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Brayton Power Cycles and High-Temperature Salt-Cooled Reactors

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INTRODUCTION

For almost a century, the practical technology to convert heat to electricity has been the steam turbine. The last decade has seen the successful deployment of large, efficient, low-cost high-temperature Brayton power systems—typically using natural gas as a fuel. This has potentially radical implications for nuclear energy. Many high-temperature reactors have been developed; however, the economics have been unfavorable. A primary reason is the steam turbine, which has been limited to a practical peak temperature of ~550ºC. Little economic incentive exists to produce high-temperature heat if the heat cannot be efficiently converted to electricity. The development of higher-temperature Brayton cycles (with or without bottoming steam cycles) now provides the technology to efficiently convert high-temperature heat to electricity and may enable the development of four classes of large high-temperature reactors using liquid-salt coolants.

REACTOR CATEGORIES

Nuclear reactor types can be classified by power output and the peak temperatures of their coolants (Fig. 1). Light-water reactors, such as the General Electric Economic Simplified Boiling Water Reactor (ESBWR), are low-temperature, high-pressure reactors. Traditional fast reactors cooled with liquid sodium operate at medium temperatures and low pressures. Two options exist for high-temperature reactor coolants: (1) high-pressure gases and (2) low-pressure liquids with boiling points above the peak operating temperatures.

Helium is the traditional high-temperature, high-pressure gas coolant. For most applications, helium-cooled reactors are modular reactors with relatively small power output. Liquid fluoride salts with low nuclear cross sections are the traditional high-temperature, low-pressure liquid coolant. Such salts were originally developed in the 1950s and 1960s for the Aircraft Nuclear Propulsion Program and the Molten Salt Breeder Reactor Program. These programs operated various salt test loops for several hundred-thousand hours. Liquid fluoride salts can be used for multiple nuclear applications.

- *Advanced High-Temperature Reactor (AHTR).* The AHTR (Fig. 2) combines four existing technologies in a new way[1]: (1) coated-particle graphite-matrix nuclear fuels (traditionally used for helium-cooled reactors and compatible with liquid fluoride salts), (2) Brayton power cycles, (3) passive safety systems and plant designs from liquid-metal-cooled fast reactors, and (4) clean low-pressure liquid-salt coolants. The heat from the reactor core is carried by the clean salt to an intermediate heat exchanger. The intermediate heat transport loop then transfers the heat to a Brayton power cycle. Because the AHTR integrates existing technologies, it is the near-term option for salt-cooled reactors.
- *Liquid-salt-cooled fast reactor (SCFR).* SCFRs combine the AHTR plant design (Fig. 2) with traditional metal-clad-fuel fast-reactor cores. Only limited exploratory work[2] has been conducted on these reactors.
- *Molten salt reactor (MSR).* The MSR is a liquid-fuel reactor in which uranium, fission products, and actinides are dissolved in a liquid fluoride salt. The fuel salt flows through a graphite reactor core, which acts as a moderator, and then to an intermediate heat exchanger. This reactor concept was partially developed in the 1970s, and two test reactors were successfully built.[3]
- *Fusion reactors.* Clean liquid salts are major candidates for cooling inertial and magnetic fusion energy systems.[4]

SALT COOLING

The low-pressure, high-temperature salt is an enabling technology for large high-temperature reactors with passive safety systems for decay heat removal (Fig. 2). For peak coolant temperatures of 705, 800, and 1000ºC, the respective thermal-to-electric efficiencies are 48.0, 51.5, and 56.5%. Existing code-qualified metals exist for liquid-salt-cooled reactors to 750ºC. The materials challenges for MSRs with the fuel dissolved in the coolant are greater than those for clean-salt applications.

CONCLUSIONS

The development of Brayton systems has created the potential for large economic high-temperature reactors using liquid-salt coolants. While the near-term option is the AHTR, three longer-range options provide long-term fuel sustainability (breeding) and actinide-burning capabilities: SCFRs, MSRs, and fusion reactors.

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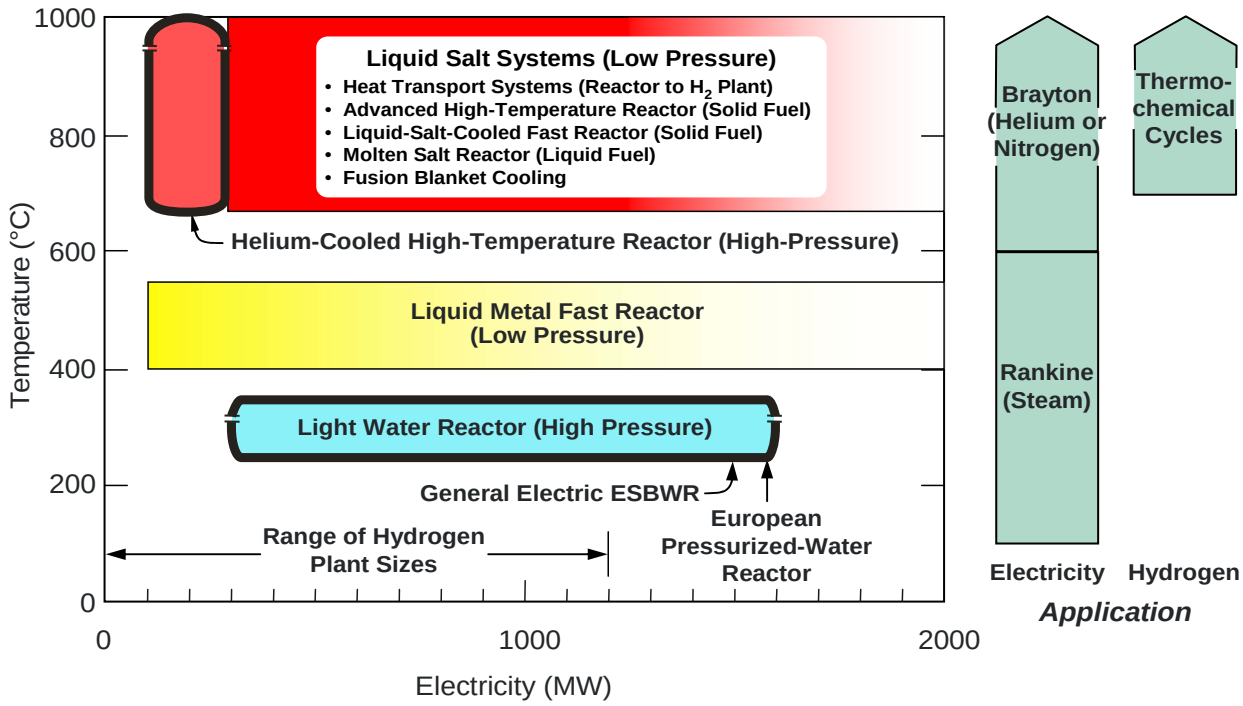

Fig. 1. Reactor type vs temperature and power output.

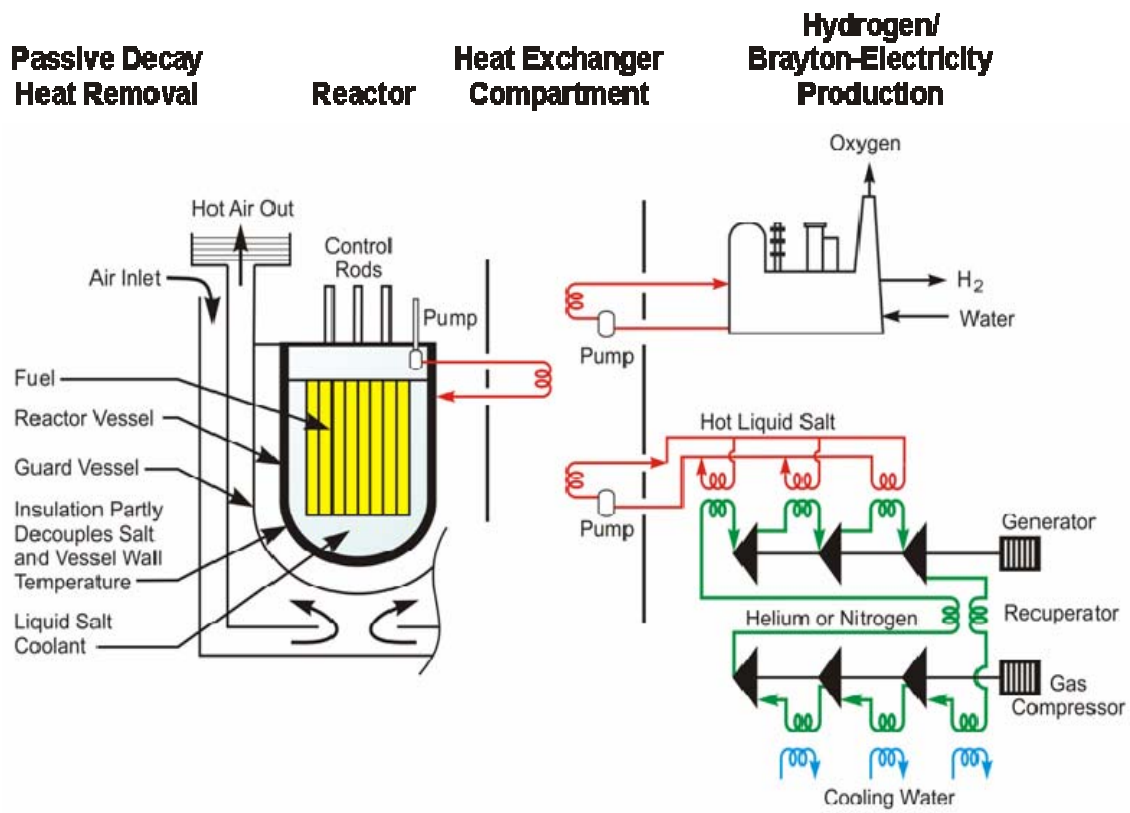

Fig. 2. Schematic of Advanced High-Temperature Reactor and Salt-Cooled Fast Reactor.