Sustainability, Water, Dry Cooling, and the Advanced High-Temperature Reactor

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INTRODUCTION

Water is a primary sustainability issue. In the United States, the largest uses for water are irrigation and cooling water for power plants, with each application using a similar amount of water. Water requirements often dictate power plant siting; thus, only a small fraction of the land area in the United States is considered suitable for siting power plants. The energy–water nexus is a primary sustainability issue that must be addressed for next-generation nuclear power plants. Oak Ridge National Laboratory, the University of California at Berkeley, and Sandia National Laboratories are developing a new reactor, the Advanced High-Temperature Reactor (AHTR), that combines high thermal efficiency and the use of a Brayton power cycle to dramatically reduce the cost and energy penalty of dry cooling systems for power plant heat rejection, thus minimizing the water used for energy production.

THE ADVANCED HIGH-TEMPERATURE REACTOR

The AHTR (Fig. 1) is a high-temperature reactor [1] that uses coated-particle graphite-matrix fuels (the same used in modular high-temperature gas-cooled reactors) and a molten-fluoride-salt coolant. The optically transparent molten salt coolant is a mixture of fluoride salts with freezing points near 400EC and atmospheric boiling points of -1400EC. Heat is transferred from the reactor core by the primary molten salt coolant to an intermediate heat-transfer loop, which uses a secondary molten salt coolant to move the heat to the turbine hall. In the turbine hall, the heat is transferred to a multi-reheat nitrogen or helium Brayton cycle power conversion system.

The 2400-MW(t) AHTR facility layout is similar to that of the S-PRISM sodium-cooled fast reactor designed by General Electric. Both reactors operate at low pressure and high temperature; thus, they have similar designs. The AHTR uses the same basic design of air-cooled passive decay-heat-removal system. Three peak reactor coolant temperatures are being considered: 705, 800, and 1000EC. For electricity production, a recuperated helium Brayton cycle [2] is used with three stages of reheating and six stages of intercooling. The helium pressure is reduced through three turbines in series, with reheating of the gas to its maximum temperature with hot molten salt before it reaches the next turbine. The reheat Brayton cycles are significantly more efficient than direct recouperated Brayton cycles.

DRY COOLING [3]

The challenge of heat rejection using dry cooling is economics. While fossil Rankine steam power plants [totaling 30,000 MW(e)] have been built with dry cooling where water was not available, the costs have been high. These penalties can be drastically reduced with higher-temperature Brayton-cycle nuclear power plants.

- Less heat rejection. Current light-water reactors (LWRs) have operating temperatures of ~270°C, with an efficiency of ~33%. The AHTR is significantly more efficient because of its higher-temperature multi-reheat power cycle. For peak coolant temperatures of 705, 800, and 1000ºC, the respective plant efficiencies are 48, 51.5, and 56.6%. While the LWR rejects 2 kW(t) of heat per kW(e), the three AHTR designs reject, respectively, 1.08, 0.94, and 0.77 kW(t) per kW(e). The higher efficiency reduces the heat-rejection-system capacity requirements by about a factor of 2 relative to LWRs.

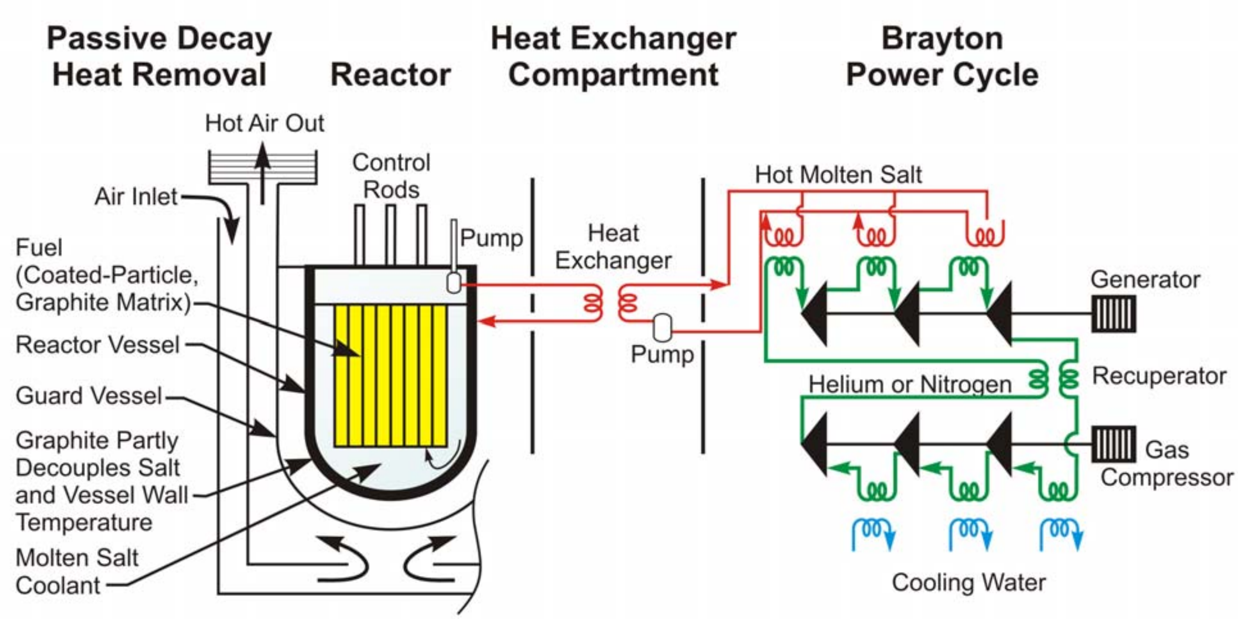

Fig. 1. Schematic of the AHTR for electricity production.

- Reduced penalty for higher heat rejection temperatures. The capital costs of dry cooling systems can be reduced by rejecting heat at a higher temperature but with the penalty of lower plant efficiency. That penalty becomes smaller as the peak temperature of the power cycle increases. For the AHTR Brayton cycle with a minimum helium temperature of 35°C, the *losses in efficiency* for a 10ºC rise in the compressor inlet temperature were calculated to be 1.5, 1.3, and 1.1%, respectively, for AHTR peak coolant temperatures of 705, 800, and 1000ºC.

- Heat rejection over a temperature range. Dry cooling involves heating air (i.e., raising the temperature). If the heat from the power cycle can be rejected over a temperature range rather than at a single temperature, the appropriate design of countercurrent dry-cooling-tower heat exchangers maximizes the temperature drop across the heat exchangers, which reduces their required size. With dry cooling, Brayton cycles have major advantages over Rankine (steam) cycles that deliver rejected heat at a constant temperature. This Rankine-cycle characteristic is consistent with evaporative cooling, in which water is vaporized at a nearly constant temperature. In contrast, a Brayton cycle delivers rejected heat over a temperature range that matches dry cooling. In the Brayton cycles described herein, the heat is rejected over a 50ºC range, with the helium being cooled from ~85 to 35°C.

CONCLUSIONS

Water is a primary sustainability issue. Power plant heat rejection by dry cooling can eliminate this sustainability issue, but the economic cost of dry cooling for lower-efficiency Rankine-cycle LWRs is high. Water sustainability is a strong incentive for the development of next-generation high-temperature multi-reheat Brayton-cycle nuclear power plants.

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