Making Core Melt Accidents Impossible in a Large 2400-MW(t) Reactor

Charles W. Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008
Oak Ridge, TN 37831-6179
Tel: (865) 574-6783
Fax: (865) 574-0382
E-mail: forsbergcw@ornl.gov

Per F. Peterson
University of California, Berkeley
4153 Etcheverry, Berkeley, CA 94720-1730
Tel: (510) 643-7749
E-mail: peterson@nuc.berkeley.edu

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Charles W. Forsberg
Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831-6165
E-mail: forsbergcw@ornl.gov

Per F. Peterson
University of California, Berkeley
4153 Etcheverry; Berkeley, CA 94720-7749
E-mail: peterson@nuc.berkeley.edu

Abstract—There are significant benefits in building power reactors in which no accident can cause catastrophic core damage. To prevent major reactor core damage from decay heat after an accident, the fuel must not reach its failure temperature. If core cooling is lost, the core temperatures can be controlled by the combined mechanisms of (1) absorbing decay heat in the structure of the reactor and (2) transporting heat by the environment with systems that require no external activation. While this approach can be used in small reactors [up to 600 MW(t)], it has not been proposed for use in large reactors. We propose that a new reactor, the Advanced High-Temperature Reactor, may be built with this capability in sizes greater than 2000 MW(t). This development is a consequence of using a high-temperature fuel with a high-temperature, low-pressure liquid coolant.

I. INTRODUCTION

Two failure modes can destroy a nuclear reactor core: (1) a power excursion, such as happened at Chernobyl, and (2) failure to adequate cool the reactor core after reactor shutdown, such as occurred at Three Mile Island. The first can be prevented by appropriate reactor core design. The second failure mode is fundamentally more difficult to address; the decay heat that nuclear reactors generate after they have been shut down cannot be turned off.

If reactor power levels are low (and thus the decay heat is sufficiently small after reactor shutdown), decay heat removal can be achieved by conduction and radiation of heat from the reactor core to the environment. As the reactor power level increases, the peak temperature in the reactor core necessary to transfer decay heat to the environment increases. If this temperature exceeds the failure temperature of the reactor fuel, large-scale release of radionuclides from the fuel occurs.

In power reactors, there are strong economic incentives to build large reactors because of their typically lower-cost-per-unit output. The question is this: How large can the reactor be built and still be small enough to ensure that decay heat after a reactor accident cannot cause massive fuel failure when passive safety systems such as heat conduction are used? Current evaluations[1] indicate that the modular high-temperature gas-cooled reactor (MHTGR) may be built in sizes up to 600 MW(t) with fully passive decay-heat-removal systems and the capability to withstand beyond-design-basis accidents. We propose that a new reactor,[2] the Advanced High-Temperature Reactor (AHTR), may be built in sizes in excess of 2000 MW(t) with these same capabilities. If this can be demonstrated, it creates the potential for large economic reactors without the potential for large accidents. This paper provides the first description of the proposed beyond-design-basis-accident strategy for the AHTR.

II. REACTOR DESCRIPTION

The AHTR[2] is a high-temperature reactor (Fig. 1) that uses coated-particle graphite-matrix fuels and a molten-fluoride-salt coolant. The fuel is the same type that is used in MHTGRs, with fuel failure requiring temperatures exceeding 1600EC. The molten-salt coolant is a mixture of fluoride salts, typically containing a mixture of zirconium, sodium, and other fluoride salts with freezing points near 400EC and atmospheric boiling points of - 1400EC. The reactor operates at atmospheric pressure. At operating conditions, the molten-salt heat-transfer properties are similar to those of water. During operation, the molten salt coolant exit temperatures exceed 750EC. Heat is transferred to a multi-reheat helium Brayton cycle for the production of electricity. The thermal efficiency is 48% at 750EC. The molten salt pumps are located above the reactor core; thus, the reactor cannot lose its coolant except by vessel failure.

The reactor core physics are generally similar to those for the MHTGR because the molten salt coolant has a low neutron absorption cross section. Reactor power is limited by a negative temperature coefficient, control rods, and other emergency shutdown systems. The option exists to include neutron absorbers (rare earth fluorides) in containers with temperature-fusible openings (similar to fire sprinkler systems) above the reactor core in the coolant. This type of system would add neutron absorbers to the coolant should coolant overheating occur. Once activated, such systems assure shutdown independent of core temperatures (cold core after cool down) or control rods.

III. DECAY HEAT REMOVAL

The AHTR uses passive decay-heat-cooling systems. For the analysis herein, an air-cooled passive decay-heat-removal system[2] was examined that is similar to that developed for the General Electric sodium-cooled S-PRISM.[3,4] The reactor and decay heat cooling system is located in an underground silo. In this pool reactor, decay heat is (1) transferred to the reactor vessel graphite reflector by natural circulation of the molten 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 of the guard vessel by natural circulation of ambient air. The rate of heat removal is controlled primarily by the radiation heat transfer through the argon gas from the reactor vessel. Radiation heat transfer increases by 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. The reactor vessel is lined with a graphite reflector; thus, the vessel temperature is significantly lower than the reactor core and coolant. The design allows transfer of the heat by efficient liquid natural convection from the center of the reactor core (hot-spot location) to near the vessel wall.

The reactor size is limited by the ability to transfer decay heat from the nuclear fuel to the outside surface of the reactor vessel (Fig. 2) in an emergency. The use of a molten salt coolant and a high-temperature fuel allows much higher reactor power ratings than those found in other reactors with similar passive safety systems *in the same size reactor vessel*. Increasing the power output for the same plant footprint improves economics. An evolution in the design of passive safety systems has allowed reactors of larger size to use passive safety systems.

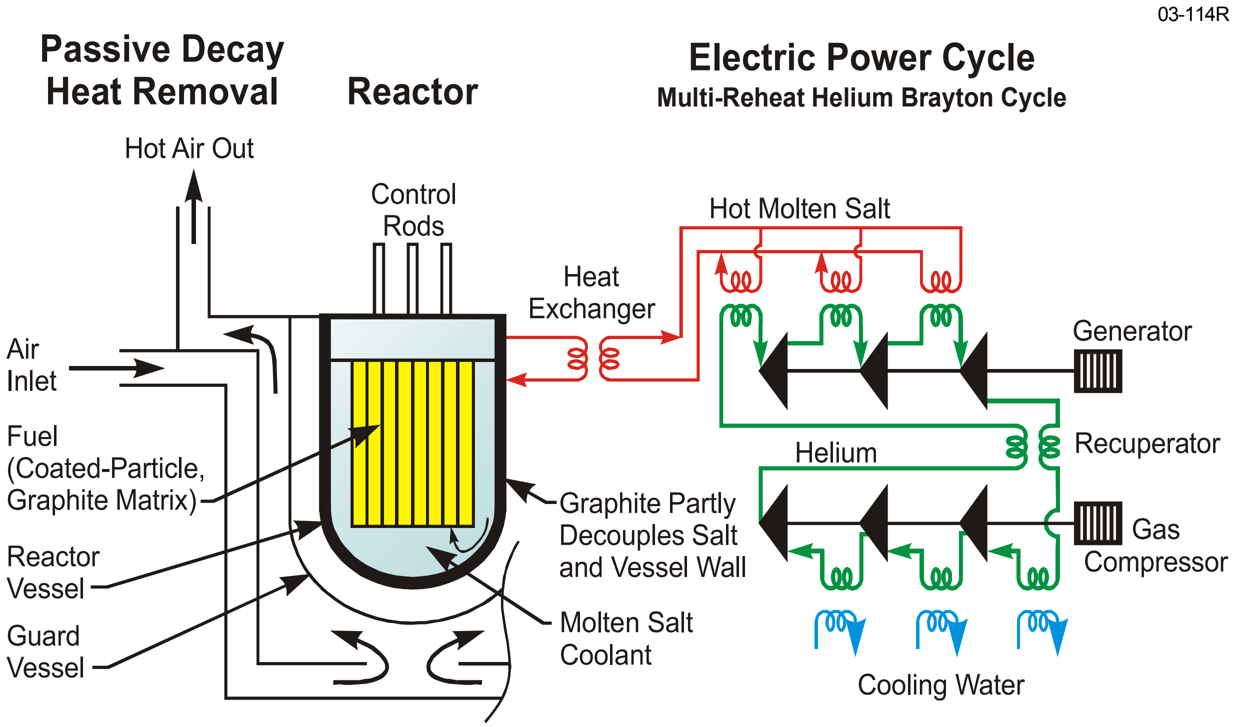

Fig. 1. Schematic of the Advanced High-Temperature Reactor for electricity production.

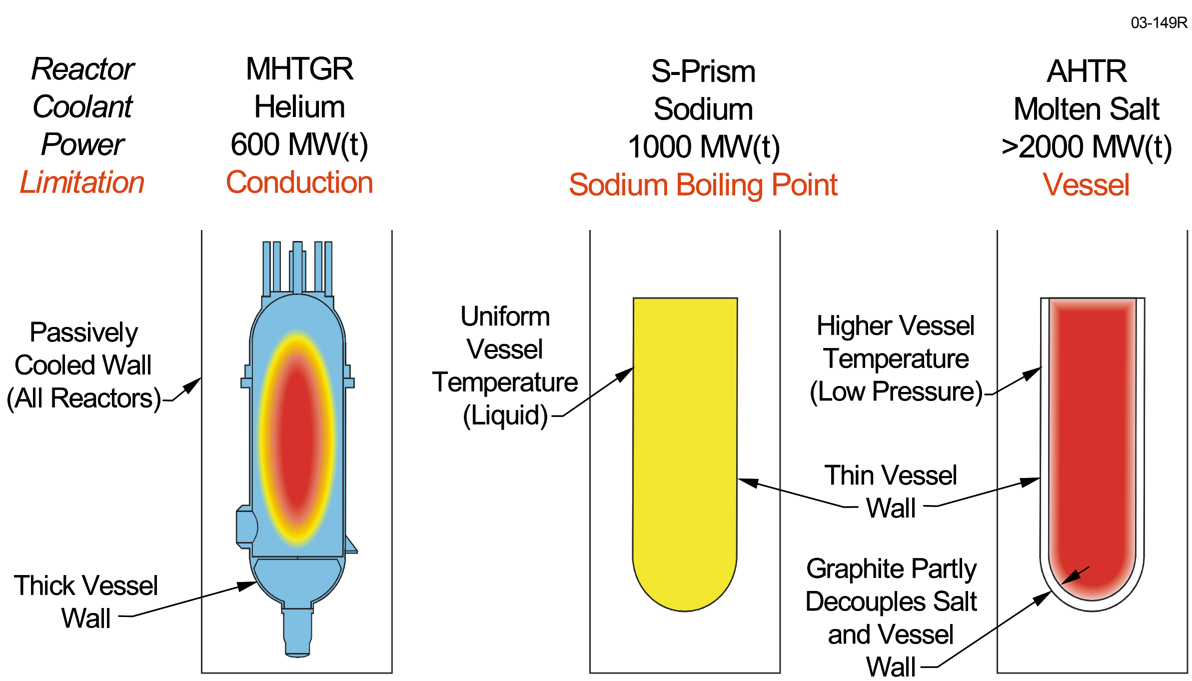

Fig. 2. Evolution of passive decay heat removal systems in similar size reactor vessels.

- *MHTGR*. In an emergency[1] decay heat must be moved from the center of the reactor core to the vessel boundary by conduction and radiation. This process requires a large temperature drop to transfer heat through the graphite-matrix coated-particle fuel, the graphite reflector, and a thick-wall pressure vessel. To ensure that the fuel in the center of the reactor does not overheat and release large quantities of radionuclides in an accident, the power output of the reactor is limited to 600 MW(t). Heat conduction from the center of the reactor to the outside of the pressure vessel limits the power level of the reactor.

- *Sodium-cooled reactors (General Electric S-PRISM)*. In an emergency[3,4] decay heat is transferred from the center of the reactor core to the vessel wall by natural circulation of sodium. Natural circulation of a liquid is an efficient way to transfer heat to the entire vessel with a temperature drop of a few tens of degrees. If the fuel in the center of the reactor is not to fail in an accident, the power production must be limited to -1000 MW(t). The heat rejection capability of the S-PRISM is greater than that of the MHTGR because the circulating sodium ensures that the entire surface area of the reactor vessel is at a relatively uniform high temperature. In the MHTGR, only some surfaces of the reactor vessel are hot and efficiently rejecting heat while those parts of the vessel that are far from the reactor core are cool and reject little heat. The ultimate power limitation of the S-PRISM is that the peak coolant temperature must be significantly below the boiling point of sodium.

- *AHTR*. Decay heat removal in the AHTR[2] is similar to that in a sodium-cooled reactor. However, for the AHTR, the fuel failure temperature is above the molten-salt coolant boiling point of 1400EC. The peak temperature is thus limited only by the temperature limits of the low-pressure reactor vessel. With current vessel materials, the vessel temperature can be as high as 750EC. The combination of a high-temperature fuel and a low-pressure liquid coolant may allow a reactor power level of -2400 MW(t) with passive decay heat cooling. Because the coolant and fuel can reach such extreme temperatures, the vessel has an internal insulation layer (the core graphite reflector that also reduces neutron damage to the reactor vessel) to reduce heat losses during normal operation. This allows molten salt and fuel temperatures above reactor vessel temperatures.

IV. BEYOND-DESIGN-BASIS ACCIDENT

In a beyond-design-basis accident, it is assumed that the air-cooled passive decay-heat-cooling system has failed and that significant structural failures (vessel failure, etc.) have occurred. Decay heat[5] continues to heat the reactor core but decreases with time (Table I). 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 by (1) absorption of decay heat in the reactor and silo structure and (2) transfer of decay heat through the silo walls to the environment. For the MHTGR,[1] the maximum size of reactor that can withstand this accident without major fuel failure is -600 MW(t).

Table I. Decay Heat Removal Requirements per 1 MW(t) Reactor Output

Time (days)	**Decay power [MW(t)]**	**Integrated decay heat (MWd)**
0	5.77×10^{-2}	0.00
1	5.11×10^{-3}	7.25×10^{-3}
2	4.11×10^{-3}	1.19×10^{-2}
3	3.56×10^{-3}	1.57×10^{-2}
5	2.91×10^{-3}	2.21×10^{-2}
10	2.13×10^{-3}	3.45×10^{-2}
21	1.51×10^{-3}	5.40×10^{-2}
42	1.05×10^{-3}	8.02×10^{-2}
70	7.82×10^{-4}	1.05×10^{-1}
180	3.86×10^{-4}	$1.69 \times 10^{-}1$
365	2.01×10^{-4}	2.23×10^{-1}

Work has begun to define the maximum size AHTR that can withstand this type of accident based on the earlier work on MHTGRs. The choice of a (1) a high-temperature fuel and (2) a low-pressure (relatively chemically inert), high-temperature coolant enables construction of larger reactors with this capability. The beyond-design-basis strategy can be understood by following the sequence of expected events and defining the mechanisms to prevent massive fuel failure (Fig. 3).

- *Reactor vessel heatup*. After loss of decay heat cooling, the initial event is heatup of the reactor vessel. The AHTR thermal inertia per megawatt thermal in the reactor vessel exceeds that of the MHTGR; that is, the peak fuel temperatures increase at a slower rate after loss of all cooling. This slower increase occurs despite the fact that the AHTR vessel volume (2400 MW(t), 9.2-m diam., 1260 m^3) is almost identical to that of the MHTGR (600 MW(t), 8.4-m diam., 1210 m^3) and reflects the more efficient use of the thermal inertia of materials within the reactor vessel.

In the MHTGR,[6] under design-basis depressurization loss-of-cooling conditions, large radial and vertical temperature gradients exist within the reactor vessel (Fig. 2). Under depressurized conditions the MHTGR peak fuel temperature reaches 1560EC after 60 hours while the peak temperatures of the reactor vessel are under 600EC. Large temperature gradients are needed to remove the decay heat by conduction. If the reactor remains pressurized with better heat transfer in the reactor vessel, the core temperature peaks at only 1240EC at 50 hours, because of the more uniform core temperature caused by natural convection of the high pressure helium coolant. Most of the mass in the reactor is far below allowable peak temperatures and not efficiently used to maximize the effective thermal inertia.

The larger total thermal inertia of the AHTR is a consequence of (1) the molten salt circulation, which ensures almost isothermal conditions within the reactor core, and (2) the higher-heat-capacity reactor core. The conceptual design of the AHTR has a 9.2-m diam., 5.0-cm-thick vessel with a 0.65-m-thick graphite liner and reflector and an effective annular core diameter of 7.8 m. Conversely, the effective core diameter of the MHTGR is only 4.9 m because of the (1) 0.22-m-thick vessel wall, (2) inner core barrel and shell for helium inlet downflow and vessel thermal conditioning, and (3) graphite reflector. In both reactors, the centers of the annular cores are filled with graphite that is included in the calculations of core heat capacity. In the vertical direction, the MHTGR heats the 1.6-m-thick graphite reflector, located above the 7.9-m-high core. Conversely, the AHTR provides a 6.8-m-deep molten-salt pool above the core. Thus for the AHTR, the ratio of the active volume to absorb heat relative to the that of the MHTGR, is 4.1: $(7.8/4.9)^2 \times (6.8+7.9)/(1.9+7.9)$. Furthermore, in the MHTGR a significant fraction of the thermally active volume is occupied by helium, which has negligible heat capacity. Conversely, in the AHTR, all of the active volume is occupied by graphite or by molten salt, which has a larger specific heat capacity than graphite.[2]

- *Vessel failure*. High temperatures ultimately cause the vessel to fail. Molten 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 molten salt between the reactor vessel and silo efficiently transfers heat from the reactor vessel to the silo wall. Several different molten salts are being considered as reactor coolants. The freezing points are typically 350EC or somewhat higher. When the salt contacts the cold silo wall, it freezes. Unlike water, the salt will not leak out. Furthermore, no major chemical reactions that generate heat or gases will occur, which is not the case with sodium.

- *Silo-wall heat conduction*. The silo wall contains low-cost thick steel rings that are similar to those used in the mining industry to line deep mine shafts and prevent their collapse. In the mining industry, these rings are referred to as tubing or “ausbau.” The diameter of the AHTR silo is similar to that of large mine shafts, but the depth is only 20 m. Under operating conditions, the rings are cooled by exposure to outside air that is drawn down in the silo, and then flows up on the other side of a partition to remove heat from the guard vessel. Following vessel failure, the rings conduct heat up the silo wall and distribute it above the coolant salt layer.

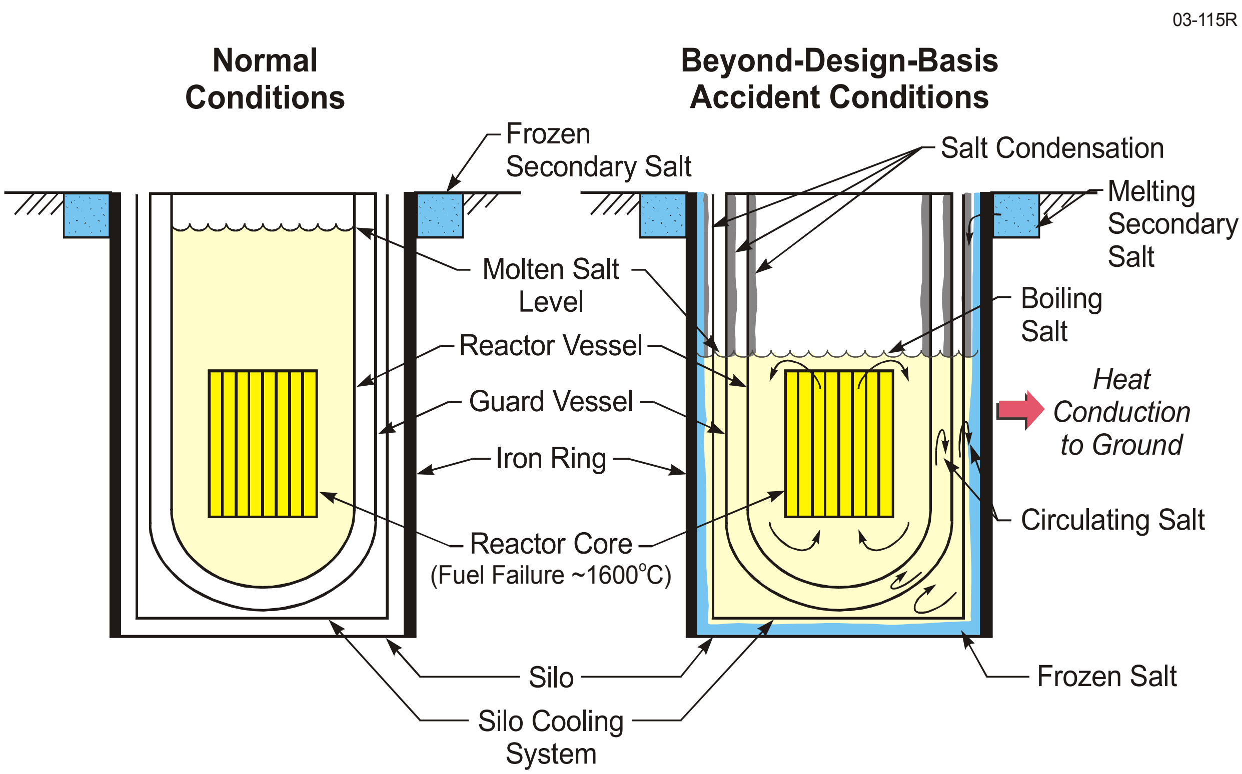

Fig. 3. Beyond-design-basis accident.

- *Secondary-salt melting*. Near the top of the silo is an annular ring of a secondary solidified molten 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.

  – Heat absorption. Typical fluoride salts have a volumetric heat capacity[2,7] of - 4000 kJ/(m^3 EC). If the secondary salt was allowed to be heated to 1000EC, it would absorb 0.046 MWd/m^3. The heat of vaporization for typical fluorides is about 0.16 MWd/m^3. Depending upon design, the heatup and selected boiloff of secondary salt components can absorb several days of decay heat.

  – Salt selection. Unlike the reactor coolant salt, the secondary salt has no requirement for low nuclear cross sections to minimize neutron absorption. A variety of chloride and fluoride salts are potential candidates. Studies have not yet been conducted to define the preferred salt based on cost and performance requirements (compatibility with coolant salt and melting point). If appropriate low cost salts are found, the option exists for the secondary-salt inventory to absorb days to weeks of decay heat.

- *Heat conduction to earth*. Heat is conducted to the earth surrounding the silo and ultimately to the environment. The 600-MW(t) MHTR uses the same approach for ultimate heat rejection in a beyond-design-basis accident. However, significant differences are noted between gas-cooled and molten-salt-cooled reactors in their ability to reject heat to the ground.

  – Heat transfer area. The flooding of the silo with molten salt increases the effective surface area of heat transfer from the reactor vessel to the silo wall. If the silo is full of molten salt, the entire silo wall, not a small section of the wall, rejects heat to the environment. The placement of the reactor core at the very bottom of the reactor vessel allows full utilization of the complete silo area. Because molten salt heat fluid is used for heat transfer, heat rejection rates can be further increased by (1) increasing silo depth or (2) designing the top of the silo with its shorter pathway for heat rejection to the environment. The effective heat transfer area is thus doubled.

  – Uniform temperatures. Natural circulation of the molten salt results in a relatively uniform temperature throughout the silo. The vertical temperature gradient will be only a few tens of degrees.

  – Temperature drops. The peak temperature of the fuel is fixed by the need to avoid fuel failure. Temperature drops occur from the fuel to reactor vessel wall, from the vessel wall to silo wall, and from the silo wall into the earth. Liquid cooling (reactor coolant and secondary salt) minimizes the first two temperature drops. This allows for higher silo temperatures, which, in turn, allow greater heat rejection to the ground.

Extrapolations from the MHTGR (considering heat capacity, effective silo surface area, and available temperature to drive heat from the silo wall to the environment) indicate that a 2400 MW(t)-AHTR with beyond-design-basis-accident capabilities could be built. However, major uncertainties remain, because such systems imply high temperatures near the silo and reactor facilities. There are many design choices and tradeoffs.[8]

Most fission products (including cesium and iodine) and all actinides escaping the solid AHTR fuel are soluble in the molten salt and will remain in the molten salt at very high temperatures. Fluoride salts were chosen for the liquid-fueled molten-salt reactor because actinides and fission products dissolve in the molten salt at very high temperatures.[9] This same characteristic applies to the AHTR and provides the reactor with a second, independent beyond-design-basis-accident mitigation system to prevent radionuclide release to the environment.

V. CONCLUSIONS

The AHTR is a new reactor concept. The unique characteristic of the reactor is its combination of a very-high-temperature fuel (graphite-matrix coated-particle fuel) with a low-pressure, very-high-temperature molten-salt reactor coolant. Combining these two technologies may enable the construction of large reactors with passive safety decay-heat-removal systems and ensure that catastrophic fuel failure cannot even occur in beyond-design-basis accidents. Some of the characteristics of such large reactors have been defined. Major work is required to develop these concepts into a workable design, understand the complex technical, safety, and economic tradeoffs, and provide a definitive estimate on the largest possible reactor that can withstand beyond-design-basis accidents.

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