A Modular Radiant-Heat-Initiated Passive Decay-Heat-Removal System for Salt-Cooled Reactors

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A MODULAR RADIANT-HEAT-INITIATIED PASSIVE DECAY-HEAT-REMOVAL SYSTEM FOR SALT-COOLED REACTORS

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The Advanced High-Temperature Reactor (AHTR), also called the liquid-salt-cooled very high temperature reactor, is a new reactor concept that combines four existing technologies to create a new reactor option: coated-particle graphite-matrix fuels (the same fuel as used in high-temperature gas-cooled reactors), a liquid-fluoride-salt coolant with a boiling point >1200°C, Brayton power cycles, and passive safety systems. A new passive decay-heat cooling system has been invented that is actuated by the increased temperature of the salt under accident conditions and uses radiant heat transfer from and through the salt to a heat exchanger. This safety system takes advantage of two physical properties of the system: (1) the transparency of the salt coolant and (2) the increase in the radiant heat transfer from the salt to a decay-heat exchanger, which is proportional to the temperature of the hot salt to the fourth power (T^4) minus the temperature of the heat exchanger surface to the fourth power (T^4). For a high-temperature reactor, small increases in coolant temperatures dramatically increase radiant heat transfer.

I. INTRODUCTION

The Advanced High-Temperature Reactor (AHTR)[1–3] is a new reactor concept (Fig. 1) that combines in a novel way four established technologies: (1) coated-particle, graphite-matrix nuclear fuels (the same fuels used in gas-cooled high-temperature reactors); (2) Brayton power cycles; (3) passive safety systems and plant designs previously developed for liquid-metal-cooled fast reactors; and (4) low-pressure liquid-salt coolants. Depending upon the specific goals for the reactor, the peak coolant operating temperatures are between 700 and 950°C, with reactor outputs up to 4000 MW(t). The reactor may be used either to produce electricity or to provide heat for hydrogen production. The size and peak coolant temperatures depend upon the mission,[1] with higher temperatures required for hydrogen production.

The optically transparent liquid-salt coolant with potentially some absorption in the infrared is a mixture of fluoride salts[4] with atmospheric boiling points >1200°C. 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 using a multi-reheat nitrogen or helium Brayton power cycle (with or without a bottoming steam cycle). Electrical efficiencies are expected to be near 50%. The AHTR capital costs have been estimated to be 50 to 60% those of a modular gas-cooled or liquid-metal-cooled reactor for equivalent electrical output.[2] This is a consequence of economics of scale; higher potential efficiencies; and the higher volumetric heat capacity of liquid salts, which reduces equipment size relative to those for other coolants.

Several different reactor core designs[3] are being evaluated, including use of a prismatic fuel, a pebble-bed fuel, and a pin-type fuel. An engineering elevation view is shown in Fig. 2.

II. DECAY-HEAT-REMOVAL SYSTEM

Several alternative passive decay-heat-removal systems have been investigated.[3] The 2400-MW(t) baseline concept has a *closed* primary loop immersed in a tank containing a separate buffer salt that provides a heat sink for various transients. The temperature of the buffer-salt tank is near the coldest temperature in the primary system. If the intermediate heat-transport loop fails, hot primary coolant exits the primary heat exchanger and dumps heat to the buffer pool through the uninsulated piping from the heat exchanger back to the reactor core.

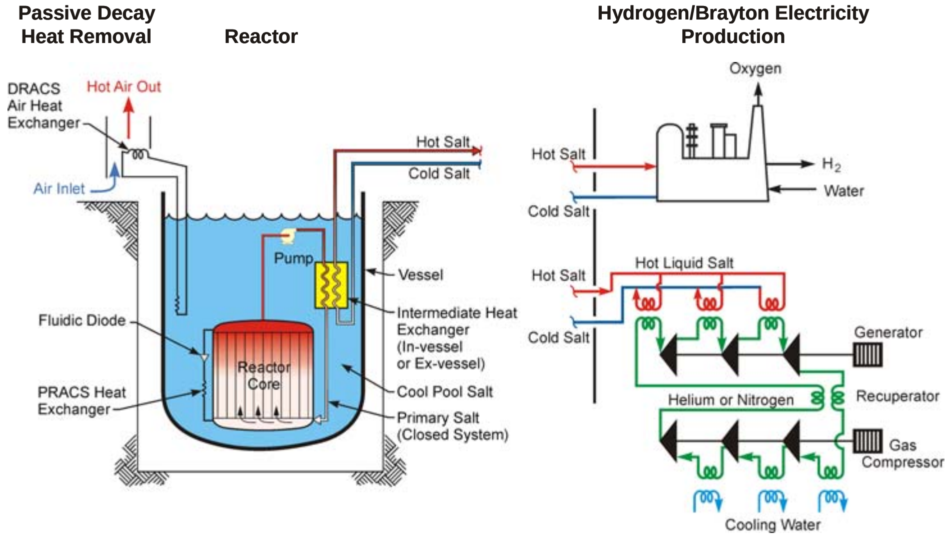

Fig. 1. AHTR layout for hydrogen production or electricity production.

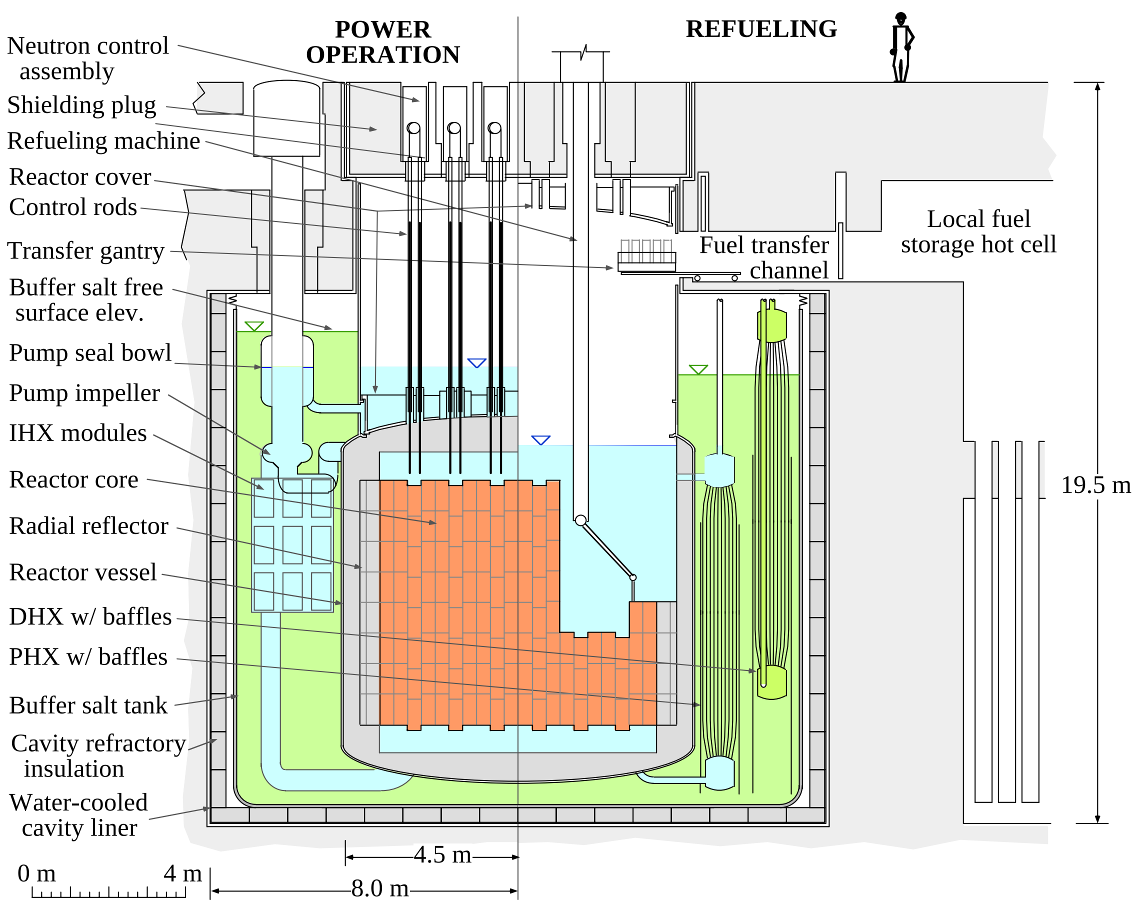

Fig. 2. Cross section of a 2400-MW(t) Advanced High-Temperature Reactor with prismatic fuel.

If the primary pumps fail, heat is also rejected from the primary system to the buffer salt through the Pool Reactor Auxiliary Cooling System (PRACS) heat exchangers. Each PRACS consists of a loop connecting the bottom reactor plenum to the top reactor plenum. The loop contains a fluidic diode and PRACS heat exchanger (PHX) to dump heat from the primary system to the pool. The fluidic diode is a no-moving-parts one-way valve that has high flow resistance in one direction and low flow resistance in the other direction. Typically the flow resistance in one direction is 50 or more times higher than that in the other direction. Such valves are used in a variety of chemical industries and have been used in some nuclear systems, such as the German sodium-cooled fast reactors.

During normal operations the pumps push liquid salt through the core and attempt to push liquid salt through the PRACS loops; however, the flow is very limited because of the fluidic diodes. Upon loss of forced circulation, decay heat is removed by natural circulation up through the reactor core and down through the PRACS fluidic diodes and PHXs.

The cool pool salt serves several functions.

- *Heat sink*. The pool provides a heat sink during the first few hours after the loss of decay-heat removal, thus minimizing the size of the decay-heat system required in the long-term to reject heat from the pool to the environment.
- *Minimization of materials requirements*. The primary vessel and components are bathed in a cooler salt with excellent heat transport capabilities. With appropriate design, the only components that operate at the peak temperatures of the reactor are short lengths of pipe, the pump heads, and the heat exchangers. This minimizes the challenges associated with high-temperature materials.
- *Accident protection*. The pool provides protection under severe accident conditions. The pool salt contains neutron absorbers; thus, any failure of the primary system boundary allows pool salt to enter the reactor and causes it to shut down. The pool salt has a high solubility for most fission products and thus provides a secondary barrier against fission product releases. Last, in a beyond-design-basis accident (major structural failure such as vessel failure), the pool salt thermally couples the reactor core with the silo and the ground to provide a method to remove decay heat below fuel-failure temperatures.

With a two-salt system, the pool salt does not have the nuclear requirement for low neutron absorption. This enables the selection of low-cost salts[5] and the option of choosing a large pool with a high salt inventory.

Heat removal from the buffer salt to the environment occurs primarily through Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers. This is a closed natural-circulation heat-transfer system consisting of two heat exchanges and associated piping. The decay heat exchanger (DHX) in the pool vessel is at a lower elevation than the heat exchanger outside the reactor containment. Inside the natural-circulation decay-heat-transport system, a fluid (e.g., a liquid salt, liquid metal, or other heat transfer fluid) absorbs decay heat from the DHX that is submerged in the pool salt. As the fluid is heated, its density decreases. The fluid flows by natural circulation through pipes to the upper heat exchanger outside the reactor containment. The heat is then rejected to the air, and the fluid is cooled. As the fluid is cooled, it becomes denser and flows by natural circulation back through pipes to the DHX. This type of natural-circulation decay-heat-transport system is used in some sodium-cooled fast reactors. Many variants of this system exist, including one that rejects the reactor decay heat to a water bath rather than to an air-cooled heat exchanger.

III. PASSIVE DECAY-HEAT-REMOVAL SYSTEM

The traditional DRACS system has doors on the air-cooled heat exchanger or other devices to limit heat losses during normal operation. A new type of DRACS has been invented that has a totally passive system with no moving parts to turn on and off the heat transfer from the reactor pool to the environment. Such systems have potentially much higher reliability than active systems that use air doors, valves, or other moving components that require control systems to initiate operation. This new system also has the unique capability for use as part of an active decay-heat-removal system to remove decay heat after reactor shutdown for purposes such as lowering the reactor system temperature for refueling or maintenance.

A schematic of the system is shown in Fig. 3. The passive decay-heat-removal system has the same components as DRACS and consists of a natural circulation decay-heat-transport system consisting of (1) a heat exchanger in the reactor vessel, (2) piping, and (3) a second heat exchanger outside the reactor containment.

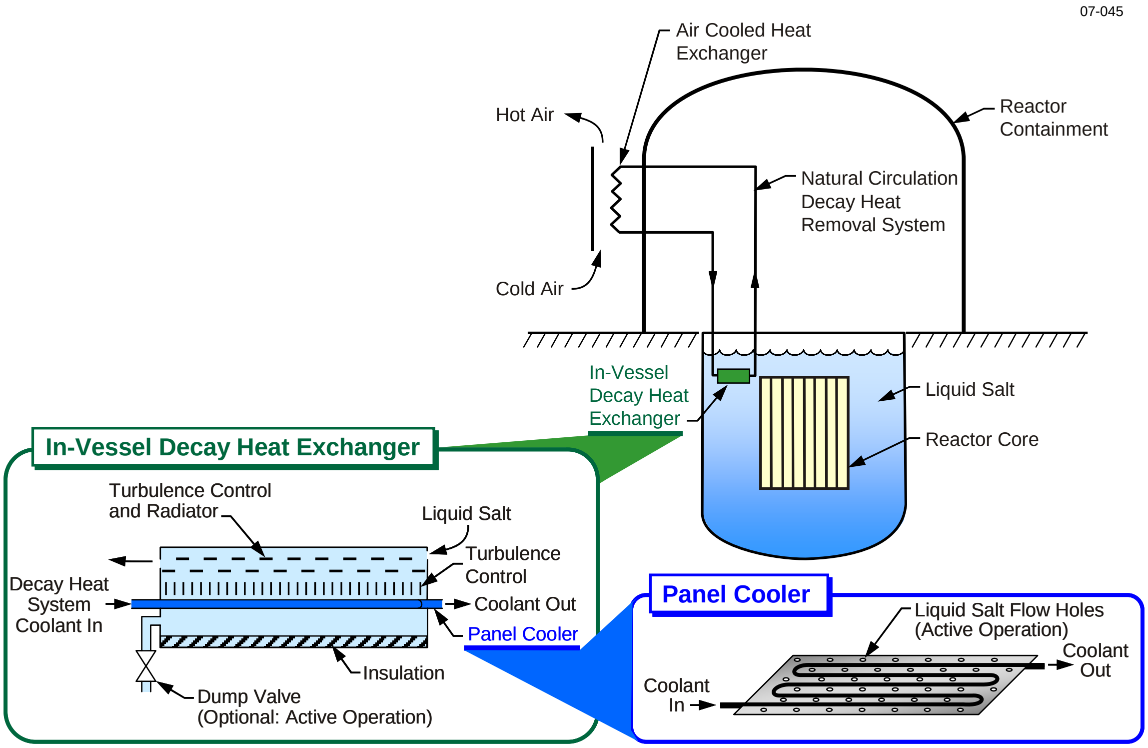

Fig. 3. Thermal-radiation-initiated passive decay-heat-removal system.

The invention consists of (1) a method to turn the passive decay-heat-removal system on or off depending upon the temperature of the liquid-salt coolant and (2) use of the same system as part of an active decay-heat-removal system. The rate of heat rejection is strongly dependent upon the temperature of the liquid salt in the pool. It consists of the following items associated with the heat exchanger in the pool of liquid salt.

- A nearly horizontal heat exchanger. One design would use a panel-cooler heat exchanger with the tubes for the decay-heat cooling system running through the panel cooler.
- An enclosed box with insulation on the bottom and side with the panel heat exchanger inside the box and directly above the insulation.
- Flow channels for the pool salt enter and leave the box near the top. The exit channels are slightly lower than the entrance channels. Therefore, if the liquid salt is cooled, a natural-circulation flow of liquid-salt coolant occurs as the salt flows horizontally near the top of the box.
- A series of baffles and other structures to help maintain horizontal liquid-salt-coolant flow through the box and minimize vertical mixing.

The operation of the system as a passive safety system is as follows.

- DRACS operation results in the panel heat exchanger in the pool having a lower temperature than that of the liquid-salt reactor coolant at all times.
- Liquid salt near the panel heat exchanger is cooler, and thus denser, than the liquid salt in the upper part of the enclosed box or elsewhere in the vessel. As a consequence, the liquid salt in the bottom of the box with the heat exchanger is stagnant (i.e., it does not flow).

- During normal reactor conditions, the liquid salt near the heat exchanger is cool. At the same time, the liquid salt near the top of the box, which is in contact with the rest of the liquid-salt coolant in the reactor vessel, is somewhat warmer. However, the rate of heat transfer from the hot salt to the heat exchanger is low because the heat must be conducted through a nonflowing salt layer.

- If the reactor core overheats, the heat is dumped to the pool salt and the hot pool salt that slowly flows through the top of the box increases in temperature. The hot salt heats the top of the box and the baffles. Radiant heat is transferred to the heat exchanger via radiation from the hot salt and hot upper components in the box in contact with the hot salt. The panel-cooler type of heat exchanger ensures that radiant heat from above is absorbed by the panel and conducted through the metal to the decay-heat-system fluid. The box, baffles, and heat exchanger surfaces may be treated to maximize radiation heat transfer.

- The heat transfer is strongly dependent upon temperature. Radiant heat transfer is proportional to the temperature of the hot salt to the fourth power (T^4) minus the temperature of the heat exchanger surface to the fourth power (T^4). Small rises in temperature result in large increases in heat transfer to the decay heat exchanger. Increased heat transfer also occurs via thermal conduction caused by the larger temperature difference between the hot salt (and surfaces in contact with the hot salt) and cold radiator. As a result, there is a switch mechanism. During normal operation, only a limited amount of heat is transferred to the decay-heat-removal system. As the temperature of the salt coolant increases, the quantities of heat transferred rise dramatically with temperature.

The system shuts off the heat removal process if the salt temperature drops below its design point. This avoids the potential for overcooling—including inadvertent freezing of the pool salt. Heat exchanger area and other design parameters allow the optimum pool salt temperatures to be maintained. The panel cooler design allows variable distances between tubes with variable metal area for radiation heat transfer per tube. There is a large experience base with such designs because variants of this type of design are used in fossil-fuel boilers in the high-temperature zones where radiation heat transport is important. In an engineered system, the in-vessel decay heat exchanger would consist of multiple insulated boxes with panel coolers stacked on top of each other.

The system has the additional capacity to actively control salt pool temperatures, and thus reactor temperatures, during shutdown by varying the rate of heat removal by the decay-heat-removal system. This is accomplished via addition of a control valve to the bottom of the box. If the valve is open, the hot pool salt will enter the box, flow by the heat exchanger, and then exit the bottom of the box. The rapid flow of salt by the heat exchanger greatly improves the heat transfer from the salt to the heat exchanger compared with radiant heat transfer and allows for significantly greater heat rejection rates than are possible in a passive operating mode.

The salts are generally transparent; however, there is potentially some absorption in the infrared, particularly for Be-based salts.[6–7] Consequently, the design must consider the specific salt that is used.

IV. CONCLUSIONS

The characteristics of this system make it potentially suitable for liquid-salt-cooled high-temperature reactors as a modular decay heat removal system. The operating reactor and accident temperatures are in the range of temperatures in which radiant heat transport can be made a primary mechanism of heat transport via selection of the appropriate geometry. The liquid salts are transparent—a requirement for the operation of this system, in which the temperature dependence of radiant heat transfer is the turn-on and turn-off switch mechanism for system operations. Significant analysis and improved physical measurements of the optical properties of the salts are required to fully assess and develop the concept.

REFERENCES

1. C. W. FORSBERG, “Goals, Requirements, and Design Implications for the Advanced High-Temperature Reactor,” ICONE14-89305, CD-ROM, *14th International Conference on Nuclear Energy, American Society of Mechanical Engineers, Miami, Florida, July 17–20, 2006,* American Society of Mechanical Engineers (2006).

2. C. W. FORSBERG, “The Advanced High-Temperature Reactor: High-Temperature Fuel, Liquid Salt Coolant, and Liquid-Metal-Reactor Plant,” *Progress in Nuclear Energy,* **47**, *1–4*, 32–43 (2005).

3. D. T. INGERSOLL, C. W. FORSBERG, and P. E. MACDONALD, *Trade Studies on the Liquid-Salt-Cooled Very High-Temperature Reactor: Fiscal Year 2006 Progress Report*, ORNL/TM-2006/140, Oak Ridge National Laboratory, Oak Ridge, Tennessee (2006).

4. D. F. WILLIAMS, L. M. TOTH, and K. T. CLARNO, *Assessment of Candidate Molten Salt Coolants for the Advanced High-Temperature Reactor (AHTR)*, ORNL/TM-2006/12, Oak Ridge National Laboratory, Oak Ridge, Tennessee (2006).

5. D. F. WILLIAMS, *Assessment of Candidate Molten Salt Coolants for the NGNP/NHI Heat-Transfer Loop*, ORNL/TM-2006/69, Oak Ridge National Laboratory, Oak Ridge, Tennessee (2006)

6. P. F. PETERSON and H. ZHAO, "A Flexible Baseline Design For the Advanced High Temperature Reactor Utilizing Metallic Reactor Internals (AHTR-MI)," *2006 International Congress on Advances in Nuclear Power Plants (ICAPP '06), Reno, Nevada, June 4-8, 2006*, American Nuclear Society, La Grange Park, Illinois.

7. P. M. BARDET and P. F. PETERSON, "Options for Scaled Experiments for High-Temperature Liquid Salt and Helium Fluid Mechanics and Convective Heat Transfer," *Nuclear Technology* (In Press).