Gus Merwin, test engineer at Kairos Power, supervising a salt material compatibility test in the Kairos Power laboratory at corporate headquarters in Alameda, California.

Kairos Power: DOE-NE Integrated Research Project to Nuclear Startup

by Paul Menser for DOE's Nuclear Energy University Program

Kairos Power, a California-based company aiming to transform the energy landscape in the United States by combining existing technologies in new and exciting ways, is modernizing fluoride-salt-cooled high-temperature reactor (FHR) technology for an emerging stage of commercialization. Although the concept itself is not new, novel developments in associated technology have made the reactor a viable power production and heat processing option. This is important to the economy as other energy sources continue to become more expensive in the United States. Additionally, the technology has the potential to provide a reliable and steady foundation of energy to the other renewable sources on the grid, which have intermittent power sources.

Based on research funded through the Department of Energy's (DOE) Nuclear Energy University Program (NEUP), Kairos is using past data to create current solutions.

Advances made in understanding and predicting the performance of passive safety systems have created new and unexpected opportunities for decades-old ideas.

The idea of an FHR dates back to 2001, when the Generation IV forum chose molten salt reactors as one of six concepts to pursue. In 2004, DOE's Office of Nuclear Energy (DOE-NE) started supporting FHR development on a small scale through its laboratories and university research programs. In 2010, DOE-NE endorsed FHRs as a potential means for achieving the administration's research and development (R&D) goals for nuclear energy.

FHRs rely upon technology that was not available during the earlier molten salt reactor (MSR) era back in the 1950s. Still, by the time the government's MSR program was cancelled in the 1970s, substantial technical progress had been made on other reactor classes and technologies that support FHRs. For example, data collected in the mid-1980s at Argonne National Laboratory's Idaho Experimental Breeder Reactor-II indicated that decay heat from low-pressure, liquid-cooled reactors could be passively rejected to the local air without fuel damage. Similarly, the ongoing advanced gas reactor fuel testing program demonstrated ceramic-coated-particle fuel could be mechanically robust and manufactured at an acceptable price.

Today, nearly 20 years later, Kairos's founding officers—CEO Mike Laufer, Chief Technology Officer Ed Blandford and Chief Nuclear Officer Per Peterson—plan to have a demonstration reactor in operation before 2030.

The FHR concept combines three elements:

1. Li_2BeF_4, a lithium-beryllium-fluoride salt known as Flibe;

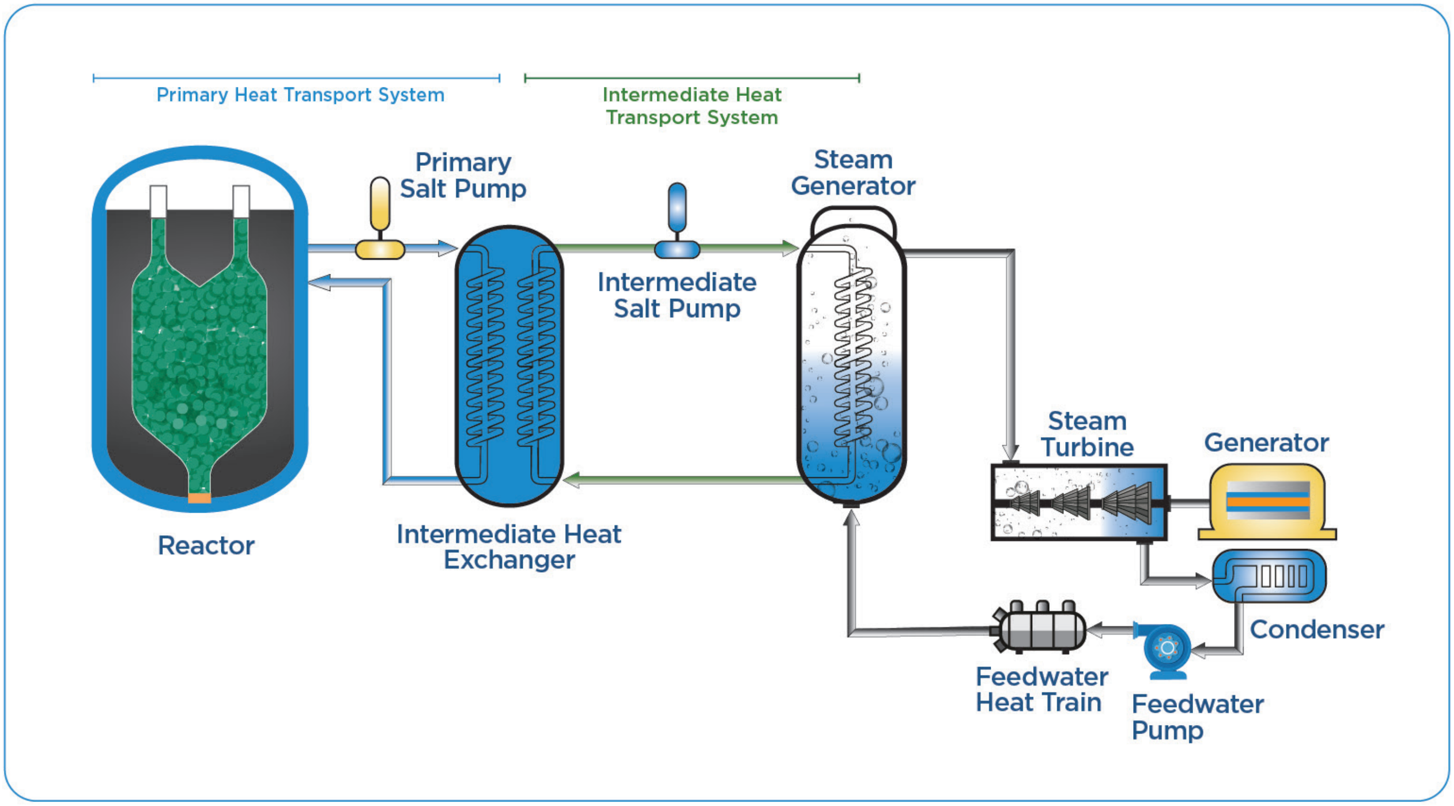
2. Tri-structural isotropic (TRISO)-coated particle fuel embedded in small graphite pebbles, originally developed for high-temperature gas-cooled reactors (HTGRs); and

3. Low-pressure, High temperature, thin walled vellel and piping originally developed for sodium cooled fast reactors.

With the cancellation of DOE's molten salt reactor program in the 1970s, expertise in the technology was no longer a priority for national laboratory or university projects. Subsequently Flibe was studied for use as a coolant in fusion systems, but capabilities to work with Flibe experimentally were lost.

Although the company wasn't incorporated until 2016, Kairos's story actually began in 2011. Through NEUP, a three-year Integrated Research Project (IRP) was awarded to MIT and its partners at the University of California, Berkeley (UCB) and the University of Wisconsin, Madison (UW). The proposal opened with this statement:

"(The objective) is to develop a path forward to a commercially viable salt-cooled solid-fuel high-temperature reactor with superior economic, safety, waste, non-proliferation, and physical security characteristics compared to light-water reactors."



The Kairos Power FHR (KP-FHR) is a novel advanced reactor technology that leverages TRISO fuel in pebble form combined with a low-pressure fluoride salt coolant. The technology uses an efficient and flexible steam cycle to convert heat from fission into electricity and to complement renewable energy sources.

"This was the first project that used Flibe salt as a coolant for solid fuel in a reactor," said Todd Allen, the materials testing lead on the 2011 IRP project.

What followed were workshops in 2012 involving graduate students from all three institutions. Their involvement—the questions they asked, the discoveries they made and the perspectives they offered—gave the IRP a different kind of energy. "These were the first students in a generation that worked on developing a molten salt reactor."

During the IRP workshops, retired Oak Ridge National Laboratory personnel in their late 70s and 80s provided guidance on technical direction, insight and discussion of pertinent issues; this allowed for knowledge transfer to graduate students working on the projects.

As a result of these collective IRP projects, dozens of graduate students have now graduated and are contributing in this area as university professors and national laboratory or industry staff.

IRPs represent the program-directed component of NEUP by providing research and development (R&D) solutions most directly relevant to the near-term, significant needs of the NE R&D programs. IRPs complement the other NEUP components, which include program supporting and mission supporting university-based R&D, university reactor and research equipment infrastructure upgrades, and Integrated University Program student fellowship and scholarship grants. They are significant three-year awards for projects that address specific research issues and capability gaps identified and defined by the NE R&D programs. They are intended to develop a capability within each specified area. These projects are multidisciplinary and require multi-institutional partners.

In the case of FHR, each university involved had unique features to contribute:

- Materials irradiations: MIT students developed, built and operated test capsules with prototypical materials in 700°C salt in the MIT reactor under prototypical temperature and irradiation conditions expected in the FHR. Identical tests were conducted outside the reactor at UW to understand and separate out the effects of salt corrosion and irradiation on materials.

- Materials testing: UW has built and now operates systems to purify the fluoride salts required for the FHR. Students used these salts in 700°C corrosion tests to evaluate different potential materials for the FHR.

- Thermal hydraulic tests: UCB has built large-scale thermal-hydraulic test loops that use an organic simulant, in which students conducted experiments to provide required experimental data for reactor design.

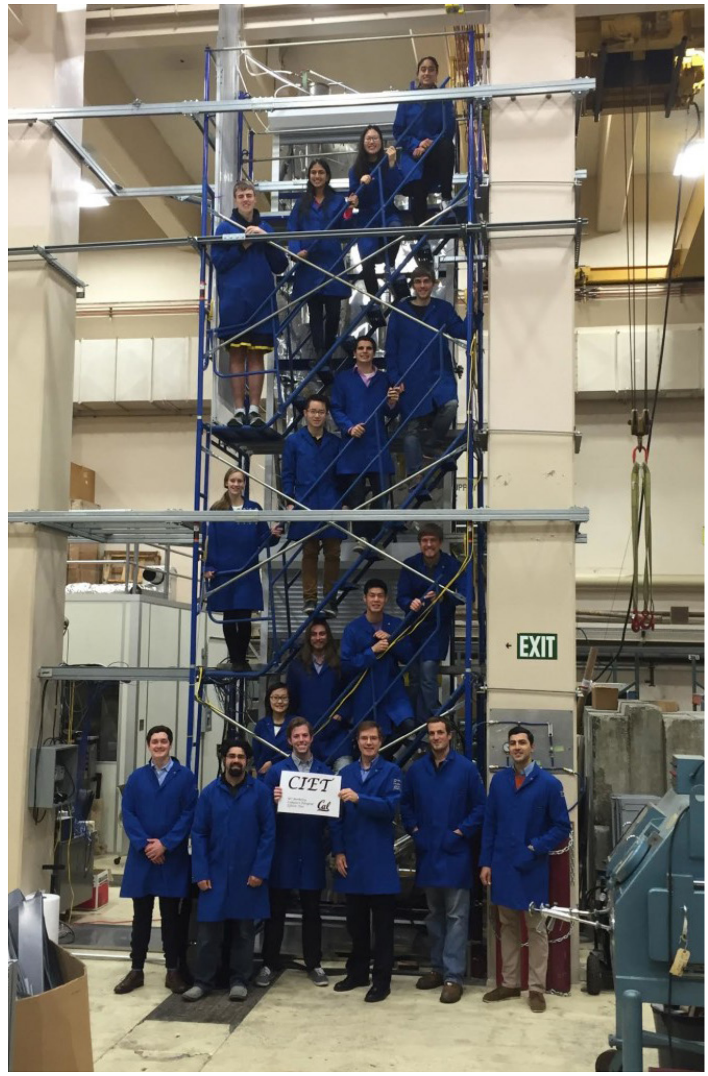
This 2011 IRP project provided a renewed DOE investment in molten salt reactor technology, which now has a dedicated work scope area in DOE's Consolidated Innovative Nuclear Research funding opportunity. This is supported by research at Oak Ridge National Laboratory.

By the end of the project, the IRP had produced four white papers and more than 100 technical reports and papers summarizing the three activities and associated experimental work. A subsequent IRP was then funded in 2014, with University of New Mexico joining the original partner universities.

All of this has helped develop a workforce for the FHR project. By December 2018, Kairos had hired 26 researchers who had done graduate work on the IRP.

Meanwhile, a second FHR-focused IRP was awarded in 2014, involving Georgia Institute of Technology, The Ohio State University, Texas A&M University at College Station, Texas A&M University at Kingsville, and several other national and international partners.

"It presented them with a real interesting and advanced learning experience," said Regis Matzie, a retired Westinghouse chief technical officer who chaired the original IRP advisory panel. As they explored the FHR concept, they came to the conclusion that it took the best aspects from several forms of power generation. For example:



Students pose on the Compact Integral Effects (CIET) Test facility, a scaled thermal hydraulics facility that provides data on salt cooling behavior in FHRs. The CIET team included now Kairos CEO, Dr. Michael Laufer (front, second from right) and Dr. Per Peterson, Kairos Chief Nuclear Officer (front, fourth from right).

- Gas-cooled reactors: TRISO fuel, structural ceramics, and high-temperature power conversion;

- Molten salt reactors: fluoride salt coolant, a structural alloy and hydraulic components;

- Liquid metal reactors: passive decay heat removal, low-pressure design and hot refueling;

- Light water reactors: high heat capacity coolant and transparent coolant; and

- Advanced coal plants: a supercritical water-power cycle and structural alloys.

FHRs afford lower power costs (due to a low-pressure primary system enabling functional containment) and thermal efficiency at least 12 percent higher than light water reactors (due to high temperature delivery of heat). Also, with low water consumption and no need for a grid connection for process heat, they seem to be more easily siteable.

In addition to the technical aspects of the project, a significant amount of the IRP work has been focused on the regulatory aspects of getting an FHR licensed by the U.S. Nuclear Regulatory Commission. In fact, the first series of workshops was aimed at addressing the best way to go about licensing this technology. As a result, Kairos has leapfrogged to newer safety codes developed by DOE.

"If we had not done that work in advance, it would have been a much more daunting prospect," Peterson said. "It is remarkable, the quality of the work and how much has been documented."

The data collected in experiments done decades before and advancements in current reactor technology, along with the NEUP funding, have provided a unique story and a prime moment to commercialize remarkable technology that potentially offers a viable energy solution.

Related NEUP Projects:

11-3272 High-Temperature Salt-Cooled Reactor for Power and Process Heat; and

14-7476 Integrated FHR Technology Deveopment: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics with Associated Benchmarking.

Release Date: October 2019

Kairos Power Continues Partnership with DOE-NE on Reactor Development

Kairos Power was recently awarded two project partnerships through DOE-NE's U.S. Industry Opportunities for Advanced Reactor Development funding opportunity, which funds advanced reactor technology that will be deployed in the mid- to late-2020s. Two projects, totaling over $11 million ($5.5 million in DOE funds, $5.8 million in Kairos Power cost share), will support development and licensing activities to accelerate development of the Kairos Power FHR (KP-FHR).

- **Development of Modeling and Simulation Pathways to Accelerate KP-FHR Licensing**

  This project advances the schedule in critical advanced modeling and simulation capabilities needed for the FHR's license application. The team consists of NEAMS developers at Idaho National Laboratory, Argonne National Laboratory and Los Alamos National Laboratory. They will develop modeling tools that will be useful to both Kairos Power and other molten salt and fluoride high-temperature reactor development programs.

- **Technology Pre-application Licensing Report on the Development of a Mechanistic Source Term Methodology for the KP-FHR.**

  This project will develop a mechanistic source term for the KP-FHR design, including consideration of radionuclides generated and transported in the fuel particle and the barriers to release for licensing basis event analyses.