

## SFR COMPONENT DESIGN AND BALANCE OF PLANT PROJECT

**J.J. Sienicki<sup>(1)</sup>, G. Rodriguez<sup>(2)</sup>, S. Kotake<sup>(3)</sup>, N. Kishohara<sup>(4)</sup>, Y. Sakamoto<sup>(5)</sup>,  
J.B. Kim<sup>(6)</sup>, Y.S. Joo<sup>(7)</sup> and J.E. Cha<sup>(8)</sup>**

(1) James J. Sienicki – Argonne National Laboratory (*sienicki@anl.gov*)

(2) Gilles Rodriguez – Commissariat à l'énergie atomique (*gilles.rodriguez@cea.fr*)

(3) Shoji Kotake – Japan Atomic Energy Agency

(4) Naoyuki Kishohara – Japan Atomic Energy Agency (*kishohara.naoyuki@jaea.go.jp*)

(5) Yoshihiko Sakamoto – Japan Atomic Energy Agency

(6) Jong-Bum Kim – Korea Atomic Energy Research Institute (*jbkim@kaeri.re.kr*)

(7) Young-Sang Joo – Korea Atomic Energy Research Institute

(8) Jae-Eun Cha – Korea Atomic Energy Research Institute

### I. INTRODUCTION

The SFR Component Design and Balance of Plant Project was formally initiated on October 11, 2007 with the signature of the Project Arrangement by the Commissariat à l'Énergie Atomique (CEA), the U.S. Department of Energy (DOE), the Japan Atomic Energy Agency (JAEA), and the Korea Atomic Energy Research Institute (KAERI). U.S. participants are Argonne National Laboratory (ANL) and Sandia National Laboratories (SNL). The main objective of the Project is to enhance the performance and economic competitiveness of Sodium-Cooled Fast Reactors (SFRs) through the development of advanced components and component-related technologies or through research and development of advanced energy conversion approaches such as the supercritical carbon dioxide (S-CO<sub>2</sub>) Brayton cycle. In addition, the Project recognizes the significance of the experience that has been gained from SFR operation and upgrading in France, Japan, the Russian Federation, as well as the United States. This paper summarizes recent highlights of the Project with a focus upon the year 2008.

### II. LESSONS LEARNED FROM SFR UPGRADING

CEA and JAEA have contributed the experience and lessons learned in upgrading PHÉNIX for improved safety and plant life extension through work carried out between November 1998 and early 2003, and upgrading JOYO to improve fast flux irradiation capabilities through work performed between October 30, 2000 and September 21, 2001.

The PHÉNIX experience encompassed in-service inspection and repair including under-sodium viewing by means of ultrasonic inspection of the conical shell supporting the reactor core, ultrasonic investigation of reactor vessel welds, upper hangers in the reactor vessel, primary and intermediate sodium circuits including the steam generators, and the fuel storage vessel, modification and repair of the steam generators involving cleaning using water of surfaces having residual sodium and reuse of drained sodium without caustic corrosion, replacement of the intermediate heat exchangers, changing (permutation) of a primary sodium pump, and changing (permutation) of control rod mechanisms as well as installation of an

additional and new complementary shutdown system rod to assure reactor shutdown. The in-depth renovation of PHÉNIX demonstrated that the major technical operations were industrially feasible such as the ability to clean steam generators and reuse them afterwards and the ability to carry out ultrasonic investigations of the reactor vessel. Due to the success of the various operations, the operational life of PHÉNIX which commenced in 1974 was extended by ten years until March 2009

To increase the JOYO power level from 100 to 140 MWt, the intermediate heat exchangers, dump (sodium-to-air) heat exchangers, connecting sodium piping, and electric motors of the primary and secondary sodium pumps were replaced while maintaining a sodium level and fuel assemblies inside of the reactor vessel. In the particular instance of replacing the original sodium piping with new piping, work planning with the benefit of tests using full-size mockups, reduction of worker exposure time through training, installation of temporary shielding, and transparent seal bags were effective in reducing worker exposure and preventing the spread of contamination. Pipes were cut using a combination of initial bite cutting in an air atmosphere followed by roller press down cutting inside of a seal bag with measures to prevent foreign material (*i.e.*, small cut pieces or worker tools) from entering piping. Residual sodium was removed using cloths wetted with alcohol and water.

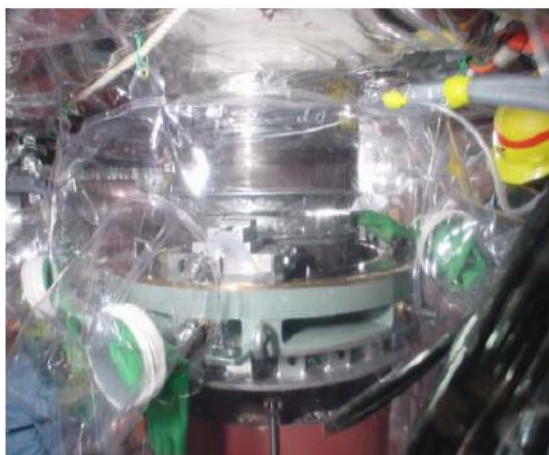


Figure 1: Seal Bag for Prevention of Oxygen Ingression at JOYO.

Experience and lessons learned from the PHÉNIX work were reported in a summary report containing an in-depth bibliography of reports by the participating organizations. The JOYO upgrading experience and lessons learned were reported in a summary report and two detailed JAEA reports in Japanese.

### III. IN-SERVICE INSPECTION

CEA, JAEA, and KAERI have contributed information on the ongoing development of new and complementary in-service inspection technologies for in-vessel sodium components. JAEA is developing two ultrasonic sensors for under-sodium viewing. The first sensor is for real-time imaging to inspect for dislocations or deformations of structures. It is a piezoelectric element sensor that has a resolution of approximately 2 mm and supports an image processing time of approximately 0.5 second per image. The second sensor is for inspection to detect fatigue cracks. It is an optical diaphragm-type sensor and has a high resolution of approximately 0.3 mm. The sensors would be mounted on an under-sodium vehicle which would be driven or held on station in the sodium inside of a reactor vessel using six small magneto-hydrodynamic sodium pumps.

KAERI is developing a waveguide sensor approach enabling the ultrasonic transducer to be supported outside of the sodium pool and at a lower temperature at the reactor vessel upper head thereby minimizing the challenges to transducer performance and survival due to high sodium temperature, sodium chemical activity, and radiation from the nuclear core. The waveguide sensor is based upon the generation and transmission of Lamb waves (*i.e.*, surface waves propagating in an elastic solid) along a metallic strip waveguide. As shown in Figure 2, a 10 m long waveguide sensor module was fabricated incorporating from top to bottom a piezoelectric element ultrasonic transducer, a liquid wedge producing an A0 mode Lamb wave having a low frequency range below 2 MHz (Such zero-order Lamb wave modes exist over a range of frequencies and can transmit a significant amount of energy with low attenuation.), a waveguide strip plate surrounded

by an acoustical shielding tube, and an emission face for the ultrasonic beam. The waveguide sensor approach has been demonstrated by feasibility experiments in water. The 10 m long waveguide sensor has a resolution of approximately 2 mm.

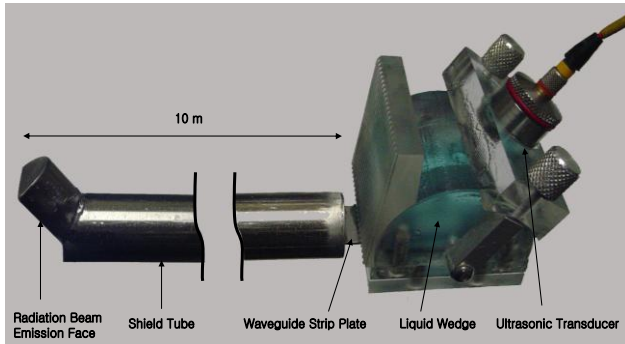


Figure 2: KAERI Waveguide Sensor Module.

CEA is developing an approach for inspection of in-vessel sodium components for dislocations or deformations using ultrasonic transducers strictly located outside of the reactor vessel.<sup>1</sup> The ultrasonic waves must thus propagate across several interfaces in traveling through the reactor vessel, potentially an intermediate structure, and finally the structure to be inspected. Initial development has focused upon a configuration involving three vertical steel walls for which two approaches have been investigated. The first employs ultrasonic waves at normal incidence using a single transducer and tuning the signal frequency and duration to promote constructive interference of the various reflected waves which is dependent upon the thicknesses and separation distances of the walls. The second approach utilizes oblique incidence and employs two transducers to take advantage of the existence of angular conditions for which transverse waves can have amplitudes exceeding those of longitudinal waves at normal incidence.

#### IV. LEAK-BEFORE-BREAK

KAERI is developing an evaluation approach for application of the leak-before-break principle to sodium piping and structures fabricated from Mod.9Cr-1Mo (G91) ferritic steel. To this end, KAERI has been performing creep-fatigue crack initiation and crack growth

tests, fatigue crack growth tests, and creep crack growth tests on Mod.9Cr-1Mo tubular specimens including defects. Fatigue crack growth rates have been obtained for temperatures of 500, 550, and 600°C and for load ratios of 0.1 and 0.3, and the information was contributed to the Project. Test data will be used to develop high temperature defect assessment procedures.

#### V. SUPERCRITICAL CO<sub>2</sub> BRAYTON CYCLE

ANL, SNL, JAEA, and KAERI have contributed results from ongoing work covering complementary facets of the development of the supercritical carbon dioxide (S-CO<sub>2</sub>) Brayton cycle for advanced energy conversion for SFRs. Test results have been contributed on the performance testing of small-scale diffusion-bonded heat exchangers representative of compact heat exchangers having cores similar to those envisioned for use as recuperators in the S-CO<sub>2</sub> cycle, testing of a small-scale S-CO<sub>2</sub> compressor, experiments on sodium-CO<sub>2</sub> interactions, and CO<sub>2</sub> corrosion and carburization tests.

ANL provided results from performance testing of a small-scale 17.5 KW nominal heat duty Printed Circuit Heat Exchanger<sup>TM</sup> (PCHE<sup>TM</sup>, Heatic Division of Meggitt (UK) Ltd.) for CO<sub>2</sub>-to-CO<sub>2</sub> heat exchange under prototypical low temperature recuperator (LTR) conditions of pressure, temperature, and scaled flowrate. The ANL S-CO<sub>2</sub> Heat Exchanger Testing Facility was modified from its earlier configuration for CO<sub>2</sub>-to-water heat exchange testing to a new configuration incorporating a low pressure S-CO<sub>2</sub> loop with electrical resistance heating and a separate high pressure S-CO<sub>2</sub> loop having a different flowrate with heat rejection to water. The two loops are thermally connected through the PCHE which has a core mocking up a portion of the core of a full-size LTR module. Data was obtained for sixty-three sets of steady state operating conditions for which heat exchange rates and pressure drops were determined. Friction factor and heat transfer correlations for zigzagged semicircular micro-channels<sup>2</sup> were tested against the data.



was also provided on the design and construction of a split flow S-CO<sub>2</sub> recompression loop incorporating the main compressor together with a second recompressing compressor.

JAEA and KAERI contributed results from sodium-CO<sub>2</sub> interaction tests. Chemical reaction tests were carried out at JAEA by contacting a small pool of sodium with overlying CO<sub>2</sub> gas.<sup>3</sup> Continuous reactions between sodium and CO<sub>2</sub> accompanied by flames occurred at temperatures higher than 570 to 580°C. This threshold exceeds the core outlet temperature in SFR designs. The main reaction products were determined to be Na<sub>2</sub>CO<sub>3</sub> and gaseous CO; the heat of reaction was measured as 50 to 75 KJ/mol of sodium. KAERI has constructed a new apparatus to investigate sodium-CO<sub>2</sub> interactions in both a sodium pool configuration with CO<sub>2</sub> above the sodium pool (*i.e.*, surface reaction tests) and a vertical cylindrical capsule in which CO<sub>2</sub> is injected near the bottom of a small column of sodium (CO<sub>2</sub> injection tests). Some tests were conducted in the pool configuration up to 600°C at 0.1 MPa exhibiting a reaction threshold temperature of 510°C above which the reaction occurs much more rapidly, similar to the threshold effect at 580°C in the JAEA tests. KAERI is analyzing the results to determine reaction rates.



Figure 6: KAERI Sodium-CO<sub>2</sub> Reaction Test Facility

CEA shall also perform sodium-CO<sub>2</sub> interaction tests in which a CO<sub>2</sub> jet is directly injected inside of a 2 Liter sodium pool in the DISCO<sub>2</sub> (Determination of Sodium-CO<sub>2</sub> Interactions) facility. Local temperatures will be measured with a movable comb of thermocouples (Figure 8). Results will be utilized in adjusting existing modeling for sodium-water reaction kinetics<sup>4</sup> for application to sodium-CO<sub>2</sub> reactions. Tests will begin during 2009 and shall be reported to the Project.

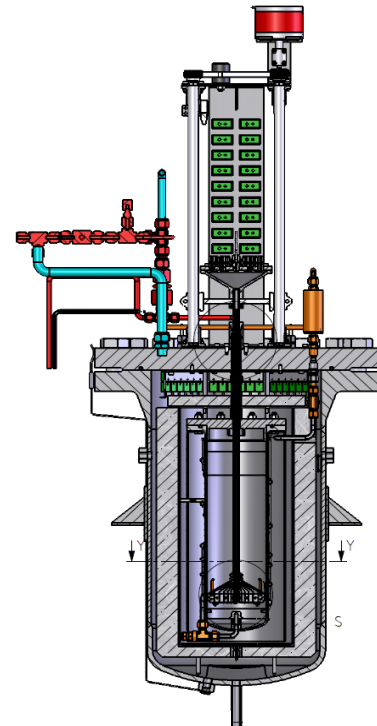


Figure 7: CEA DISCO<sub>2</sub> Sodium-CO<sub>2</sub> Interaction Facility.

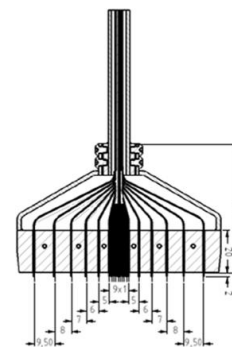


Figure 8: Comb of Thermocouples Inside of the DISCO<sub>2</sub> Vessel Moved by a Stepping Motor.

JAEA contributed data on CO<sub>2</sub> corrosion and carburization of 12 Cr martensitic steel and the Japanese fast reactor stainless steel, 316FR, in flowing CO<sub>2</sub> at 10 MPa. No breakaway phenomena were observed for either material in 5 000 hour tests which confirmed good corrosion resistance for the stainless steel material.

The corrosion of 12Cr steel versus time followed a parabolic curve. Similar tests are in progress at CEA.

ANL, JAEA, and KAERI contributed analyses of the behavior of SFRs incorporating S-CO<sub>2</sub> Brayton cycle power converters. The ANL Plant Dynamics Code for system level transient analysis of a SFR with a S-CO<sub>2</sub> Brayton cycle power converter was used to calculate the cycle behavior following a reactor scram in the 96 MWe (250 MWt) Advanced Burner Test Reactor (ABTR) SFR concept.<sup>5</sup> An interval of 400 seconds is required for the primary sodium coolant flow to transition to natural circulation following receipt of the scram signal resulting in tripping of the primary sodium pumps and disconnection of the generator from the electrical power grid. The S-CO<sub>2</sub> cycle is calculated to continue to remove heat from the reactor at a diminishing rate via the intermediate sodium circuit over the 400 seconds. Power continues to be generated in the turbine which spins the compressors which are installed on a common shaft while heat is rejected in the cooler. However, the cycle pressures and temperatures decrease during this time such that the minimum cycle pressure and temperature are calculated to fall below the critical values. The calculation shows that there is a window of 400 seconds for startup of the normal shutdown heat removal system incorporating a shutdown heat removal S-CO<sub>2</sub> pump and cooler. During this window, the S-CO<sub>2</sub> cycle continues to cool the reactor. CEA, ANL, and SNL have recently initiated a new collaboration under the Project which includes the creation of a postdoctoral position at CEA Cadarache involving work with the Plant Dynamics Code.

JAEA contributed a preliminary concept for a SFR with a S-CO<sub>2</sub> Brayton cycle power converter<sup>6</sup> in which the intermediate sodium

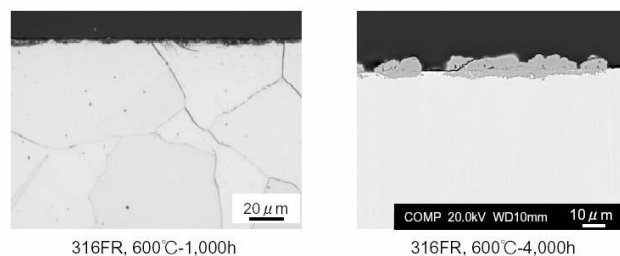


Figure 9: Micrographs from JAEA CO<sub>2</sub> Stainless Steel Oxidation and Carburization Tests.

circuit is eliminated.<sup>7</sup> The resulting plant efficiency is approximately 42% and the volume of the reactor building is reduced by 20% by adopting the S-CO<sub>2</sub> cycle and eliminating the intermediate sodium circuit. Both a helical coil tube sodium-to-CO<sub>2</sub> heat exchanger and a compact diffusion-bonded sodium-to-CO<sub>2</sub> heat exchanger were designed for the SFR. As part of the safety evaluation of a sodium-CO<sub>2</sub> reaction event, calculations were performed for a postulated double-ended guillotine rupture failure of one tube of the helical coil sodium-to-CO<sub>2</sub> heat exchanger installed in the primary sodium circuit.<sup>8</sup> The calculated maximum pressure in the primary sodium circuit resulting from the release of CO<sub>2</sub> is 0.28 MPa which does not threaten the primary circuit structural integrity. A voiding reactivity due to gas in the core is calculated to reach 0.046 \$ which has no significant effect upon core safety.

KAERI has developed the STASCOR computer code modeling the chemical reactions between sodium and CO<sub>2</sub> in a flowing sodium circuit. The long-term behavior following a postulated tube rupture was evaluated for a shell-and-tube type sodium-to-CO<sub>2</sub> heat exchanger in the KALIMER-600 design.

## VI. CONCLUSION

The SFR Component Design and Balance of Plant Project is facilitating the fruitful exchange of information and establishment of collaborations mutually beneficial to all participants. The lessons learned during upgrading of PHÉNIX and JOYO are of great significance and benefit all members of the Project. The research and development of in-

service inspection approaches is following three parallel paths each of which is highly innovative in its own right. Significant improvements or breakthroughs in the ability to perform in-service inspection of in-vessel sodium components may result from this ongoing work. Data needed for the evaluation of leak-before-break for Mod.9Cr-1Mo ferritic steel sodium piping and components is systematically being generated. Finally, the Project is making highly significant contributions

to the development and demonstration of S-CO<sub>2</sub> Brayton cycle advanced energy conversion spanning the development and performance testing of compact heat exchangers, development and testing of small-scale S-CO<sub>2</sub> turbomachinery and a complete integrated cycle, sodium-CO<sub>2</sub> interaction testing, CO<sub>2</sub> oxidation and carburization tests, as well as the analysis of system behavior for SFRs incorporating S-CO<sub>2</sub> Brayton cycle power converters.

### Acknowledgements

The reported work represents the efforts of over sixty individuals at CEA Cadarache, CEA Marcoule, LCND Laboratory (Aix en Provence), ANL, Kansas State University, SNL, JAEA, Tokyo Institute of Technology, Mitsubishi Heavy Industries, and KAERI.

### References

1. Baque, F., C. Lhuillier, G. Gobillot, P. Brau, M.A. Ploix and J.M. Augem, "Ultrasonic Techniques for Improving Inspection of Sodium Cooled Systems," Paper 80, *Proceedings of ANIMMA '09*, Marseille, France, June 7-10, 2009.
2. Southall, D., R. Le Pierres and S.J. Dewson, "Design Considerations for Compact Heat Exchangers," Paper 8009, *Proceedings of ICAPP '08*, Anaheim, California, June 8-12, 2008.
3. Ishikawa, H., S. Miyahara and Y. Yoshizawa, "Experimental Study of Sodium-Carbon Dioxide Reaction," *Proceedings of ICAPP '05*, Seoul, Korea, May 15-19, 2005.
4. Gicquel, L., P. Hobbes, A. Saboni, N. Simon and C. Latge, "Modeling of Supercritical Carbon Dioxide Jets in Liquid Sodium," *Proceedings of SFGP '09*, Marseille, France, October 14-16, 2009.
5. Sienicki, J.J., A. Moiseyev, D.H. Cho, Y. Momozaki, D.J. Kilsdonk, R. Haglund, C.B. Reed and M.T. Farmer, "Supercritical Carbon Dioxide Brayton Cycle Energy Conversion for Sodium-Cooled Fast Reactors/Advanced Burner Reactors," *GLOBAL 2007, Advanced Nuclear Fuel Cycles and Systems*, Boise, Idaho, September 9-13, 2007.
6. Muto, Y. and Y. Kato, "Design of Turbomachinery for the Supercritical CO<sub>2</sub> Gas Turbine Fast Reactor," *Proceedings of ICAPP '06*, Reno, Nevada, June 4-8, 2006.
7. Mito, M., N. Yoshioka, Y. Ohkubo, N. Tsuzuki, and Y. Kato, "Fast Reactor with Indirect Cycle System of Supercritical CO<sub>2</sub> Gas Turbine Plant," *Proceedings of ICAPP '06*, Reno, Nevada, June 4-8, 2006.
8. Ohyama, K., M. Kishida, M. Mito, N. Yoshioka, and Y. Kato, "Design Study of CO<sub>2</sub>-Na Reaction Events of Super-critical CO<sub>2</sub> Indirect Cycle Gas Turbine Fast Reactor," *Proceedings of ICAPP '07*, Nice Acropolis, Nice, France, May 13-18, 2007.

