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Integrated FHR Technology Development: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal-Hydraulics and Neutronics with Associated Benchmarking

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ABSTRACT

The objective of this Integrated Research Project (IRP) is to address four major challenges in the development of a commercial Fluoride High-Temperature Reactor [FHR]: tritium control; corrosion control and materials selection; thermal-hydraulics and neutronics; and evaluation model benchmarking. No FHR has ever been built. It has been over 40 years since a new reactor concept has been developed.

The FHR is an advanced reactor that uses the same coated-particle fuel used in High-Temperature Gas-cooled Reactors (HTGRs) and a low-pressure liquid fluoride salt coolant. This combination enables the FHR to deliver heat to the power cycle between 600 and 700°C for efficient electricity production. Power cycle options include steam, helium Brayton, supercritical carbon dioxide, and a nuclear air-Brayton combined cycle (NACC). NACC is the same power cycle technology used in jet engines and natural gas plants and takes advantage of recent advances in this technology including lower water cooling requirements. NACC can operate on nuclear heat to produce base-load electricity. Peak power can be produced by addition of natural gas (or hydrogen or biofuels in the future) after nuclear heating with a natural gas to electricity conversion efficiency of over 66%. These capabilities boost plant revenue and enable a future low-carbon grid by providing efficient variable electricity on demand.

The Integrated Research Project (IRP) combines the unique capabilities of the Massachusetts Institute of Technology (MIT) with its research reactor for irradiating materials, the University of California at Berkeley (UCB) with its thermal-hydraulic test loops, the University of Wisconsin at Madison (UW) with its salt corrosion laboratory, and the University of New Mexico at Albuquerque (UNM) with its heat transfer laboratory, to address these challenges.

Tritium control and the role of carbon. Neutron irradiation of the coolant generates tritium—about three orders of magnitude greater than today's PWRs and three orders less than a fusion reactor. Tritium diffuses through hot metals including decay heat cooling systems and the power cycle. To prevent release from the environment, methods are required to contain and recover the tritium. Because proposed fusion reactors have much larger tritium inventories, much work has been done by the fusion energy community. However, unlike proposed fusion power reactors the FHR contains carbon in different forms. Carbon acts

as an absorber for tritium and limited data and modeling indicates rapid removal of tritium from the salt by carbon through absorption. Absorption depends upon carbon form, surface area, and irradiation damage to the carbon. MIT and UW will measure tritium production and transport under prototypical FHR conditions, including uptake into carbon and permeation through container walls with permeation barriers (double walls and oxide layers). A combination of cold testing at UW and reactor irradiations at MIT will provide fundamental data to validate tritium models and design FHR tritium control systems.

Corrosion control with redox control, impurity control and materials selection. The FHR uses a clean (non-fuel bearing) fluoride salt. It is imperative to understand if proposed materials of construction (graphite, metallic alloys, composites, fuel cladding [TRISO particles and compacts] will survive prototypical reactor conditions of molten fluoride salt. MIT and UW will develop redox control strategies and conduct experiments on candidate materials of construction to determine their use in a commercial FHR. This activity involves working with ORNL, INL, and other organizations that will provide input and prototypic materials that will be tested. UW has the only existing, certified laboratory facility in the U.S. for testing materials in molten flibe salt. MIT has the only U.S. reactor where neutron irradiation tests of candidate materials in molten flibe (primary coolant for FHR) salt at 700°C under prototypical conditions have been performed, and the required associated laboratory facilities. The UW/MIT facilities enable testing with and without irradiation fields to enable understanding of chemistry control and materials options. The experimental work lays the groundwork for larger qualification tests in the DOE test reactors, and for ASME Section III code qualification of new FHR structural materials.

FHR experiments and modeling for thermal hydraulics and neutronics. To design and license FHRs, their steady-state and transient response must be predicted. UCB pioneered the use of heat transfer oils as simulant fluids for fluoride salts, and has developed extensive experimental facilities to perform separate effect tests to measure local heat transfer coefficients and pressure losses, and constructed the Compact Integral Effects Test (CIET) facility to perform integral effects tests for FHRs and their passive decay heat removal systems. UNM has developed the capability to perform separate effects tests for FHR heat exchangers, particularly twisted-tube designs that maintain good convective heat transfer performance even at transition and low Reynolds numbers. Coupled with salt heat transfer data from the proposed UW natural circulation loop, national and international partners, and with neutronic data from international partners, this effort will support the development and validation of transient response evaluation models for FHRs.

Benchmarking and Validation. Reactor design involves the use of various computer codes, or "evaluation models" (EMs) for neutronic, thermal hydraulic, and materials/coolant/tritium analysis and design. As discussed in USNRC Regulatory Guide 1.203, the assessment of EMs capability to predict safety-relevant behavior should include validation by comparison to well-scaled separate effect and integral effect test data and by benchmarking exercises involving code-to-code comparisons. EM benchmarking has not been performed for the FHR. Wide participation is important to develop confidence in predictions for safety and design. UCB and UNM will lead the effort for a series of code benchmarking and validation workshops in neutronics, thermal hydraulics, and materials/coolant/tritium modeling, that will also create mentoring and collaboration opportunities for students and young researchers. In addition to the participation of MIT and UCB, this effort will include participants from national laboratories (ORNL, INL), other universities, Westinghouse, and international organizations (Cambridge University, United Kingdom; Chinese Academy of Science; and the Czech Republic Research Centre Rez). The work involves laboratory tests by UCB, UNM, MIT, UW, and others and a series of workshops where users of codes can perform code-to-code comparisons and comparisons with experimental data, and then predict experimental results before the experimental data is published. Project funding is $5,000,000 over 3 years.