Appendix 8.0

Energy Conversion

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CONTENTS

FIGURES

TABLES

ACRONYMS

ANL	Argonne National Laboratory
CO_2	carbon dioxide
FY	fiscal year
GIF	Generation IV International Forum
GFR	Gas-Cooled Fast Reactor
kWe	kilowatt electric
LFR	Lead-Cooled Fast Reactor
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
MW	megawatt
MWe	megawatt electric
MWt	megawatt thermal
NGNP	Next Generation Nuclear Plant
PCS	power conversion system
R&D	research and development
S-CO_2	supercritical carbon dioxide
SFR	Sodium-Cooled Fast Reactor
SNL	Sandia National Laboratories

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A8.1 INTRODUCTION AND BACKGROUND

A8.1.1 Energy Conversion Crosscut Description

Generation IV Energy Conversion research and development (R&D) is investigating advanced power conversion systems (PCSs) which have the potential for higher conversion efficiency, or lower capital costs. Energy conversion technologies that optimize the use of the thermal output of advanced reactors will result in more cost effective nuclear electricity, the most important single metric for determining Generation IV system viability. The Generation IV Energy Conversion Program is evaluating options for higher efficiency and lower capital costs to compare the cost benefit of the various approaches.

Generation IV reactors encompass a wide range of thermal output conditions. The current emphasis is on PCSs for two high-priority Generation IV reactor types:

- Metal-cooled or intermediate temperature reactor systems with outlet temperatures in the range of 500 to 700°C. These systems include the Sodium-Cooled Fast Reactor (SFR), Lead-Cooled Fast Reactor (LFR), and Gas-Cooled Fast Reactor (GFR)
- Very-high-temperature reactor systems (i.e., the Next Generation Nuclear Plant [NGNP]) with an inert gas coolant at outlet temperatures up to 950°C.

For these higher output temperatures, closed Brayton cycles using either inert or carbon dioxide working fluids are considered the most promising power conversion approaches. Brayton cycle PCSs have the capability to operate at much higher temperatures than current Rankine cycles, and are relatively compact, with the potential for lower capital costs.

A8.1.1.1 Brayton Cycle Power Conversion Systems

Current Light-Water Reactor (LWR) power plants use steam Rankine cycles for electrical generation with net efficiencies of about 33%. The steam Rankine cycle is an efficient option for LWR outlet temperatures in the 300 to 350°C range. Supercritical Rankine cycles, which are in use in some coal-fired plants, extend the applicable temperature range, but materials issues become significant above 500°C. Brayton cycles (gas turbine) using inert gas or other working fluids are well matched to the higher temperatures of the Generation IV reactors. Extensive technology development for both open-cycle turbomachinery and the Brayton-Rankine combined-cycle gas turbines in the commercial sector provides a technology basis for developing closed-cycle Brayton systems for Generation IV. Other advanced power conversion technology options such as Stirling cycles and advanced direct conversion approaches (magneto-hydrodynamics, thermal-photovoltaics) are considered longer-term options. For the intermediate and higher temperature ranges applicable to most Generation IV systems, Generation IV research efforts are focusing on Brayton cycles using inert or carbon dioxide working fluids.

A8.1.1.2 Supercritical Carbon Dioxide Cycle Development

Based on the current Generation IV priorities, Energy Conversion R&D is focusing on the development of Brayton cycles for the metal-cooled, intermediate-temperature reactor systems. Previous Generation IV studies have identified the supercritical carbon dioxide (S-CO_2) split flow Brayton cycle as the highest priority due to the potential for high system efficiency in the range of 500 to 700°C, and the potential for reduced capital cost. The S-CO_2 Brayton cycle provides high efficiency with relatively little increase in complexity. Energy Conversion R&D for the next ten-year period will focus on establishing the viability and performance of this cycle for metal-cooled reactors.

A8.1.1.3 High-Temperature Helium Brayton Cycle Development

Previous Generation IV studies also examined conversion options for the NGNP to optimize efficiency and understand cost/efficiency trade offs. These studies were directed at providing a basis to evaluate future PCS design or support procurement decisions for high-temperature Helium Brayton cycles at temperatures up to 950°C. Under the current funding assumptions for FY 2007 and FY 2008, there will be no further examination of the He Brayton cycle options for NGNP, since these studies are part of the Industry design studies underway for NGNP. Generation IV analytical studies will be performed in the future if required to support power conversion assessments for NGNP.

A8.1.1.4 Overall System Timeline Supercritical Carbon Dioxide Cycle Development

The S-CO_2 cycle is applicable to several current Generation IV concepts, including the SFR and LFR reactors. The development timeline for the S-CO_2 cycle will be timed to support reactor technology selection timelines. The development of the S-CO_2 cycle will be carried out through a series of component and small scale PCS experiments to validate models and address key technology issues. The objective is to provide information on the cost and performance of S-CO_2 Brayton cycles to support technology selection decisions, including selection of the reactor technology for transmutation and sustainable nuclear energy. To provide the necessary power conversion cost and performance information needed, the R&D effort will proceed in the following general sequence:

2006–2007

- Power conversion cycle analyses and conceptual designs will be performed to address viability issues and estimate costs and performance potential for S-CO2 Brayton cycles.

2008–2010

- Laboratory scale demonstrations of key system components and small-scale PCSs to demonstrate key technologies and validate performance potential.

2011–2016

- Construction and demonstration of pilot scale systems to confirm engineering approach and performance, and support commercialization cost estimates.

This sequence of power cycle analyses and small-scale component and system experiments will address key technology issues and uncertainties, and provide the basis for validated models to support the design of pilot scale experiments for selected systems. The pilot scale experiments will demonstrate engineering approaches, confirm performance potential, and refine estimates of PCS costs.

A8.2 RESEARCH AND DEVELOPMENT STRATEGY

A8.2.1 Objectives

The primary objective of Energy Conversion R&D will be the development and demonstration of the S-CO_2 cycle, and confirmation of performance and cost to support the development of metal cooled fast reactor systems.

A8.2.2 Scope

A8.2.2.1 Supercritical Carbon Dioxide Cycle Development

The scope of research activities for the S-CO_2 cycle for the FY 2007 to FY 2016 time-period addresses the key technology and demonstration issues for the S-CO_2 cycle. These studies will address S-CO_2 turbomachinery design, main compressor operation near the critical point of CO_2, control strategies for the split flow cycle, and materials compatibility issues for the S-CO_2 system. S-CO_2 plant layout and conceptual designs will provide a basis for system economic estimates. These studies establish a baseline S-CO_2 system design, and resolve materials and systems technology issues. Ultimately, scaling experiments will be performed to demonstrate key technologies and system performance. These studies will move forward at a rate consistent with available resources and will include the following elements:

1. S-CO_2 PCS design studies for full scale power systems for next generation reactors to define system requirements and key issues
2. Analytical studies of key cycle technology issues—turbine, compressor and heat exchanger designs, and operation of the main compressor near the critical point of carbon dioxide (CO_2), and bearing and sealing technology options for S-CO_2 turbomachinery
3. Development of modeling and simulation tools to investigate control strategies and stability issues for the split flow cycle
4. Design studies for scaled S-CO_2 component and systems to allow small-scale experimental demonstration of key technologies—compression near the critical point, materials, system stability and control strategy evaluation
5. Construction and operation of small-scale experiments for experimental evaluation of compressor operation, recuperators, and a full small-scale S-CO_2 system to evaluate control and operational strategies (~ 1 MW)
6. Construction and operation of a pilot-scale S-CO_2 PCS to confirm performance and costs (~10's MW).

A8.2.3 Viability Issues

Brayton cycle systems and the sophisticated turbomachinery technology involved have been extensively developed for many commercial applications. Although no supercritical CO_2 systems have been built and tested, the development of the split-flow S-CO_2 cycle is enabled by the extensive technology base that has been established in gas turbine development for the aircraft, aerospace and combined cycle power industry. However, the high pressures (~20 bar) and unique compression and control issues involved in the S-CO_2 cycle also introduce new technology issues that must be addressed in the research program. The primary viability issues for S-CO_2 cycle development include:

- Design and operation of the turbine and compressors, particularly the main S-CO_2 compressor (which operates near the critical point of the CO_2 working fluid)
- Control algorithms and transient and off-normal S-CO_2 split flow cycle operation (applicability of inventory and bypass controls, and design and demonstration of key technologies)
- Materials issues associated with high temperature CO_2 and materials of construction
- Development and construction of small-scale, cost-effective, experimental approaches to validation of key technologies for S-CO_2.

A8.2.4 Research Interfaces

Energy Conversion research activities primarily involve U.S. national laboratories and universities. However, there has been increasing participation through contracts with industry addressing heat exchanger and turbomachinery design and fabrication issues. It is also expected that there will be greater involvement by other Department of Energy Offices (Energy Efficiency and Renewable Energy, Fossil Energy, Naval Reactors) in these activities in the future.

A8.2.4.1 Relationship to Generation IV International Forum Research and Development Projects

Although there is no specific Generation IV International Forum (GIF) R&D activity focused on electrical power conversion at this stage, Energy Conversion research activities support the GIF advanced nuclear reactor technology assessment.

A8.2.4.2 University Collaborations

The university research community is involved in the design and analysis of the S-CO_2 system through both direct support contracts and Nuclear Energy Research Initiative projects.

A8.2.4.3 Industry Interactions

It is anticipated that industry involvement will continue to increase as engineering analyses and lab scale experiments progress. Industry participation will be essential to provide input on the viability and fabrication issues associated with the S-CO_2 system.

A8.2.4.4 International Nuclear Energy Research Initiative

Although there are currently no International Nuclear Energy Research Initiative interactions on power conversion, it is anticipated that collaborative research activities will be identified for the S-CO_2 cycle development, which is of interest for all of the metal-cooled concepts. The possibility of collaboration with other interested countries (Japan and France) is being pursued.

A8.3 HIGHLIGHTS OF ENERGY CONVERSION RESEARCH AND DEVELOPMENT

Energy Conversion research activities for FY 2006 included studies on He Brayton cycles for high temperature gas cooled reactors, S-CO_2 cycles for SFR, LFR and GFR and intermediate loop heat transport. These activities were funded through the Energy Conversion Crosscut in FY 2006. The Generation IV power conversion studies for FY 2007 will focus only on the S-CO_2 cycle development for the intermediate temperature Generation IV reactors. The technical work packages for this S-CO_2 development will be funded through the SFR system integration task. The FY 2007 Energy Conversion Crosscut work package will cover only the National Technical Director coordination functions.

FY 2007 activities focus on the development of the S-CO_2 cycle for intermediate temperature reactors (500 to 700°C) due to the potential for very high efficiency and very compact turbomachinery. Work at Massachusetts Institute of Technology (MIT) has developed preliminary turbine and compressor designs for S-CO_2 systems based on National Aeronautics and Space Administration design codes adapted for S-CO_2 working fluid properties. Designs for 300 MWe turbines and compressors have been developed that are very compact (approximately 0.8 meters in diameter) and are also very efficient (~90%). A particularly unique requirement is the operation of the main compressor near the critical point of CO_2. Recent industry review studies have suggested radial compressors or mixed radial-axial stages for this application. Investigation of radial units for S-CO_2 compressors will be a priority for FY 2007. The initial assessment is that these components will require significant design efforts to accommodate the CO_2 working fluid conditions, but that these designs are feasible based on adaptations of current technology. The four major tasks for FY 2007 are:

1. **S-CO_2 Conceptual Design Studies.** These analytic studies will define system configurations, performance potential, and interface issues. They will also provide the basis for cost benefit estimates of S-CO_2 systems in comparison with alternative cycles.
2. **S-CO_2 System Control Studies**. This task area will evaluate system dynamic response for various control approaches for the split flow cycle.
3. **S-CO_2 Supercritical Compression Studies**. This task area will develop small scale experiment designs to provide data to evaluate turbomachinery operation near the critical point of CO_2 as well as evaluate control and stability implications.
4. **Small Scale S-CO_2 Brayton System Development**. This task area is developing a small scale S-CO_2 system to provide a data base for demonstration of key control and stability issues and validation of models. The construction of this nominal 1 MW system will begin in FY 2007, and be completed in stages to address key issues as early as possible and accommodate funding profiles. A fully recuperated, split flow system at the MW level is planned for completion in the FY 2009 or FY 2010 time frame – depending on resources.

A8.3.1 Supercritical Carbon Dioxide Conceptual Design Status

Conceptual designs for a 300 MWe S-CO_2 plant have been developed as a basis for preliminary cost and configuration evaluations. These system designs address the heat transfer issues associated with the lower thermal conductivity of CO_2, and the compact turbomachinery, resulting in relatively compact designs for S-CO_2 in comparison with similar sized conventional or supercritical Rankine steam systems. Preliminary cost estimates, which will be revised as the design matures, indicate as much as a 20% reduction in the cost of an S-CO_2 plant in comparison with a similar sized supercritical steam system coupled to a high-temperature gas reactor. Recent studies have examined the potential for higher power S-CO_2 systems to accommodate higher output reactors. A 1200 MWe concept was developed based on two 600 MWe S-CO_2 modules. The higher output modules require manifolding of multiple ducts to maintain duct sizes within the limits of current practice. The key remaining issues requiring further analysis and experimental demonstration are associated with the main compressor, which operates very near the critical point of CO_2, and the related issue of overall system control strategy with the split flow two-compressor configuration. These issues are currently being addressed in analytic studies, but will ultimately require experimental validation in scaled S-CO_2 system or component tests. This experiment must be of sufficient scale to credibly investigate the key technologies, but be achievable within research funding constraints.

A8.3.2 Supercritical Carbon Dioxide System Control Studies

Evaluation of the dynamic response of the S-CO_2 cycle is a key issue for system viability. Work has been initiated at Argonne National Laboratory (ANL) to investigate control strategies for this cycle, and work is underway at both ANL and MIT to develop improved models for simulating the dynamic response of these systems. Sandia National Laboratories (SNL) has developed a closed Brayton cycle unit (30 kWe) that provides the capability to experimentally simulate inventory and bypass configuration strategies to validate models being developed at ANL, MIT and SNL. These experiments cover a range of working fluids, including CO_2. The capability to perform supercritical compression studies will be completed in FY 2008. Based on earlier turbomachinery studies, the main compressor is now planned to be a radial compressor as it will allow a wider range of operational conditions which will also provide greater flexibility in control system strategies.

Initial work to investigate control strategies for the S-CO_2 Brayton cycle is based on models developed for an S-CO_2 cycle coupled to an autonomous load-following 400 MWt (181 MWe) LFR. The goal of power cycle control is to adjust the cycle conditions such that in steady state, heat removal from the reactor matches the load demand from the electric grid. There are several approaches to decreasing the generator power which involve either reducing the power produced by the turbine, increasing the power consumed by the compressors, or decreasing the heat addition to the cycle. Initial studies examined several possible approaches. In-reactor heat exchanger bypass will allow only part of the flow to go to the heat exchanger, thereby decreasing the heat removal rate. A turbine inlet throttle valve introduces a pressure drop before the turbine, reducing the pressure ratio available for the turbine. Turbine bypass provides a bypass flow to the turbine, increasing the flow rate through the compressors. Compression work increases relative to the expansion work. Inventory control removes some portion of the CO_2 mass from the cycle, reducing pressure and S-CO_2 mass flow rates. Flow split control adjusts the CO_2 flow split between the compressors, which could be used in conjunction with other strategies.

Improved dynamic response models are also being developed. The Gas-Pass dynamic simulation and control code for gas reactor systems has been significantly updated and improved by MIT and ANL. The significant changes include updating the FORTRAN-90 code and incorporating accurate working fluid properties as functions of temperature to account for the non-linear behavior of CO_2 near the critical point. Current modification efforts are incorporating accurate turbomachinery off-normal performance models to prepare for detailed S-CO_2 dynamic system studies. These modifications to Gas-Pass will allow accurate representation of complex real fluid phenomena experienced in the S-CO_2 PCS.

These control mechanisms are effective over some range of operational conditions determined by factors such as the working range for each compressor, compressor stalling and choking conditions, choking conditions in the turbine, or inventory tank volume (for inventory control). These initial studies indicated that turbine bypass control was useful for small, fast changes (within 10% of nominal load), where inventory control may not be fast enough. Inventory control was estimated to be useful over a range of 50 to 90% load. Current calculations suggest that none of the remaining control strategies are capable of controlling the cycle at less than 50% load. Flow split control was considered to be useful in combination with other controls to extend their range. The use of radial compressors is expected to provide additional flexibility in control strategies. Analysis of S-CO_2 control strategies will continue to be a priority for FY 2007.

A8.3.3 Supercritical Carbon Dioxide Compression Studies

S-CO_2 compression studies are being performed to identify small scale experiment designs to provide data to evaluate turbomachinery operation near the critical point of CO_2. Based on FY 2006 industry design input, radial compressors offer a wider operational range for the main compressor, with only a small efficiency penalty in comparison with the more efficient axial compressors. To evaluate the operational characteristics of compression near the critical point of CO_2 and the implications for S-CO_2 system performance and control, the Energy Conversion Program will design and construct a small scale S-CO_2 compressor unit to provide data over the range of system conditions. The main compressor unit will also be the first stage of the small scale S-CO_2 Brayton unit. Construction will begin in FY 2007 with the initial experiments planned in mid FY 2008.

A8.3.4 Small Scale Supercritical Carbon Dioxide System Development Status

The Generation IV Energy Conversion Program is developing a small scale S-CO_2 system to provide a database for demonstration of key technology issues and validation of models. The construction of this nominal 1 MW system will begin in FY 2007 with the construction of the main compressor unit. The recuperated split flow Brayton system will be completed in stages to address key issues as early as possible and accommodate funding profiles. The fully recuperated, split flow system at the MW level is planned for completion in the FY 2009 or FY 2010 time frame – depending on resources.

A8.4 PROJECT COST AND SCHEDULE

A8.4.1 Fiscal Year 2007 Project Budget

For FY 2007 through FY 2016, the Generation IV Energy Conversion Program will focus on completing the development of the S-CO_2 cycle to the level necessary to confirm viability and performance potential for Generation IV reactors. The emphasis will be on experimental demonstration of the systems and concepts developed in the DOE programs over the past several years. Laboratory and pilot scale demonstrations will be necessary to support technology selections. The major Energy Conversion tasks are the development and scaled demonstration of the S-CO_2 cycle for intermediate outlet temperature Generation IV systems. The FY 2007 budget associated with these activities is shown in Table A8.1.

Table A8.1. FY 2007 budget profile for Energy Conversion activities ($K).

Energy Conversion	FY-07[a]
Total	279

a. FY 2007 budget includes FY 2006 carryover funds. Energy Conversion is also funded at $800K for S-$CO_2$ Technology under SFR.

A8.4.2 Ten-Year Project Schedule

The schedule for the major Energy Conversion tasks will be aligned with Generation IV reactor systems decisions for sustainable nuclear energy systems, and the NGNP. Information on the S-CO_2 power conversion performance and cost, and the assessment of advanced technology options for high temperature systems should be available to support these reactor system evaluations. Proposed schedules for the development and scaled demonstration of the S-CO_2 cycle systems are summarized in Figure A8.1.

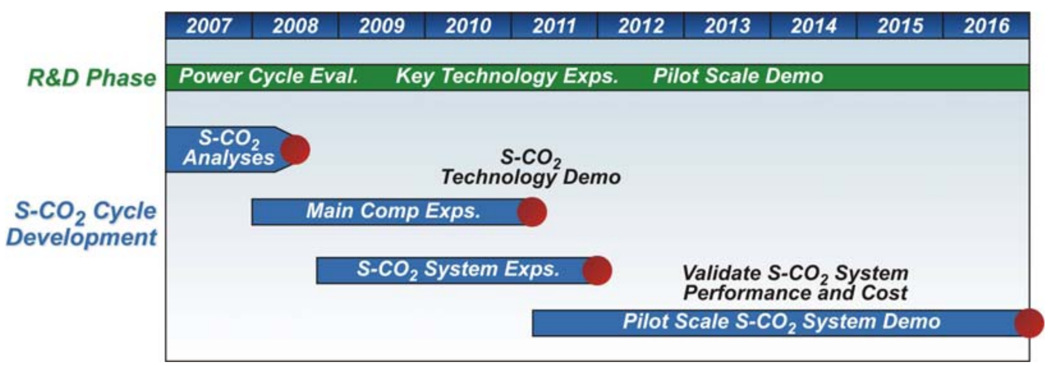

Figure A8.1. Schedule for S-CO_2 Research Activities (Crosscut and SFR Energy Conversion tasks).

A8.4.3 Ten-Year Project Milestones

The major milestones for crosscutting Energy Conversion research activities coincide with the stages of demonstration of S-CO_2 power conversion cycle for sustainable nuclear energy systems. The major milestones are summarized below.

FY 2007

- Complete design of a phased S-CO_2 small-scale test bed system to allow early testing of the main compressor and subsequent testing of a full S-CO_2 system
- Initiate construction an S-CO_2 main compressor test loop to demonstrate compression near the critical point of CO_2
- Construct experimental apparatus for S-CO_2 heat transfer for recuperator conditions.

FY 2008

- Complete construction of the S-CO_2 main compressor test loop and perform initial experiments
- Complete S-CO_2 heat transfer experiments for small-scale compact heat exchangers for recuperator conditions
- Begin construction of S-CO_2 small scale Brayton cycle components at the MW scale.

FY 2009

- Complete S-CO_2 main compressor experiments
- Construct turbine, recuperators, and balance of system for an S-CO_2 cycle small-scale demonstration loop as permitted by resources (utilize main compressor and alternator components developed in previous years).

FY 2010

- Complete construction of turbine, recuperators, and balance of system for an S-CO_2 cycle small-scale demonstration loop
- Begin initial small-scale S-CO_2 recuperated split flow system experiments to demonstrate system operation, control strategies, efficiency.

FY 2011 – 2012

- Complete small-scale S-CO_2 system experiments
- Complete design of a pilot scale S-CO_2 loop for demonstration of system performance and cost
- Begin construction of turbomachinery, heat exchangers, and balance of system for pilot-scale S-CO_2 cycle loop.

FY 2013 – 2016

- Complete construction of turbomachinery, heat exchangers, and balance of system for pilot-scale S-CO_2 cycle loop
- Complete pilot-scale experiments to demonstrate all key technology and performance issues for S-CO_2 cycle.