INL/EXT-05-00307

FY-05 Second Quarter Report On Development Of A Supercritical Carbon Dioxide Brayton Cycle: Improving PBR Efficiency And Testing Material Compatibility

NERI Quarterly Progress Report

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NERI QUARTERLY PROGRESS REPORT

Project Title: Development of a Supercritical Carbon Dioxide Brayton Cycle: Improving PBR Efficiency and Testing Material Compatibility

Covering Period: January 1, 2004 through March 31, 2004 (2nd quarter report, 2005)

Date of Report: April 30, 2005

Recipient: Kenny Osborne, DOE-ID

Award Number: M2SF 02-0190

Project Number: 02-190

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Project Objective: The objective of this research is to improve a helium Brayton cycle and to develop a supercritical carbon dioxide Brayton cycle for the Pebble Bed Reactor (PBR) that can also be applied to the Fast Gas-Cooled Reactor (FGR) and the Very-High-Temperature Gas-Cooled Reactor (VHTR). The proposed supercritical carbon dioxide Brayton cycle will be used to improve the PBR, FGR, and VHTR net plant efficiency. Another objective of this research is to test materials to be used in the power conversion side at supercritical carbon dioxide conditions. Generally, the optimized Brayton cycle and balance of plant (BOP) to be developed from this study can be applied to Generation-IV reactor concepts. Particularly, we are interested in VHTR because it has a good chance of being built in the near future.

Background: The VHTR configuration is very important along with the choice of the working fluid. We started investigating a number of various VHTR configuration particularly in the power conversion unit. This will be our main focus for the year 3 activities. In conjunction with this main focus, our study will include the combined cycle, cycle with multiple reheat option, the recompression cycle, and others.

Highlights of the **second quarter activities of FY-05** are summarized below:

- The improvement of the cyccle efficiency was investigated using a number of different configurations: Combined cycle, reheat cycle, and other cycles. The configuration includes the hydrogen-generating plant for the cycle efficiency. Preliminary results indicate that the use of CO_2 in the combined cycle results in the smaller size of intermediate heat exchanger and turbomachinery, which is the advantage over helium, but the system pressure is higher than that of helium.

- From the aforementioned study, the use of CO_2 Brayton cycle for the reheat configuration gives 59% cycle efficiency. The detailed calculations are being performed.

- The paper entitled “Brayton Cycle for High-temperature Gas-Cooled Reactors”, was published in *Nuclear Technology*, Vol. 149, March 2005. A per entitled “Power Conversion Study for High Temperature Gas-Cooled Reactors”, was accepted for presentation at ICAPP-05, which will be held in Seoul, Korea.

- Final, coarse-grained MA 754 CO_2 corrosion test begun and is projected to run for 500 hours.

- A second long-term supercritical CO_2 testing system has been constructed and will enable simultaneous testing of multiple materials at 1000^{o}C for exposure times up to 5000 hours.

- The manuscript, entitled “Elevated Temperature Strength of Fine-Grained INCONEL Alloy MA754”, was accepted for publication by Metallurgical Transactions, A, and highlights the results of mechanical property testing of fine-grained MA 754.

Status:

Task 1. Development of CO_2 Brayton Cycle

Tasks 1-1, 1-2, 1-3, 1-4, and 1-5 were completed in the second and the third quarter of FY-03.

Task 2. Improvement of HTGR Net Efficiency

The objective of this task is to improve the overall plant cycle efficiency by the combination of increasing the efficiency of each component in the secondary side of the HTGR. To accomplish this task, we performed a number of HYSYS simulation to investigate a number of different cycle configurations: combined cycle and reheat cycle. In this report, results from the combined cycle are included.

- **Combined cycle**

The cycle configuration is shown in Figure 1.

This indirect configuration is a Brayton cycle and a Rankine cycle.

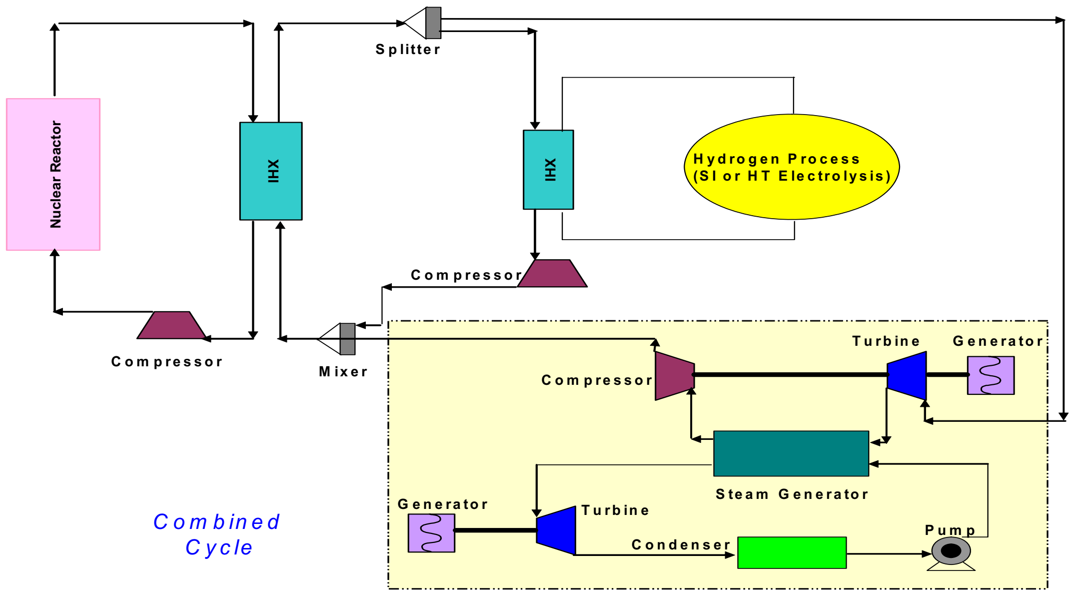

Figure 1. The combined cycle.

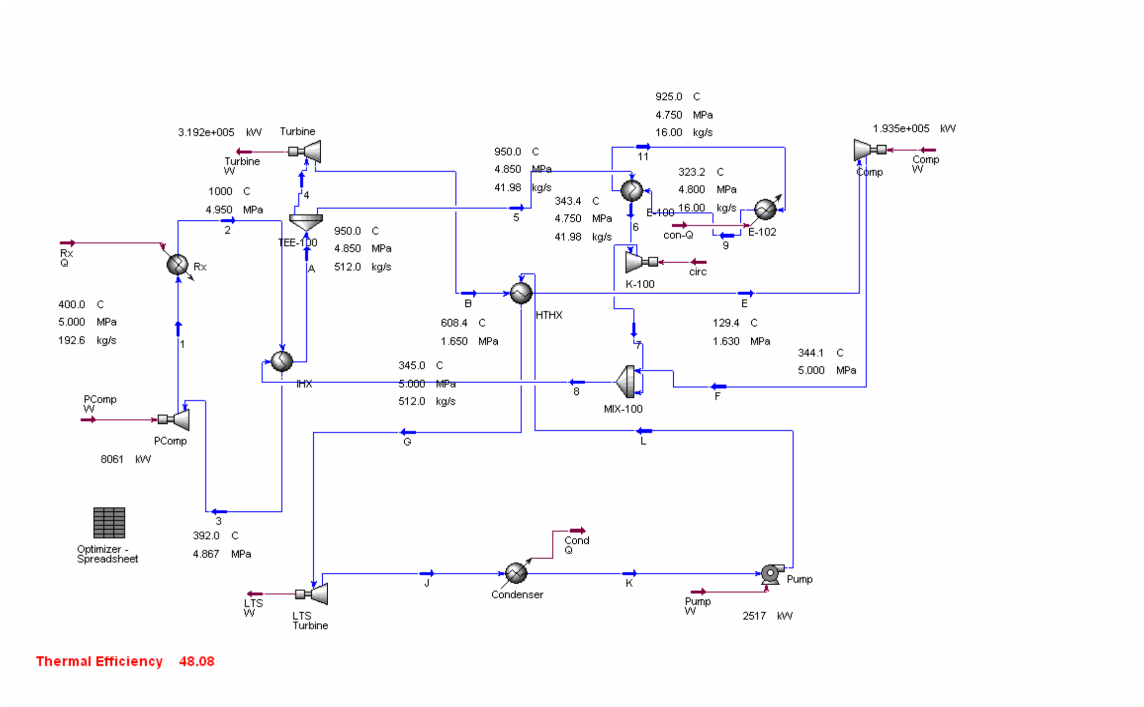

Figure 2. Snapshot of HYSYS model of the combined cycle with N_2/He.

This configuration was developed by Framatome (Copsy et. al, 2004). Heat from the reactor (600 MWt) is transferred to a power conversion unit in which the heat transfer fluid is a binary mixture of nitrogen (80% by wt.) and helium (20% by weight). The majority of fluid is 0.636 mole fraction of helium vs. 0.364 mole fraction of nitrogen. This indirect cycle design facilitates an improvement of the cycle efficiency using a Rankine bottoming cycle. The key difference of this concept is the reduction of the reactor inlet temperature and lower pressures compared with that of GT-MHR and others. With reduced inlet temperature, the flow rate and circulator power is lower and lower pressures results in less stress problems in material and reduce wall thickness of reactor and other units in the system.

INL developed a combined cycle using CO_2 as the working fluid in the Brayton cycle rather than N_2/He proposed by Framatome. All the operating conditions are considered to be INL's intellectual properties. Table 1 shows the main differences between Framatome's N_2/He cycle and CO2 cycle developed by INL. For these calculations, hydrogen generation process was included in both configurations. In terms of the overall cycle efficiency, the efficiency is nearly the same (48%) for both configurations. The main advantage of the CO_2 cycle over the N_2/He cycle is that CO_2 cycle reduces the size of the intermediate heat exchanger, turbines, and compressors due to the reduced volumetric flow of CO_2 compared to N_2/helium.

Table 1. Comparison of the combined N_2/He and combined with CO_2 cycle.

	Combined Cycle with N_2/Helium in Brayton Cycle	**Combined Cycle with CO_2 in Brayton Cycle**
Reactor Power	600 MW-thermal	600 MW-thermal
Configuration	Indirect	Indirect
Fluid in the reactor	Helium	Helium
Fluid in Brayton Cycle	N_2/He	CO_2
Reactor Inlet	400°C	400°C
	5 MPa	5 MPa
Reactor Outlet	1000°C	1000°C
	4.95 MPa	4.95 MPa
IHX Outlet	392°C	392°C
	4.867 MPa	4.867MPa
Turbine Inlet	1000°C	1000°C
	4.95 MPa	11 MPa
Compressor Inlet	129.4°C	119.6°C
	1.63 MPa	1.63 MPa
Hot Pinch temperature	285.5C	305.9
Cold Pinch Temperature	283.1 C	282.8 C
UA *	8.61e7 kJ/C-hr	3.03e7 kJ/C-hr
Std. Vol. Flow	4800 m^3/h	3489 m^3/h
Cycle Efficiency	48 %	48 %

UA is the universal heat transfer coefficient and A is the heat transfer area.

- **Reheat cycle**

This configuration is shown in Figure 3.

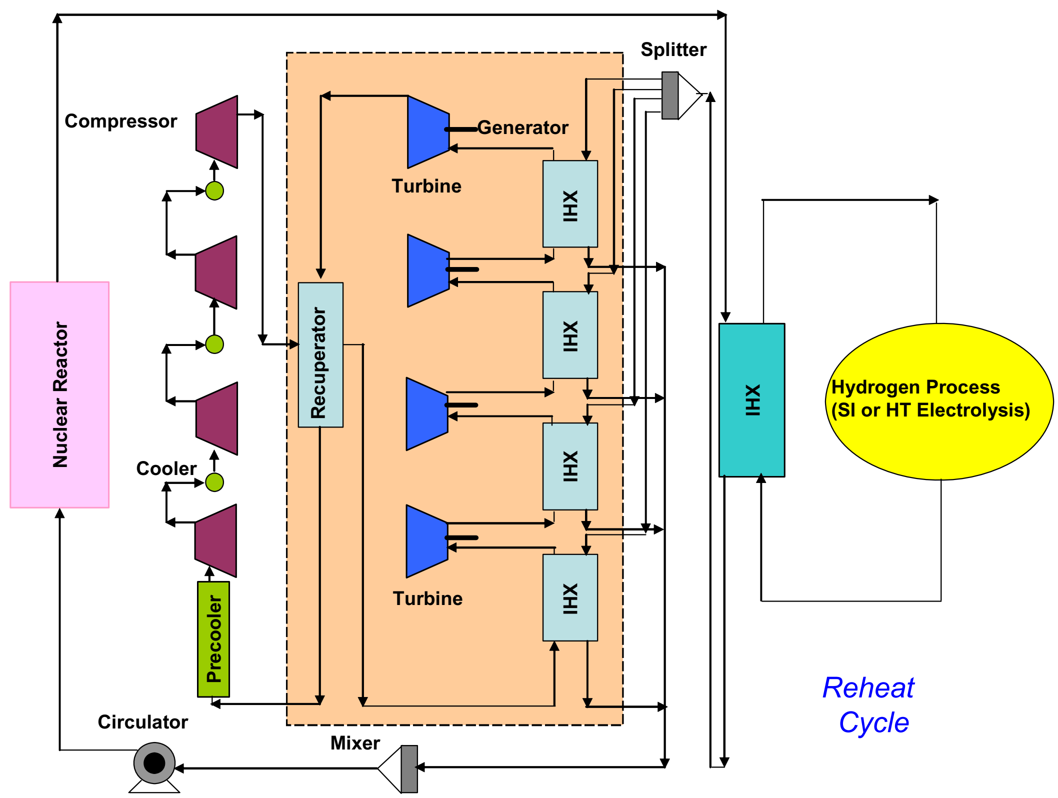

Figure 3. Reheat Cycle with CO_2 fluid in the power conversion unit.

The idea of this configuration (Ingersoll et. al, 2004) is to enhance the cycle efficiency by increasing the inlet temperatures to the turbines by using four intermediate heat exchangers. This configuration consists of the primary loop with an intermediate heat exchanger that couples the hydrogen-generating plant. The heat transfer media of the primary loop is helium and CO_2 was used in the power conversion unit. The reactor power is 600 MW thermal and the energy to the turbomachinery is transferred to four turbines and compressors. The preliminary calculations indicate that the cycle efficiency is approximately 59%. The detailed calculations are being performed. From the detailed study, the pros and cons of this configuration compared with others will be discussed.

References:

Copsey, B. et. al., “The Framatome ANP Indirect- Cycle very High Temperature Reactor”, Proceedings of ICAPP’04, Pittsburgh, PA, June 13-17, 2004.

Ingersoll, D et. al., “Status of Preconceptual design of the Advanced High-Temperature Reactor”, ORNL/TM-2004/104, May, 2004.

Plans for Next

We plan to explore further the Brayton cycle improvement using various power conversion configurations. The baseline cases will be established with helium and eventually with high pressure CO_2 system for comparison.

There are no concerns and no issues.

Status:

Task 3. Material Compatibility

Testing efforts have been somewhat hampered by the need to move the supercritical CO_2 testing system to a new location to accommodate equipment for other programs. During this move the system was dismantled and numerous improvements were made to make the system more reliable and allow for longer exposure times. Modifications to the safety documentation indicating the new location was submitted and approved. Testing will resume 04-25-05.

Task 3-2-2 Corrosion Testing of MA 754 in Supercritical CO_2

Approximately 350 hours of a long-term (500 hour) test has been completed. This is the last coarse-grained sample to be tested at 1000 ºC and 1500 psi. Currently, no indications of sample degradation have been observed (i.e. leaks, system de-pressurization, or visual observations). After completing the 500 hour test the sample will be sectioned, analyzed, and compared to the previous coarse-grained test samples exposed for shorter periods of time. The corrosion testing is expected to be completed early in the third quarter.

Task 3-2-3

Fine-grained test samples have been machined and are ready for testing under similar conditions as the coarse samples. Test times will be approximately 100, 250, and 500 hours for these three samples. Analysis results will be compared to the coarse grained samples. Testing will commence as soon as the last large-grained MA 754 corrosion test has been completed (Task 3-2-2).

Task 3-3 Corrosion behavior of I-617 in supercritical CO_2

A new CO_2 test loop is being constructed to allow long-term testing of I-617 to be performed (up to 5000 hours) at 1000 ºC and 1000 psi. This is an improved test loop system that can test multiple samples simultaneously instead of a single, large hollow tube. Multiple ~ 6-mm diameter x 25-mm long samples will be contained within long, thick-walled stainless steel tubes inside a horizontal furnace. A large test sample matrix from the multiple samples can then be generated. In addition, up to 6 different thick-walled tubes can be run simultaneously allowing samples from different materials to be tested within each tube, respectively. Safety considerations require the operating pressure to be reduced to 1000 psi to eliminate the possibility of creep rupture in the stainless tubes. Based upon previous results and experience this lower pressure should not significantly affect the response of the samples during testing.

The required components have been procured and testing will begin as soon as the system is assembled, approximately 4 weeks.

Plans for Next

- Complete corrosion testing of coarse-grained MA 754 and compose a manuscript for a peer-reviewed journal reporting the results. Task 3-2-2.
- Begin corrosion testing fine-grained MA 754. Task 3-2-3
- Begin corrosion testing of I-617. Task 3-3-1

Project Milestones
The project milestones are shown below:

Milestone/Deliverable Description	Planned Completion	Actual Completion
1. Development of CO2 Brayton Cycle	30 June 2003	Completed
1-1 Development of the efficiency equation of turbine and compressor for the real gas	31 March 2003	Completed
1-2 Check of supercritical CO2 properties with equation of state	31 March 2003	Completed
1-3 Selection of the optimization computer code	31 March 2003	Completed
1-4 Layout of CO2 thermal cycle and initial calculations	31 March 2003	Completed
1-5 Perform baseline calculations	30 June 2003	Completed
2. Improvement of Brayton cycle efficiency	30 September 2005	Starts in the 4th quarter of FY-03
2-1. Enhancement of each component's efficiency	31 March 2004	Starts in the 4th quarter of FY-03
2-2. Optimization of PBR schematic	30 September 2005	Starts in the 2nd quarter of FY-04
2-2-1 Develop PBR optimization model	30 September 2005	Starts in the 2nd quarter of FY-04
2-2-2 Efficiency and cost comparison calculations	30 September 2005	Starts in the 2nd quarter of FY-04
3. Material testing	30 September 2005	In progress
3-1 Characterization of creep deformation of MA 754	30 September 2004	Completed
3-1-1 Characterization of initial microstructure	30 June 2003	Completed

3-1-2 High temperature mechanical and creep properties of MA 754	31 December 2003	Completed
3-1-3 Mechanical and creep properties fine-grained MA 754	31 August 2004	Completed
3-2 Thermogravimetric analyses	30 April 2005	In progress
3-2-1 Design and construction of supercritical CO2 test loop	30 June 2003	Completed
3-2-2 Corrosion testing of MA 754 in supercritical CO2	30 April 2005	In progress
3-3 Corrosion behavior of I-617 in supercritical CO_2	31 August 2005	Starts 2nd quarter of FY05
3-3-1 – Corrosion rate determination	31 August 2005	
3-3-2 – Composition of Corrosion products	31 August 2005	
3-4 Final report on corrosion behavior of MA 754 and I-617 in supercritical CO_2	30 September 2005	Starts 4th quarter of FY05