally important, the safety strategy for these plants protects the public against radionuclide release in the event of an assault (Criteria PR1-2) on the plant. Thus, the safety strategy has the potential to reduce the physical protection requirements.

FUNCTIONAL SAFETY REQUIREMENTS

Based on earlier work [34], functional safety requirements for the AHTR have been developed (see Fig. 5). The functional requirements start with the top-level requirement to maintain control of the radionuclides. These functional requirements define what the safety systems must accomplish. The combination of functional requirements, regulatory requirements, and safety goals is used as a basis for choice of safety systems.

CONCLUSIONS

The development of the AHTR has progressed from an ideal to a preliminary concept, where alternative systems are being evaluated to determine the optimum configuration or configurations for different missions. With this progress is the requirement to more precisely define goals and requirements to provide a basis for choosing preferred structures, systems, and components. An initial set of goals and requirements has been defined. Although some of the goals for electricity production will differ from those for hydrogen production, many of the other goals and requirements are identical.

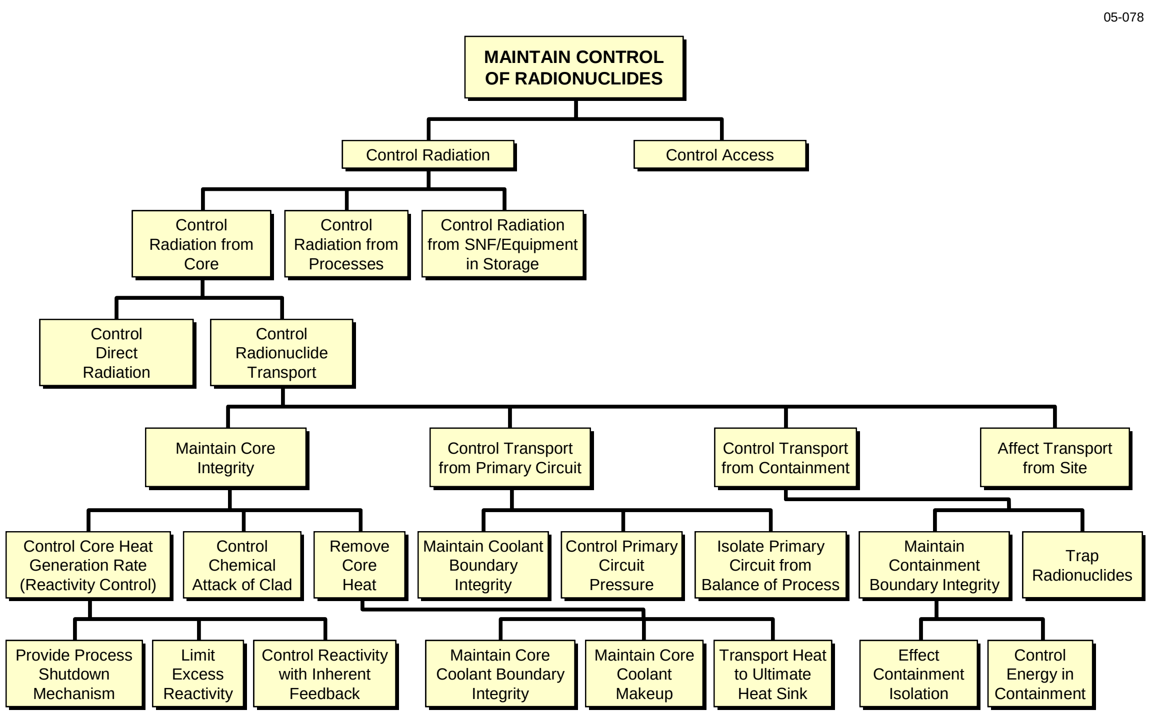

FIG. 5 AHTR FUNCTIONAL SAFETY REQUIREMENTS

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