**FINAL REPORT**

**Project Title:** Development and Analysis of Advanced High-Temperature Technology for Nuclear Heat Transport and Power Conversion

**Covering Period:** April 15, 2005 through December 31, 2009

**Date of Report:** March 1, 2010

**Recipient:** University of California, Berkeley
University of California, Berkeley
Nuclear Engineering Department,
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**Award Number:** DE-FC07-05ID14669

**Subcontractors:**

**Other Partners:**

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**Project Team:**

**Project Objective:** This project by the Thermal Hydraulics Research Laboratory at U.C. Berkeley studied advanced high-temperature heat transport and power conversion technology, in support of the Nuclear Hydrogen Initiative and Generation IV. The project was extended, with continuation funds, for a fourth year of work. The project focused on fundamental and applied questions for high-temperature heat transport using different combinations of gases (e.g., helium) and liquids (e.g., clean liquid salts). The project made contributions in multiple task areas. The project contributed to identifying design requirements the 50 MW(t) Next Generation Nuclear Plant (NGNP) intermediate heat exchanger (IHX) system, and pursued scaled experiments using simulant fluids to study liquid salt heat transfer in heated channels. In this area UCB developed a new design approach for a thermal-creep resistant IHX based on a capillary tube and shell design. Finally, the work developed improved design options for the Advanced High Temperature Reactor (AHTR), a liquid-salt cooled variant of the VHTR. Here UC Berkeley was tasked to develop refueling and other design aspects for the liquid-salt cooled pebble bed AHTR (PB-AHTR). In the fourth year of this work, UCB studied a high power density, 900 MWth modular PB-ATHR. This research resulted in two patent applications (see patents section) and seventeen research publications [1-17]. All tasks have been completed for this project.

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**Background:**

The Next Generation Nuclear Plant (NGNP) will employ an engineering-scale 50 MW(t) intermediate loop to demonstrate the production of hydrogen. To achieve high efficiency (>50%), high temperatures (core outlet temperature up to 1000°C) are required for the baseline sulfur-iodine (S-I) thermochemical process. At temperatures in this range, metallic intermediate heat exchanger (IHX) materials may be subjected to creep deformation, requiring either pressure balanced operation or other design modifications. A major design issue for the NGNP intermediate loop involves the selection of the intermediate fluid. In general, the use of high-pressure helium involves large-diameter pipes and very large pumping power. If a liquid salt is used instead, the pumping power drops with a factor of 100 and the MS piping is 1/5 the diameter. Thus a part of this project studies the application of liquid salts to the NGNP intermediate loop.

In addition, advanced multiple-reheat gas Brayton cycles provide a potentially attractive approach to the production of electrical power from heat delivered by high temperature coolants such as liquid salts, lead, and potentially sodium. In this project, we have developed multiple-reheat power cycle designs (the liquid coolant gas cycle, MCGC) for the liquid-salt cooled Advanced High Temperature Reactor (AHTR) that increase cycle efficiency 5 to 10% relative to Brayton power conversion cycle without reheat. We have updated these MCGC designs with a detailed heater system design, based on results from the He-to-MS IHX design work of Task I.

Finally, UC Berkeley, in collaboration with ORNL and SNL, developed the original concept for the AHTR. By using a clean liquid-salt coolant with NGNP-type fuel, in a pool-type configuration similar to the S-PRISM sodium cooled reactor, the AHTR achieves over 4 times larger thermal inertia than gas-cooled reactors, permitting thermal power of 2400 MW(t) or higher. Recent economics analysis of the AHTR showed potential cost capital cost reduction approaching 50% compared to a gas-cooled, 600 MW(t) NGNP reactor. This work has been developing key aspects of the AHTR design and development path plans in support of LS-VHTR activity at ORNL and INL. *Based on direction from the DOE, portion of the UCB NERI work was reprogrammed to support the identification and analysis of refueling methods for the NGNP, where UCB has focused on demonstrating the viability of pebble fuels.* Major advances, both experimental and analytical, have been made in demonstrating the viability of the Pebble Bed AHTR. Work is now nearing completion, under a one-year increment of continuation funding, to develop a design and development plan for a 900 MWth modular PB-AHTR.

**Status:** We have completed the full work scope for this NERI project, summarized in the tables in the next section, as well as additional work scope for a one-year continuation. An initial patent application was filed in Nov., 2008. A second provisional patent application was filed in April, 2009 for design features of the new Pebble Bed AHTR (see Patents section).

**Task 1:** We have developed and demonstrated new computational models for the IHX compact heat exchangers based on the effective porous media (EPM) approximation, and have completed transient analysis of a representative compact IHX design. The final report was issued as a PhD dissertation during

the last quarter.

**Task 2:** The Scaled High Temperature Heat Transfer (S-HT$^2$) loop was built to measure mixed convection heat transfer and pressure loss in the Pr, Re, and Gr range needed to model liquid salt systems. Collection of heat transfer data has been completed.

**Task 3:** This task is complete, with the results presented at the 2006 ICAPP meeting [10-12].

**Task 4:** This task is complete, with the final design report and development plan report presented as a paper at the June 2008 ICAPP conference [1].

**Milestone Status Table:**

| ID Number | Task / Milestone Description | Planned Completion | Actual Completion | Comments |
|---|---|---|---|---|
| 1 | NGNP IHX design option comparison | | | |
| 1.1 | Coordinate with program sponsors to develop high-level design parameters/requirements for IHX reference designs | 7/15/05 | 1/3/06 | Complete |
| 1.2 | Generate Phenomena Identification and Ranking Table (PIRT) for NGNP IHX and intermediate loop system | 10/15/05 | 3/31/07 | Completed |
| 1.3 | Issue draft IHX and intermediate-loop design and analysis report for comment | 4/15/06 | 3/31/07 | Complete |
| 1.4 | Issue Revision 2 IHX and intermediate-loop design and analysis report integrating review comments | 10/15/06 | 11/30/07 | Complete (See reference [3] |
| 1.5 | Issue Final IHX and intermediate-loop design and analysis report | 4/15/07 | **(delay)** | We continue to delay work in this task area while completing the IHX transient test model |
| 2 | Scaled transient heat transport integral experiments | | | |
| 2.1 | Develop preliminary experiment design and description for the Scaled High Temperature Heat Transfer (S-HT2) loop and issue for review | 7/15/05 | 1/10/06 | Complete |
| 2.2 | Develop final S-HT2 experiment design and description and issue for review | 10/15/05 | 11/1/06 | Complete. Construction has been completed and operation has been initiated. |
| 2.3 | Demonstrate fabrication of PYREX components for test loop and procure other loop components | 4/15/06 | 11/1/06 | Complete |

| ID Number | Task / Milestone Description | Planned Completion | Actual Completion | Comments |
|---|---|---|---|---|
| 2.4 | Perform cold, low-pressure fluid-mechanics characterization of the S-HT2 test loop, including hot-wire measurements of gas inlet and outlet flow distribution and PIV characterization of liquid inlet and outlet manifold flows | 10/15/06 | 5/1/06 | Complete |
| 2.5 | Perform heated, full pressure steady state S-HT2 loop heat transfer tests | 4/15/07 | 6/15/07 | Complete |
| 2.6 | Perform transient heat transfer and structure thermal response testing using the S-HT2 test loop | 4/15/08 | Delay | |
| 3 | Multi-reheat helium Brayton power conversion | | | |
| 3.1 | Develop preconceptual design for LFR multiple-reheat helium Brayton cycle power conversion system | 4/15/07 | 12/1/06 | Completed ahead of schedule |
| 3.2 | Develop design and analysis report for LFR multiple-reheat helium Brayton cycle power conversion system | 4/15/08 | 12/1/06 | Complete |
| 3.3 | Develop design and analysis report for AHTR-IT and AHRT-VT multiple-reheat helium Brayton cycle power conversion systems | 4/15/08 | 12/1/06 | Complete |
| 4 | Advanced High Temperature Reactor (AHTR) design analysis | | | |
| 4.1 | Develop AHTR-LT, AHTR-IT and AHTR-HT intermediate heat transport loop designs based on Task 1 results | 10/15/06 | 12/10/05 (early) | Completed ahead of schedule |
| 4.2 | Develop AHTR-LT, AHTR-IT and AHTR-HT scaled integral test designs based on Task 2 results | 4/15/07 | 2/28/07 | Complete |
| 4.3 | Develop AHTR-IT and AHTR-VT design report and development plan report based on Task 1, 2, & 3 results | 4/15/08 | 4/15/07 | Complete |
| 4.4 | Develop modular PB-AHTR point design and development plan | 4/14/09 | | |

**Patents:** High Power Density Liquid-Cooled Pebble-Channel Nuclear Reactor, Patent application serial number PCT/US08/83234, filed on Nov. 12, 2008.

Annular Core Liquid-Salt Cooled Reactor With Multiple Fuel and Blanket Zones, Provisional Patent application serial number 61/167,899, filed on April 9, 2009.

**Publications/Presentations:**

[1] Philippe Bardet, Edward Blandford, Massimiliano Fratoni, Aurelie Niquille, Ehud Greenspan, and Per F. Peterson, "Design, Analysis and Development of the Modular PB-AHTR," 2008 International Congress on Advances in Nuclear Power Plants (ICAPP '08), Anaheim, CA, June 8-12, 2008.

[2] E.D. Blandford and P.F. Peterson, A Novel Buoyant Shutdown Rod Design for the Passive Reactivity Control of the PB-AHTR," 4th International Topical Meeting on High Temperature Reactor Technology, Washington, DC, Sept. 28 – Oct. 1, 2008.

[3] E. Urquiza-Fernández, P.F. Peterson and Ralph Greif, "Multi-Scale Thermal Analysis for Compact Plate-Type Heat Exchangers" American Institute of Chemical Engineerrs (AIChE '07) Annual Meeting, Salt Lake City, UT, Nov. 4-9, 2007

[4] A. Griveau, "Modeling and Transient Analysis for the Pebble Bed Advanced High Temperature Reactor (PB-AHTR), Masters Report, UCBTH-07-001, February 2007.

[5] Per F. Peterson, "Capillary Tube and Shell Heat Exchanger Design for Helium to Liquid Salt Heat Transfer," Report UCBTH-07-003, U.C. Berkeley, May 7, 2007.

[6] P. Bardet, J.Y. An, J.T. Franklin, D. Huang, K. Lee, M. Toulouse and P.F. Peterson, "The Pebble Recirculation Experiment (PREX) for the AHTR," presented at Global 2007, Boise, Idaho, September 9-13, 2007.

[7] A. Griveau, F. Fardin, H. Zhao, and P.F. Peterson, "Transient Thermal Response of the PB-AHTR to Loss of Forced Cooling," presented at Global 2007, Boise, Idaho, September 9-13, 2007.

[8] M. Fratoni, F. Koenig, E. Greenspan, and P.F. Peterson, "Neutronic and Depletion Analysis of the PB-AHTR," presented at Global 2007, Boise, Idaho, September 9-13, 2007.

[9] Per F. Peterson, “Guidelines for Trade-Studies for Comparison of Liquid Salt and Helium Intermediate Coolants for the NGNP,” Report UCBTH-07-002, U.C. Berkeley, February 20, 2007.

[10] W. Huang, H. Zhao, and P.F. Peterson, “Multi-scale Stress Analysis for Compact Plate Heat Exchangers,” 2006 International Congress on Advances in Nuclear Power Plants (ICAPP '06), Reno, NV, June 4-8, 2006.

[11] H.Zhao and P.F. Peterson, “Low-Temperature Multiple-Reheat Closed Gas Power Cycles for the AHTR and LSFR,” 2006 International Congress on Advances in Nuclear Power Plants (ICAPP '06), Reno, NV, June 4-8, 2006.

[12] P.F. Peterson and H.Zhao, “A Flexible Baseline Design For the Advanced High Temperature Reactor Utilizing Metallic Reactor Internals (AHTR-MI),” 2006 International Congress on Advances in Nuclear Power Plants (ICAPP '06), Reno, NV, June 4-8, 2006.

[13] P.F. Peterson, H. Zhao, and G. Fukuda, "Functional Requirements Overview For a 50-MW(t) Liquid-Salt Intermediate Loop for NGNP," U.C. Berkeley Report UCBTH-05-007, Rev. B, December 29, 2005.

[14] P.F. Peterson and H. Zhao, "Design and Development Strategy for a First-Generation Commercial Advanced High Temperature Reactor with Metallic Vessel Internals (AHTR-MI)," U.C. Berkeley Report UCBTH-05-005, Rev. D, December 10, 2005.

[15] B. Laurenty, G. Fukuda, D.D. Damba, P.F. Peterson “Inhibiting corrosion by molten fluoride salts: investigation on Flinak,” AIChE 2005 Annual Meeting, Cincinnati, Ohio, Oct. 31 – Nov. 4, 2005. (Selected for AIChE Nuclear Engineering Division Student Award for Best Paper).

[16] P. Bardet and P.F. Peterson, “Design of Scaled Integral Experiments for High Temperature Liquid Salt and Helium Fluid Mechanics and Heat Transfer,” Eleventh International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 11, Avignon, France, October 2-6, 2005.

[17] H. Zhao and P.F. Peterson, “Optimization Of Advanced High-Temperature Brayton Cycles With Multiple Reheat Stages,” The 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Popes’ Palace Conference Center, Avignon, France, October 2-6, (2005).