Status Report - SmAHTR (United States of America)

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1. Overview

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- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS --

- ☑ **New Concept**

Number of Units --

Year --

Reference Plant

Name of Site --

Link to PRIS --

Net Power Output (MWe) --

Gross Power Output (MWe) --

1.1 Introduction

SmAHTR is a deliberately small (125 MWt) fluoride salt–cooled high-temperature reactor (FHR) design concept intended to match the energy requirements of coupled industrial processes. SmAHTR's overall purpose is to enable an integrated assessment of the potential performance of deliberately small FHR designs and to provide guidance to the overall FHR research and development effort. SmAHTR's development effort has been in support of the US Department of Energy (DOE) Office of Nuclear Energy's Advanced Reactor Technologies Program. SmAHTR is an early phase concept and therefore is not commercially viable at this time.

FHRs are an emerging reactor class that combines attractive attributes from previously developed reactor classes and power plants. FHRs by definition feature low-pressure liquid fluoride salt cooling; high-temperature-tolerant, salt-compatible fuel; a high-temperature power cycle; and fully passive decay heat rejection. FHRs have the potential to economically and reliably produce large quantities of electricity and high-temperature process heat while maintaining full passive safety. Leveraging the inherent reactor class characteristics avoids the need for expensive, redundant safety structures and systems and is central to making the economic case for FHRs. Additionally, as a high-temperature reactor class, FHRs can efficiently generate electricity and provide the energy for high-temperature

industrial processes (notably including the production of hydrocarbon fuel). Moreover, hightemperature operation increases FHR compatibility with dry cooling. Figure 1 shows the layout of the SmAHTR in-vessel structures.

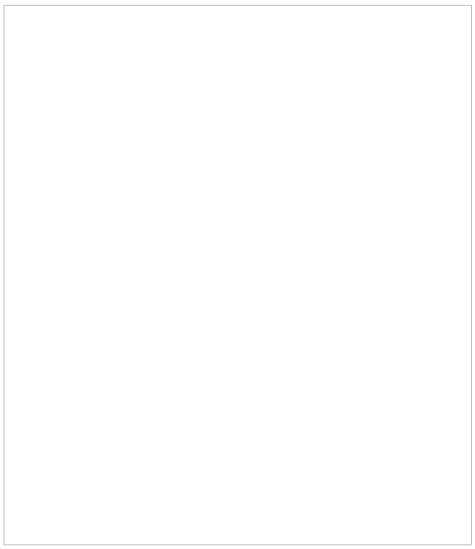


Figure 1: SmAHTR in and near vessel structures (Reproduced courtesy of ORNL)

Target Application

The particular variant of SmAHTR described in this report is designed for efficient hydrogen production using the carbonate thermochemical cycle (CTC) [1] The SmAHTR-CTC design variant is an evolution of the SmAHTR design concept first described by Greene et al. in 2010 [2]. Additional detail about the design is available in ORNL/TM-2014/88.

1.2 Development Milestones

2010	Initial SmAHTR conceptual design developed
2014	Perform refined SmAHTR concept study focused on high-temperature heat production

1.3 Design organization or vendor company

1.4 Links to designer/vendor website

1.5 Design Description

1.6 Licensing Application Support Documents

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Demonstration	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Non-electric (H2 Production)	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location		e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)		e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	Molten Salts	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	30 MWth <= Thermal power < 1000 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth
Reactor Type	MSR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR
Neutron Moderator	Other	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout		e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced	e.g. Forced (# pumps), Natural
Thermodynamic Cycle		e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)

Secondary Side Fluid		e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly/Bundle	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape		e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Other	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Under Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Thermal	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	60	Years
Lifetime Capacity Factor		%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages		# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources		# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design		n Units/Modules
Capacity to Electric Grid		MWe (net to grid)

Non-electric Capacity		e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint		m2 (rectangular building envelope)
Site Footprint		m2 (fenced area)
Emergency Planning Zone		km (radius)
Releases during Normal Operation		TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed		x – 100%, % per minute
Seismic Design (SSE)		g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	1	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)		MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)		kg
Nominal Coolant Flow Rate (primary)		kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	670	ºC
Core Outlet Coolant Temperature	700	ºC
Available Tempeature as Process Heat Source		ºC
NSSS Largest Component		e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	9000	mm
- NSSS Largest Component Diameter	3500	mm
- NSSS Largest Component Thickness		mm

- NSSS Largest Component Weight	22.5	tonne
Reactor Vessel Material	Alloy 800H and Alloy N	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design		e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory		kg
Pressurizer Design		e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume		m3 / m3 (total / liquid)
Containment Type		Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume		Years of full-power operation / m3
Non Electric Application	H2 production	-
Core Delta Temperature	30	ºC
Fuel/Core		
Single Core Thermal Power	125	MW(th)
Refuelling Cycle	6	months or “continuous”
Fuel Material	UCO	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	8	%
Average Neutron Energy		eV
Fuel Cladding Material	TRISO	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”		Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit		kg
Total Fissile Loading (initial)		kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation		Applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge		%

Core Discharge Burnup	69.0	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding/Conversion Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing		e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control		e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		n/(cm²*s)
Max. Fast Neutron Flux		n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	N/A	- / - / -
- core injection	N/A	- / - / -
- decay heat removal	N/A	- /- / -
- containment isolation and cooling	N/A	- / - / -
- emergency AC supply (e.g. diesels)	N/A	- / - / -
DC Power Capacity (e.g. batteries)		Hours
Events in which Immediate Operator Action is required		e.g. any internal/external initiating events, none
Limiting (shortest) Subsequent Operator Action Time		Hours (that are assumed when following EOPs)

Severe Accident Core Provisions		e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)		x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)		x/reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)		Months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort		Person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C]/%[M&E]	
- Site Development before first concrete		(e.g. 25/10) (30/40) (20/25) (20/10) (5/15) (----------) (to add up to 100/100)
- Nuclear Island (NSSS)		
- Conventional Island (Turbine and Cooling)		
- Balance of Plant (BOP)		
- Commissioning and First Fuel Loading		
Factory / On-Site split in [C&C] effort		%/% of total [C&C] effort in PY (e.g., 60/40)
Nuclear System		
System Steam Flow Rate		kg/s
System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s
System Feedwater Temperature		ºC

Reactor Core		
Active Core Height		m
Equivalent Core Diameter		m
Average Linear Heat Rate		kW/m
Average Fuel Power Density		kW/kgU
Average Core Power Density		MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

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4.1 Site Requirements during Construction
4.2 Site Considerations during Operation
4.3 Grid Integration

5. Technical NSSS/Power Conversion System Designn

SUMMARY FOR BOOKLET

General Design Description

Design Philosophy

The “new build” strategy being pursued for SmAHTR-CTC has three guiding principles: (1) leverage plant characteristics for maximum economic performance, (2) maximize reliability, and (3) minimize licensing risk. The design intent is to leverage the inherent reactor characteristics to drive down cost while to the extent possible staying within the structure of the current US Nuclear Regulatory Commission (NRC) licensing framework. A key element of the strategy is to rely upon SmAHTR’s strong, inherent safety characteristics to avoid the need for expensive, redundant safety structures and systems.

Power Conversion Unit

SmAHTR’s hydrogen production plant will implement the CTC. The peak cycle temperature is not greater than 650°C, and the peak pressure is at most a few atmospheres. In the CTC process, uranium valence changes drive the decomposition of water to hydrogen and oxygen.

The key innovative step is reacting triuranium octoxide (U3O8) with sodium carbonate (Na2CO3) and

steam to generate hydrogen and sodium diuranate ($Na_2U_2O_7$) at ≤650°C [3]. The reaction is suitable for implementation in a screw calciner. The relatively narrow and variable energy gap, between uranium's 6d and 5f atomic orbitals, enables uranium to assume more than one valence state under relatively mild temperatures and pressures. Shifting uranium's oxidation state liberates the hydrogen from the steam. The cycle process steps necessary to regenerate U_3O_8 and Na_2CO_3 from $Na_2U_2O_7$ are already industrially implemented in the uranium processing industry. However, the CTC to date has only been demonstrated at laboratory scale.

5.1 Primary Circuit

Reactor Pressure Vessel and Internals

SmAHTR employs an Alloy 800H reactor vessel with an Alloy N lining. The fueled core and the radial reflector are contained within a 2-cm-thick core barrel made of carbon-carbon composite that separates the up-flow from the downcomer. The inside of the core barrel facing the core has a thin plating (1 cm) of boron carbide to reduce the neutron flux on the reactor vessel. The downcomer is sized so that its transverse flow area is at least twice the incore flow area.

5.2 Reactor Core and Fuel

Reactor Core & Fuel Characteristics

Figure 2: SmAHTR fuel assembly upper end and partial core cross section (Reproduced courtesy of ORNL)

SmAHTR uses tri-structural isotropic (TRISO) coated-particle fuel embedded near the surfaces of carbon plates. SmAHTR uses the uranium oxycarbide TRISO fuel particles currently being tested under DOE's advanced gas reactor fuel development program. The fuel particles are located near the surfaces of the plates to lower the peak particle temperature by improving the thermal coupling to the coolant. The plates are configured into hexagonal assemblies with 18 plates per assembly. SmAHTR's fuel assemblies will closely resemble shortened versions of those for the larger advanced high-temperature reactor (AHTR) [4]. The fuel assemblies will be mounted together into a cartridge core using continuous-fibercomposite core support plates. SmAHTR's cartridge core enables filling of the inter-assembly volume with nuclear-grade graphite, resulting in improved neutron utilization, as shown in Figure 2. The entire core will be lifted out as a single unit for refueling. Each fuel assembly includes a molybdenum hafnium carbide control blade. While

plate-style TRISO fuel bodies have not been manufactured previously, the manufacturing process steps of any geometricshape fuel body are nearly identical.

5.3 Fuel Handling

Fuel Handling System

SmAHTR-CTC's transparent, low-pressure coolant enables refueling to be performed rapidly using conventional mechanical manipulation technology that is visually guided from above. To refuel, the reactor is first brought subcritical by inserting the control blades. Once the blades have been inserted, the reactor vessel lid can be removed. The core can then be moved via an overhead crane system into the used fuel pool. The thermally robust nature of coatedparticle fuel significantly eases the fuel transfer safety design requirements. Even just a few hours after shutdown, the core can withstand more than 15 minutes of removal from liquid cooling, during the fuel transfer process, without exceeding its allowable maximum temperature. SmAHTR-CTC uses a shielded fuel transfer ramp mechanism conceptually derived from the Phénix SFR fuel-handling system. Once the reactor vessel top has been removed, a shielded ramp is positioned (using a rail system) with its entrance over the top of the reactor vessel. The core is raised out of the vessel and up the ramp using an overhead crane; and upon reaching the top of the ramp, it is allowed to swing to its opposite side. The core is then lowered into the used fuel pool, sliding down the far side of the ramp. The corelifting mechanism includes a thermal fuse, so that if at any point during the fuel transfer the maximum allowable temperature were exceeded, the core would be passively released to slide downward into a cooled configuration. SmAHTR-CTC employs a twin cartridge-core configuration. A cartridge configuration enables the core to be moved as a single unit, minimizing the number of mechanical manipulations required for refueling. In a twin core system, one core is in the reactor vessel and the other is in the used fuel pool. The twin core configuration enables assembly-level fuel shuffling to be performed while the alternate core is in operation. SmAHTR's core needs to be moved as a single unit because of the tight clearances of its structural elements. Some radiation-induced mechanical distortion will occur during operation. The mechanical distortion will prevent the removal of individual fuel assemblies from the top. The core internal graphite pieces will be replaced as the fast neutron fluence causes excessive mechanical distortion (every few years). Separating the fuel from the graphite moderator enables separate disposal of the in-core graphite and the fuel assemblies, decreasing the volume of high-level waste. SmAHTR-CTC maximizes its neutronic efficiency by maximizing the amount of carbon in the core while minimizing the amount of FLiBe.

5.4 Reactor Protection

Reactivity Control

SmAHTR has two primary shutdown mechanisms: (1) control blades and (2) poison salt injectors. SmAHTR does not have any threshold phenomena that would occur if the primary coolant temperature were to exceed the design point by several tens of degrees for hundreds of hours. Consequently, the temperature rise can be employed to passively initiate shutdown. If SmAHTR's core outlet temperature were to exceed its design limits, the control blades would be passively inserted as a result of melt point fuses in the control blade linkages. The control blades are jointed to provide sufficient flexibility to enable insertion if their guide tubes become distorted. The control blades are also actively engaged to the drive motors. Upon loss of power, the control blades would disengage from the drive mechanisms and drop into the core. The poison salt injectors have a single-ended cylinder and plunger format. Pressurized inert gas is maintained on the closed end of

the cylinder. A sliding disk divides the cylinder volume into open and closed ends. The open end of the cylinder is filled with poison salt powder (EuF3 or GdF3). A melt point alloy holds a lid onto the open end of the cylinder during normal operations. The poison salt accumulator is located in SmAHTR's lower plenum. If the lower plenum temperature exceeds the set point value, the melt point trigger releases and the poison salt is injected into the core inlet. The melt point release mechanism can also be triggered by the plant operators via embedded electrical heaters. Both the primary and secondary shutdown mechanisms provide substantially more negative reactivity worth than would be necessary to shut down the reactor. The reactivity worth of the control blades is sufficient to shut down the reactor with the most reactive blade stuck out of the core at all points during the fuel cycle. As the intended refueling interval is only 6 months, blade insertion capability will be confirmed frequently. The solubility of the reserve shutdown poison salts is much greater than the potential concentration in the lower vessel plenum, providing confidence that the salts would dissolve completely in the primary coolant and rapidly bring the reactor subcritical.

5.5 Secondary Side
5.6 Containment/Confinement
5.7 Electrical, I&C and Human Interface
5.8 Unique Technical Design Features (if any)

6. Technology Readiness

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Decay Heat Removal

SmAHTR-CTC's normal core decay heat removal is via the intermediate cooling loop to the balance-of-plant heat rejection system. During maintenance shutdowns, SmAHTR-CTC's core will be removed to the used fuel cooling pool. Decay heat will be removed via the three independent DRACS cooling loops under loss-of-forced-flow accident conditions. The DRACS cooling loops transfer heat from the DRACS heat exchangers located within the reactor vessel to the natural draft heat exchangers (NDHXs) located at the bases of chimneys external to the reactor building. Each NDHX is located within its own chimney to avoid common vulnerability to a single external impact. During normal operation, each NDHX is contained within an insulated shell to minimize the parasitic heat loss, and resultant potential for freeze-up, and to enable tritium capture within the NDHX shell. Each DRACS loop is sized to provide ~0.5% of full-power heat rejection under fully developed flow conditions at 700°C. Only two of the three DRACS loops are required to protect against an unacceptable temperature rise following or during a protected loss-of-forced-flow accident. The ultimate heat sink is outside air. Used fuel pool normal-condition cooling is provided via a pumped salt loop to a forced convection heat exchanger coupled to the outside air. Safety-grade heat rejection is provided for the used fuel pool through a two-phase, reduced-pressure, liquidmetal thermosyphon tube wall with the hot ends of the tubes dipped into the used fuel pool and the condenser section above the top of the containment structures.

6.1 Deployed Reactors
6.2 Reactors under Licensing Review
6.3 Reactors in the Design Stage

7. Safety Concepts

SUMMARY FOR BOOKLET

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

SUMMARY FOR BOOKLET

8.1 Fuel Cycle Options
8.2 Resource Use Optimization
8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

SUMMARY FOR BOOKLET

9.1 Safeguards

The safety characteristics of FHRs arise from fundamental physics and well-designed, constructed, and maintained structures, systems, and components (SSCs). Until an approved set of reactor-class-specific general design criteria, as well as design basis accident (DBA) sequences, is available, a combination of engineering judgment and the safety characteristics of FHRs will be relied upon to guide SmAHTR-CTC design. FHRs feature full passive safety and do not require any active system or operator response to avoid large off-site release for any DBA or evaluated beyond-DBA, including earthquake, tsunami, large commercial plane impact, or permanent station blackout. More specific information about SmAHTR-CTC's safety characteristics is provided in the following paragraphs.

Large Thermal Margin To Fuel Failure

The silicon carbide barrier layer of properly operating coated-particle fuel will remain intact several hundred degrees above SmAHTR-CTC's peak fuel temperature, retaining nearly all of the fission fragments. The primary FLiBe coolant will not boil until it reaches temperatures over 1400°C. SmAHTR's core outlet temperature is 700°C. Additionally, the viscosities of fluoride salt coolants decrease with increasing temperatures, resulting in increased coolant flow to the hottest fuel, thereby reducing fuel hot spots. Further,

while the power density of FHR cores is above that of high-temperature gas-cooled reactors (HTGRs), FHRs contain larger numbers of fuel particles, resulting in low average particle power (26.5 mW/particle for the SmAHTR-CTC compared with ~150 mW/particle for the nextgeneration nuclear plant HTGR design). This limits the radiochemical challenge to the silicon carbide containment layer within the fuel.

Multiple Fission Product Barriers

As described in the previous section, SmAHTR-CTC features four independent containment layers along with a substantial radionuclide source term reduction due to the core's immersion in fluoride salt. Additionally, the low system pressure prevents the development of a significant driving force, which would cause the dispersion of radionuclides in the event of barrier failure.

Multiple Barriers To Prevent Uncovering Fuel

The reactor vessel does not include any penetrations below ~20 cm above the top of the direct reactor auxiliary cooling system (DRACS) heat exchangers. Fluoride salts have high volumetric heat capacity, and a large volume of salt is maintained over the core, providing a substantial thermal margin. Further, owing to the high melting point of the primary salt coolant, small leaks in the reactor vessel are expected to self-seal as the coolant freezes upon leaking. Although the fuel is slightly buoyant in the coolant, multiple upper core support structures, including the upper core support plate, the weight of the control blade, and the control blade guide tube, all maintain the fuel below the surface.

Strong Negative Temperature Reactivity Feedback

The strong overall reactor negative reactivity temperature feedback will prevent reactivity insertion accidents from causing fuel damage. The negative Doppler fuel temperature coefficient for fresh fuel is similar in magnitude to that of a typical pressurized water reactor. The coolant temperature feedback coefficient is also negative, but it is one order of magnitude smaller than the negative Doppler feedback, while the moderator temperature coefficient is near zero. The >700 K margin to coolant boiling, combined with the deep coolant pool, makes significant voiding of the core highly improbable. The combination of void and temperature coefficients is always negative under these circumstances, thus avoiding the potential for fuel damage reactivity accidents. Bubbles within the primary coolant flow (caused by, for example, gross failure of the reserve shutdown system piping) would be a DBA that would cause local fuel heating as the bubbles rise through the core. However, the large thermal margin to fuel failure, the rapid Doppler feedback, the limited duration of bubble passage, and the longer neutron path length in graphite-moderated cores alleviate the potential for bubble entrainment to damage the fuel. Additional safety evaluations are necessary to better assess the heat transfer consequences of the events under this scenario.

Thermally Triggered Shutdown Mechanisms

SmAHTR-CTC's most thermally sensitive component is its reactor vessel. Exceeding the reactor vessel's design temperature for long periods of time would increase its creep. However, creep is not a threshold process, and SmAHTR-CTC's reactor vessel creep budget would allow for hundreds of hours of operational time at several tens of degrees above normal. The ability of the vessel, core, and coolant to tolerate temperature rises enables the use of thermal triggers to provide negative reactivity feedback. SmAHTR-CTC's control blades feature thermal fuses (melt point alloys) located in the upper plenum that are designed to release the blades in the event of an over-temperature accident without SCRAM. Also, SmAHTR's secondary shutdown poison salt accumulators will be set to inject poison salt into the core inlet plenum in

the event of more-severe temperature excursions.

Slowly Evolving Accidents

SmAHTR-CTC has no credible primary coolant-phase-change accidents. SmAHTR-CTC also has a much lower power density core than modern light water reactors (LWRs) (~5.3 MW/m3 vs ~110 MW/m3), resulting in significantly slower transient response. The power density is calculated to be 9.4 MW/m3 if the carbon between the fuel assemblies is not considered to contribute to the core's volume (referred to as "power density in fuelled volume"). Further, the large volume of salt (the volumetric heat capacity of FLiBe is 4670 kJ/m3 -K at 700°C) and graphite in the reactor vessel provides for substantial local thermal storage to provide time for recovery operations.

Passive, Natural Circulation-Based Decay Heat Rejection

SmAHTR employs natural circulation DRACS-type decay heat rejection to the local air. Fluoride salts have large coefficients of thermal expansion that, combined with their large volumetric heat capacities, enable excellent natural circulation cooling. Similar naturalcirculation-driven emergency heat rejection is also provided to the used fuel storage pool. The DRACS are modular and independent, enabling the system to continue to function following the failure of individual units. SmAHTR-CTC's design calls for three independent DRACS and is intended to withstand DBAs with only two out of three systems in operation. Sufficient decay heat rejection is provided to avoid vessel failure in the event of complete, permanent station blackout accompanied by the loss of a single DRACS. In addition, SmAHTR-CTC will not require a dual interconnection to the grid, as the plant does not depend on the availability of electrical power to reject decay heat. SmAHTR-CTC does not require an emergency core cooling system or high-volume, safety-grade coolant makeup systems. Significantly lowering the primary coolant level in the vessel requires both primary and guard vessel failures, as no other mechanisms have been identified to remove substantial amounts of coolant from the vessel.

Low-Consequence Fuel-Handling Accidents

SmAHTR-CTC's core is slightly buoyant. However, each fuel assembly includes a molybdenum alloy control blade to provide sufficient ballast to sink the fuel in the event that the core is dropped during movement. Liquid fluoride salts are transparent, enabling fuel movement to be visually guided, thus substantially reducing the risk of unanticipated mechanical impacts while enabling visual confirmation of mechanical motion. Furthermore, since only the weighted core sinks slowly in the coolant, mechanical damage to the core or any other reactor structures as a result of its being dropped would not be anticipated.

Structurally Robust, Below-Grade Nuclear Facilities

FHR buildings and used fuel storage pools are intended to be located below grade, providing shielding from aircraft impact and wind/waterborne missiles. The DRACS cooling towers are spatially separated to avoid simultaneous failure of both as a result of a single aircraft impact and are structurally robust to minimize their vulnerability to likely natural events (e.g., large tornados or earthquakes).

Non-Water-Soluble Used Fuel

Carbon-enveloped coated-particle fuel is not water soluble, enabling used fuel assembly emplacement in shallow (<1 km) dry wells for eventual (after 6–12 months in an incontainment used fuel pool), local, intermediate-term, retrievable storage with a very low probability for radionuclide escape into the surrounding environment. The first layer of containment remains with the fuel after it is unloaded from the

core, and the silicon carbide containment layer is not anticipated to fail in the more benign used fuel storage environment. The envisioned local used fuel storage dry wells (boreholes) closely resemble cased and cemented petroleum wells, which can effectively reject decay heat to the surrounding rock as a result of their large surface-to-volume ratio.

Reactor Isolation From Non-Nuclear Facilities

SmAHTR-CTC's low-pressure liquid-salt intermediate loop prevents accidents in the CTC from adversely impacting the nuclear plant. The relatively low cost of the intermediate loop per unit of length enables separation of the reactor building from the hydrogen production facility by substantial distances (>100 m). The reactor will also be separated from potential pressure waves propagating down the intermediate loop piping by rupture disks, or other conventional pressure relief mechanisms, so that it is not credible for a disturbance (including hydrogen explosions) within the CTC to propagate to the nuclear island.

9.2 Security
9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

10.1 Project Preparation and Negotiation

Plant Economics

SmAHTR-CTC's objective is to economically and safely produce hydrogen and thereby maximize the return on investment to the plant owners. A key element in ensuring advantageous economic performance is minimizing the risk premium element of the interest rate paid during construction. The interest rate risk premium is determined based upon how confident a lender is that an FHR plant will (1) be constructed at planned cost and schedule, (2) obtain regulatory approval to operate, and (3) operate reliably for many years. SmAHTRCTC's design is not yet mature enough to develop a "bottom-up" cost model. Consequently, the economic evaluation is limited to comparison with similar technologies. Nearly all aspects of FHRs will either be less costly than or have costs equivalent to those of LWRs. The major exception to the comparative cost advantage is the markedly higher cost of the primary coolant. Initial FHRs will also incur significant first-of-a-kind expenses. For example, SmAHTR's initial fuel load of TRISO coated-particle fuel will cost much more than an equivalent LWR fuel because of the need to construct new manufacturing facilities. SmAHTR is a high-temperature reactor, which would enable it either to have higher thermal efficiency for electricity production or to produce high-temperature process heat. SmAHTRCTC's design is optimized to provide high-temperature process heat, avoiding initial competition with mature technology.

[1] J. L. Collins, et.al., Carbonate Thermochemical Cycle for the Production of Hydrogen, US Patent 7,666,387, B2, February 23, 2010.

[2] S. R. Greene, et.al., Pre-Conceptual Design of a Small Modular Fluoride Salt-Cooled High Temperature

Reactor (SmAHTR), ORNL/TM-2010/199, December 2010.

[3] J. Ferrada, et.al., “Carbonate Thermochemical Cycle for the Production of Hydrogen,” National Hydrogen Association Annual Conference and Hydrogen Expo, Columbia, South Carolina, March 30–April 3, 2009.

[4] V. K. Varma, et.al., AHTR Mechanical, Structural, and Neutronic Preconceptual Design, ORNL/TM-2012/320, Oak Ridge, TN, September 2012

10.2 Construction and Commissioning
10.3 Operation and Maintenance