PROGRESS OF THE FAST MODULAR REACTOR CONCEPTUAL DESIGN

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INTRODUCTION: General Atomics Electromagnetic Systems (GA-EMS) is developing a 44-MWe Fast Modular Reactor (FMR) as a flexible and dispatchable power source to the U.S. electricity market and beyond in the late 2030's. GA-EMS has completed the conceptual design of the FMR and confirmed the technical feasibility of the simplified design using pellet-loaded fuel rods, direct thermal cycle, passive heat removal systems, installations with air-cooling as ultimate heat sink as well as laboratory experiments of the passive safety and pre-application licensing [1]. The key design features and technologies that enable the FMR to achieve these performance goals are a coolant that is an inert, non-reactive and non-activated, helium gas to enable high temperature operation and high thermal efficiency Brayton cycle, a qualified conventional uranium dioxide (UO_2) fuel capable of high burnup and long fuel life, and silicon carbide (SiC) composite (SiGA®) cladding and internal structures that are chemically inert in the helium environment and exceptionally radiation-tolerant.

1. OVERVIEW

The entire FMR system is designed for safety, compactness, and ease of construction. The major systems and components are under-ground as illustrated in FIG. 1 where the maintenance hall is set at grade and provides access to the reactor vessel and the power conversion system.

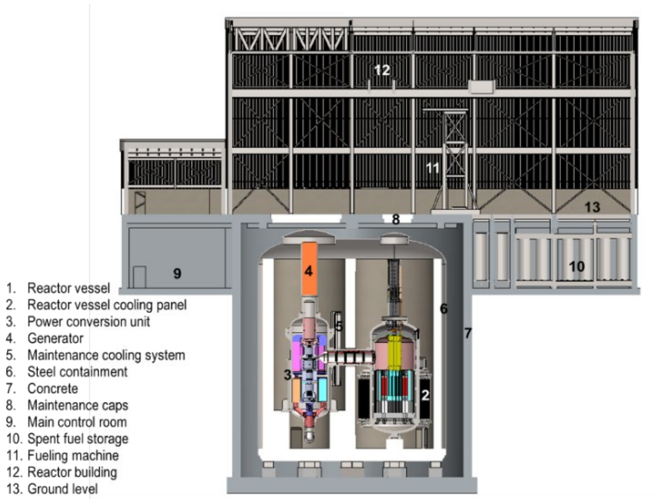

FIG. 1. FMR reactor building layout.

The reactor building consists of two structures: (1) the below-grade concrete structure including the containment building, main control room, spent fuel storage, equipment room, reactor and power conversion system and (2) an above-grade structure. Containment is the below grade, pressure-retaining vessel, containing the reactor and power generating equipment, that is sealed when the unit is normally operating.

Within the containment, the reactor vessel and the power generating equipment compartment include provisions for open communication between the compartments. Containment is completely sealed with a minimum of two equipment hatches, one over the reactor and the other over the power conversion unit (PCU). All equipment which is replaceable will be accessible through the hatches for maintenance. Personnel hatches are also provided for ingress/egress to the containment in addition to equipment hatches.

A spent fuel storage area is provided in the reactor building in the refuelling area to facilitate fuel movements, ensure passive heat removal from the spent fuel and optimize the plant layout. The spent fuel storage is separate from the containment vessel and contained within the reactor building adjacent to containment building.

The dry cooling tower building(s), heat rejection subsystem of the PCU, are sized to be effective given the specified ambient climate range. The power conversion system, including frequency converter subsystem, interfaces to the switch yard which is an interface to the outside grid to deliver electricity. The switch yard includes a medium voltage to low voltage stepdown transformer which allows either diesel generators or grid power to provide house power to the FMR for startup, shutdown, and refuelling purposes.

2. DESIGN FEATURES AND KEY TECHNOLOGIES

The FMR is a gas-cooled fast reactor (GFR) that has the characteristics of both fast reactors and high-temperature gas-cooled reactors. The key, unique design features of the FMR are helium coolant, robust SiGA composite material, dry cooling as an ultimate heat sink, and a closed Brayton cycle. When combined, these features enable passive safety, high operational margins, flexible siting, quick installation, which all contribute to market penetration in the late 2030's timeframe. The following is a list of the FMR enabling technologies and their reactor performance-related benefits:

- Fast neutron spectrum enables a long-burn fuel cycle that reduces staffing and refuelling work and provides the capability to close the fuel cycle and transmute high-level waste.
- Helium coolant maintains single phase during both high-temperature normal operation and accident conditions. The reactivity feedback during a loss of coolant accident (LOCA) is negligible. It is non-radioactive, non-corrosive, non-toxic, and optically transparent.
- SiGA composite material enables high-temperature operation for high thermal efficiency and passive safety of the reactor system owing to its structural integrity during a LOCA followed by station blackout. Its high neutron irradiation tolerance enables a high-burnup operation and a long fuel life.
- Zirconium silicide reflector provides uniform power across the core and maintains fast neutron economy.
- Reactor vessel cooling system (RVCS) provides passive safety by gravity-driven water flow in the cooling loop around the reactor vessel. This system requires no high-temperature heat exchanges for the passive safety.
- Closed Brayton cycle enhances high thermal efficiency and economics by significantly increasing electrical power output, that reduces fuel consumption and high-level waste. It eliminates the need for a steam generator that reduces plant complexity and footprint and provides rapid load-following capability along with generator field-oriented control (FOC) that enables fast-dispatching and the backing-up of intermittent renewables.
- Dry-cooled ultimate heat sink enables siting and quick installation at geographically diverse nodes and off-grid locations, without need for a large water source.

3. REACTOR SAFETY

The safety approach of the FMR is based on an enhanced defense-in-depth that is strengthened by the inherent safety feature of the negative reactivity temperature coefficient of the fuel, passive heat transfer mechanisms, and selection of materials and design features. For example, the annular core configuration reduces the power peaking and promotes cooling capability during emergencies. Low power density and high-temperature materials secure the safety margin during the highly unlikely event of an accident. To improve efficiencies, the possibility for human error is reduced by fully automatic reactor control/shutdown, lowering the risk of accidents.

The engineered safety features (ESFs) are provided to mitigate the consequences of postulated accidents, which includes reactor protection system, maintenance cooling system (MCS), RVCS, and containment. The principal role of the MCS is to provide a secondary means of removing core residual heat by forced convection whenever the normal forced cooling loop is unavailable. In this role, it is intended to control the rate of reactor heat removal to maintain the temperatures of components within the primary coolant boundary at acceptable levels. The RVCS is a totally passive safety-related system that operates continuously in all modes of plant operation. If forced cooling is lost, it functions to remove residual decay heat to ensure safety and investment protection. Heat is transferred from the reactor vessel side wall to the RVCS cooling panels principally by radiation.

3.1. Accident analysis

The limiting accident scenario considered for the FMR design is the depressurized loss of forced cooling (DLOFC). The DLOFC accident is initiated by a breach of the primary coolant pressure boundary, which causes primary system depressurization. The reactor then automatically trips based on either low primary coolant pressure or high radiation levels or high pressure in the containment. The transient cladding temperature estimated by the MELCOR code is shown in FIG. 2 at various elevations. The peak cladding temperature is maintained below the limiting temperature of 1800ºC [2].

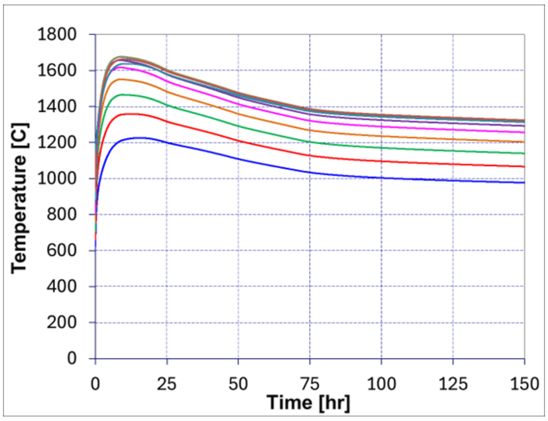

FIG. 2. Cladding temperature during the DLOFC.

3.2. RVCS experiments

The performance of the RVCS was recently tested in the University of Wisconsin's reactor cavity cooling test facility that consists of heaters, cooling pipes and water tanks and the results are shown in FIG. 3. This test facility represents a nearly full-scale 2-dimensional slice of the FMR RVCS. A series of repeatability tests have been performed under International Organization for Standardization (ISO)-17025 standards to validate the existing data set [3]. These tests demonstrated that the thermal-hydraulic performances of the single- and two-phase tests of the recent experimental campaign are consistent with those of previous experimental campaign [4,5]. Based on these test results, it is concluded that the complete database is applicable to a near full-scale benchmark of the FMR RVCS and the current RVCS design has the capability to remove the decay heat.

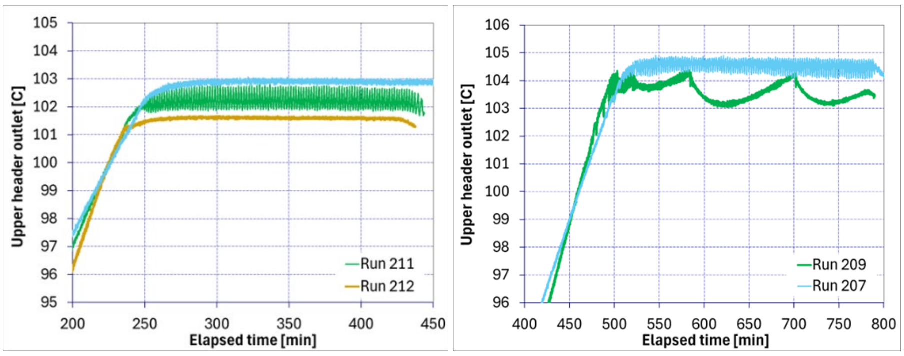

FIG. 3. Riser outlet temperature in atmospheric boiling and pressurized tank boiling tests.

4. DIRECT BRAYTON CYCLE

The PCU can achieve a net efficiency of over 42% with a higher operating temperature, wet cooling, and/or bottom cycle, which can reduce the operating cost of power generation by more than 30% when compared with the Rankin steam cycle of a commercial reactor and, as a result, could reduce the electricity cost to a competitive level with natural gas-fired electricity generation. The PCU incorporates a synchronous, high-speed generator, turbine and compressors with rotational speeds of ~13,600 rpm.

The existing and emerging technologies of the subsystems/components can drastically improve the performance of the nuclear Brayton cycle of a compact PCU as follows:

- Large active magnetic bearings can support gas turbine thrust and radial loads and enable safe turbine operation past several critical speeds.

- High strength rare earth magnets enable high-speed, compact rotors with reduced ohmic losses with greatly improved responsiveness to changes in load demands.
- High-efficiency frequency inverters allow super-synchronous rotational speeds to reduce the turbo-compressor-generator size and increase its efficiency of power conversion.
- Field-oriented load control through generator stator field commutation can eliminate the need for large, high-temperature helium flow control valves for load control.

5. CONCLUSIONS

The conceptual design project has conclusively shown the FMR is feasible. Significant maturation of the FMR design shows successful application of SiGA-cladding with conventional pellet UO_2 fuel and demonstration of the passive safety through laboratory experiments. The conceptual design also produced several pre-application documents which are now docketed with the U.S. Nuclear Regulatory Commission (NRC) including accepted Principal Design Criteria (PDC) and Quality Assurance Program Description (QAPD).

In addition to the baseload power supply, the FMR concept can provide ancillary services, such as frequency regulation, voltage support, and fast response reserves, which are vital for grid operation and maintaining system reliability. As a gas-cooled reactor, the FMR has the capability of broader process heat applications. As a fast reactor, the FMR core has the capability to recycle and transmute transuranics to close the fuel cycle, reducing the need for new uranium fuel.

ACKNOWLEDGEMENTS

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DISCLAIMER

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