Appendix 8.0
Energy Conversion

Contents

A8.1 INTRODUCTION AND BACKGROUND

A8.1.1 Energy Conversion Crosscut Description

Energy Conversion Crosscut research and development (R&D) focuses on the energy conversion technologies that support implementation of Generation IV reactor systems, either through improved efficiency, reduced costs or enabling new energy products. Energy conversion technologies that optimally couple to the performance characteristics of Generation IV reactors will result in more efficient and cost effective nuclear electricity, which is an important metric for determining next generation nuclear plant viability. The cost of electricity from a next generation nuclear plant is proportional to capital and operating cost recovery divided by the net electrical output, or:

Cost ($/kw-hr) = (Capital Cost Recovery + Operating Costs)/(Electrical Output).

Improvements in plant efficiency, derived from improvements in the power conversion cycle, increase plant output directly. If the associated incremental costs for the more efficient power conversion cycle are relatively small compared to total plant capital costs, improvements in cycle efficiency have essentially the same result as direct reductions in plant construction and operating costs. There is significant motivation to investigate power conversion system approaches that have the potential to maximize the power output of Generation IV systems.

The Energy Conversion crosscut involves research on advanced power conversion options for two major categories of Generation IV reactors:

- High temperature systems (up to 1000°C – Next Generation Nuclear Plant [NGNP])
- Intermediate outlet temperature systems (550 to 700°C range – Gas-cooled Fast Reactor [GFR], Lead-cooled Fast Reactor [LFR], Sodium-cooled Fast Reactor [SFR], and Molten Salt Reactor)

The development of power conversion options for the intermediate temperature systems is focusing on the supercritical CO_2 Brayton cycle, which has potential for optimal system efficiency in this temperature range. The assessment of high-temperature power conversion options for NGNP addresses both near-term cycle and configuration options that influence cost and performance, and longer-term advanced technology options. These studies are intended to provide a basis for evaluating future power conversion system design studies to be performed as part of the NGNP project. Initially these studies focus on engineering analyses to determine performance potential and cost implications. These studies will ultimately lead to scaling demonstration experiments for selected options to provide a validated technology basis for next generation technology decisions.

A8.1.2 Overall System Timeline

Information on efficiency and cost of power conversion systems for Generation IV reactors will be an important component of system and technology selection decisions. The selection of a sustainable nuclear energy system is currently scheduled for 2010. The performance comparisons between candidate systems will be influenced by the efficiency and cost of the power conversion option developed for that system. The Energy Conversion Crosscut needs to provide information on supercritical CO_2 Brayton cycle cost and performance by that time to support the selection decision. The Energy Conversion studies also need to address high-temperature Brayton-cycle technology options for NGNP to support the evaluation and selection of proposed power conversion system designs for the NGNP. The stages of this assessment are generally coordinated with the conceptual, preliminary, and final design stages of the NGNP.

To provide the necessary power conversion cost and performance information needed to support technology selection and implementation decisions, the R&D effort will proceed in the following general sequence:

- 2005 – 2007. Power conversion cycle assessments and analyses to address viability issues and performance potential for the range of promising power conversion cycles.

- 2007 – 2010. Laboratory scale demonstrations of components and key technologies to validate analytical assessments.

- 2009 – 2014. Pilot scale demonstrations of selected technologies to confirm engineering approaches and performance.

This sequence of analyses, component development and small-scale experiments, leading to pilot scale experiments for selected power conversion options, will demonstrate system performance potential, and refine estimates of power conversion system costs.

A8.2 RESEARCH AND DEVELOPMENT STRATEGY

A8.2.1 Objectives

The objective of the Energy Conversion Crosscut is to develop power conversion options that optimize the benefit of Generation IV reactors – either through higher efficiency for Generation IV outlet temperature conditions, lower capital or operating costs, or both. Research activities will demonstrate key technologies for selected systems to establish viability, and perform scaled demonstrations where appropriate for performance confirmation.

A8.2.2 Scope

Generation IV reactor systems cover a range of output temperatures. The Very High Temperature Reactor (VHTR) for the NGNP is considering designs for outlet temperatures of up to 1000°C. The GFR, LFR, and SFR are considering designs that result in outlet temperatures in the range of 550 to 700°C or higher. The Supercritical Water Reactor (SCWR) outlet temperatures are in the range of 400 to 500°C.

With this range of outlet temperatures for Generation IV systems, it is important to consider power conversion options that couple most effectively with system characteristics. Current light-water reactor (LWR) power plants use steam Rankine cycles for electrical generation, which provide efficiencies of about 33%. The steam Rankine cycle is an efficient option at LWR outlet temperatures, but materials and operating conditions are challenging at the higher temperature ranges characteristic of most Generation IV systems. Superheated or supercritical Rankine cycles, which are in use in some coal fired plants, extend the applicable temperature range, but these cycles have not yet been developed for the higher temperature (>600°C) Generation IV reactor conditions. Brayton cycles using inert gas or other working fluids are well matched to the higher temperatures of the Generation IV reactors. Technology developed for combined Brayton-Rankine cycle gas turbines is commercially available and provides a basis for developing a range of 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) may be developed in the longer term, but the focus of Generation IV power conversion research will be on conversion cycles that can be developed in the time frame of the Generation IV reactors – 15 to 20 years. Supercritical or superheated Rankine cycles will be considered for the SCWR, but since these systems have been developed for coal-fired plants, research on these cycles is not considered a high priority for SCWR viability. For the intermediate and higher temperature ranges applicable to most Generation IV systems, Brayton cycles using inert or other gas working fluids will be the focus of Generation IV power conversion R&D.

The higher outlet temperatures of the VHTR (and potentially other Generation IV systems) also have the potential to provide the heat source for nuclear hydrogen production. The development of hydrogen production processes are being addressed in the Nuclear Hydrogen Initiative (NHI). High temperature heat exchanger technologies are potentially relevant to both applications. Energy Conversion research is being closely coordinated with NHI in these areas. There is the potential that NGNP, or other Generation IV systems will provide both electrical generation and hydrogen production capabilities. Systems studies that address these hybrid configurations are also being coordinated between the two programs.

For FY-05, the high temperature Brayton cycle studies will address cost effective options for interstage heating or cooling approaches that provide higher efficiencies with acceptable increases in system complexity. These analyses were identified in earlier Energy Conversion studies as having the greatest potential for improved efficiency for high temperature Helium Brayton cycle systems. Further assessment of near term NGNP technology options (direct vs. indirect cycle approaches, single and multiple shaft options, and turbine design choices, etc.) will be addressed as required in support of NGNP power conversion activities.

For the intermediate temperature range application, studies focus on the supercritical CO_2 cycles. The supercritical CO_2 Brayton cycle provides high efficiency at temperatures in the range of 550 to 700°C, with relatively little increase in complexity, potentially providing a better match with projected outlet temperatures of GFR and metal cooled systems. For FY-05, these studies will focus on viability issues of S-CO_2 turbomachinery design, particularly the main compressor, and the unique control and materials compatibility issues for the S-CO_2 system. An S-CO_2 plant layout and conceptual design will be developed to provide a basis for system economics estimates. These studies will establish a baseline supercritical CO_2 Brayton design, identify the materials and systems issues and requirements, and ultimately perform scaling experiments to demonstrate key technologies.

A8.2.3 Viability Issues

Brayton cycle systems and the sophisticated turbomachinery technology involved have been extensively developed for many commercial applications. The viability issues associated with these systems for Generation IV Energy Conversion involve the application or extension of current technology to the S-CO_2 turbomachinery design and operation, and the high temperatures associated with Helium Brayton cycle applications.

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 cycle operation. (Applicability of inventory and bypass controls, and design and demonstration of key technologies.)

- Materials issues associated with direct cycle options.

- Development of small scale cost effective experimental approaches for the validation of key technologies for S-CO_2.

Viability issues associated with high temperature Helium Brayton cycles for NGNP, or future high temperature reactor systems are related to the very high temperatures proposed for the NGNP closed Brayton cycle systems. The key issues include:

- Materials issues associated with operation at or near 1000°C turbine inlet temperatures

- Design of high temperature He turbines and compressors

- Optimal power conversion configurations for Generation IV applications. (direct-indirect, integral-distributed layout, vertical-horizontal, single-multiple shaft, etc)

A8.2.4 Research Interfaces

Energy Conversion research activities primarily involve U.S. National Laboratories and Universities with input from Industry on heat exchanger and turbomachinery technology issues.

A3.2.4.1 Relationship to GIF R&D Projects

Although there is no specific Generation IV International Forum (GIF) R&D activity focused on power conversion at this early stage, Energy Conversion crosscutting research activities supports all the GIF advanced nuclear system development R&D projects as one important aspect of the ultimate economic assessment.

A3.2.4.2 University Collaborations

The University research community is heavily involved in the design and analysis of the S-CO_2 system and the assessment of high temperature Helium cycle options for NGNP.

A3.2.4.3 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.

A3.2.4.4 I-NERI

Although there are currently no International Nuclear Energy Research Initiative (I-NERI) 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. It is also expected that there will be greater involvement by other DOE Offices (namely, Energy Efficiency and Renewable Energy) in these activities, which focus on the development of more efficient power conversion systems that potentially have application to all large-scale power conversion options.

A8.3 HIGHLIGHTS OF ENERGY CONVERSION R&D

Previous Energy Conversion Program studies evaluated the cost benefit of Brayton cycle options for improved efficiency for Generation IV outlet temperature ranges. These preliminary studies concluded that several cycle variations, such as interstage heating/cooling, bottoming cycles, or non-ideal gas working fluids, could provide increased efficiency at the cost of additional complexity. The Brayton cycle cost benefit study (FY-04) also evaluated major component cost implications and concluded that supercritical CO_2 cycles at intermediate temperatures, and interstage heating/cooling options at higher temperatures merited further investigation. The Energy Conversion Program is also continuing the evaluation of S-CO_2, including turbmachinery design, plant configuration and cost estimation, and system control approaches. During FY-04, the Program also initiated a technology assessment for high temperature He Brayton cycles, to provide a basis for comparison and evaluation of future power conversion system designs for NGNP. Brief summaries of these activities are given below.

A8.3.1 Brayton Cycle Cost Benefit Study

The Brayton Cycle Cost Benefit Study (FY-04) evaluated a range of Brayton cycle technology options that could increase the efficiency and potentially the cost effectiveness of candidate power conversion cycles. The study provided perspective on the value of these modifications and on the research and development effort that would be required to implement such a system. Several possible Brayton cycle modifications were analyzed to determine the potential efficiency improvement, and estimate the incremental cost of the required component changes. A relative cost-benefit approach was developed that was based on changes from a reference recuperated helium Brayton cycle, using costs from previous high temperature gas reactor design studies to provide a baseline for modified cycle cost comparisons. Options considered included:

- Combined Cycles (Brayton and Rankine)
- Interstage cooling and/or interstage heating
- Split flow, or recompression
- Alternate working fluids (N_2, CO_2)

Efficiency improvements were calculated and the relative costs of the associated modifications were then estimated to define a figure of merit which was defined as the relative reduction in the cost of electricity generated.

All of the cycle modifications identified below showed potential for efficiency improvement over the reference recuperated Brayton cycle. However, the cost of the cycle modifications in some cases negated any potential performance improvement. The cost of electricity generated for the Brayton cycles evaluated range from 20 % cost reductions to net cost increases of up to 30 %, depending on conditions. Some of the key observations included:.

- At the higher temperature (1173 K), multiple stage interstage heating and cooling cycles resulted in a reduction of 10 to 15% in the cost of electricity – with significant improvement noted for as few as 2 to 4 stages.
- At the lower temperature (873 K), several cycle modifications showed potential cost benefit. The CO_2 split-flow cycle provides significant efficiency improvement with relatively little

increase in system complexity. Both the interstage heated and cooled system, and the Rankine bottoming cycle showed significant potential for improvement in this temperature range.

- The combined Brayton-Rankine cycle showed improvement at the lower temperatures, but not as much at the higher temperatures. Although the bottoming cycle results in increased efficiency in this range, the positive overall cost-benefit for this approach is notable since it was the most complex system examined. Further analyses based on more detailed designs will be required to confirm these results.

- Nitrogen or CO_2 working fluids in a standard recuperated Brayton cycle were not cost effective. The reduced heat transfer capability of these working fluids increases heat exchanger costs significantly, which outweigh any calculated higher efficiency.

Although reductions in the cost of power generation of 10 to 20% appear modest, these savings are significant. Achieving the same magnitude of savings from improvements in nuclear system construction costs or operating and management costs is also challenging. More efficient power conversion systems facilitate the implementation of next generation reactors.

A8.3.2 Supercritical CO_2 Brayton Cycle

The supercritical CO_2 Brayton cycle has been the focus of Energy Conversion research for the intermediate-temperature systems due to the potential for very high efficiency in the temperature range of 550 to 700°C and the very compact turbomachinery, which has the potential for reduced power conversion system capital costs. Work at the Massachusetts Institute of Technology has developed preliminary turbine and compressor designs for S-CO_2 systems based on NASA 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 diameter) and very efficient (93%). 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 extrapolations from current supercritical steam turbine designs.

Preconceptual designs for a 300 MWe S-CO_2 plant were developed as a basis for preliminary cost and configuration evaluations. These system designs take advantage of the compact turbo-machinery and address the heat transfer issues associated with the lower conductivity CO_2, resulting in relatively compact power conversion systems for S-CO_2 in comparison with similar sized supercritical steam or He Brayton 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 steam Rankine system coupled to a high temperature gas reactor. Work is currently underway to assess the system control issues associated with an S-CO_2 system and the possibilities for demonstration of key technologies and operations at a cost effective scale.

A8.3.3 NGNP Technology Options Study

In anticipation of the procurement of an advanced power conversion system for NGNP, this study was initiated to identify the major design and technology options and tradeoffs that must be considered in the evaluation of a high temperature He Brayton power conversion system (PCS). These PCS technology options affect cycle efficiency, capital cost, system reliability, maintainability and technical risk, and therefore the cost of electricity. This study showed that the key PCS design and configuration choices have a large effect on PCS power density and nuclear island size, making careful and detailed analysis of design tradeoffs important in selection of PCS options. It was also observed that high temperature reactors appear to be able to achieve lower materials-requirements (e.g., steel and concrete) at smaller unit sizes. For HTR's, a much larger fraction of total construction inputs go into the nuclear island.

PCS technology options also include variations on the cycle operating conditions and the cycle type that can have an important impact on performance and cost. These options included working fluid choices (He, N_2, CO_2) system pressures, direct vs. indirect cycles, and interstage cooling (or heating). Some of the observations from this assessment of these factors include:

- Differences between He versus N_2 working fluids were not considered critical for turbomachinery design, with the primary difference being in the heat exchanger size to compensate for the lower N_2 thermal conductivity.

- N_2 allows 3600-rpm compressor operation at thermal powers at and below 600 MW(t), while He compressors must operate at higher speeds requiring reduction gears, asynchronous generators, or multiple-shaft configurations. Turbomachinery tolerances for He systems do not appear to be a key issue.

- Direct /Indirect – Efficiency loss can be 2 to 4 %, depending on design, and the intermediate heat exchanger becomes a critical component at high temperatures.

The PCS configuration and physical arrangement of the system components influences structure sizes, pressure boundary volume and mass, gas inventories and storage volume, uniformity of flow to heat exchangers, pressure losses, and maintainability. The major factors considered in this study included, distributed vs. integrated PCS design approach, shaft orientation (vertical/horizontal), single vs. multiple shafts, and pressure boundary design. These configuration design choices were found to strongly influence both the size and cost of the PCS system, and the technology requirements for key components. Current design studies on closed high temperature Brayton cycle systems have made significantly different choices in these areas. This study identified the implications and inter-dependencies of these features, in order to illuminate the basis for particular choices when evaluating future designs. These observations illustrate the complex interactions of the many design choices that will be considered in the NGNP PCS. It is clear that detailed and integrated design efforts must be performed on candidate designs before quantitative evaluations are reliable.

A8.4 10-YR PROJECT COST AND SCHEDULE

A8.4.1 10-yr Project Budget

For FY-05 through FY-14, the Generation IV Energy Conversion Program will complete technology assessments for Generation IV power conversion options, perform preliminary design studies to confirm performance potential and cost implications, perform key technology development experiments, and initiate laboratory or pilot scale demonstrations necessary to support technology selections. The major Energy Conversion tasks are the development and scaled demonstration of the supercritical CO_2 cycle for intermediate outlet temperature Generation IV systems, and the evaluation and development of advanced technologies for performance improvement of high temperature He Brayton cycles for very high temperature Generation IV systems. The budgets associated with these major activities are summarized in Table A8.1.

Table A8.1. Total Energy Conversion Planning Level Budget FY 2005- FY 2014

FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
729										

A8.4.2 10-yr Project Schedule

The schedule for the major Energy Conversion tasks is driven by the Generation IV systems selection decisions for sustainable nuclear energy systems. Information on the S-CO_2 power conversion performance and cost for the candidate systems will be a component of the selection process. Information on advanced technology options for high temperature systems will be a component of the overall evaluation of high- temperature reactor-system economics, but will not be driven by any specific Generation IV decision date for the crosscutting activities. The schedule for the development and scaled demonstration of the supercritical CO_2 cycle for intermediate outlet temperature Generation IV systems, and the evaluation and development of advanced technologies for performance improvement of high temperature He Brayton cycles for very high temperature Generation IV systems are summarized in Figure A8.1.

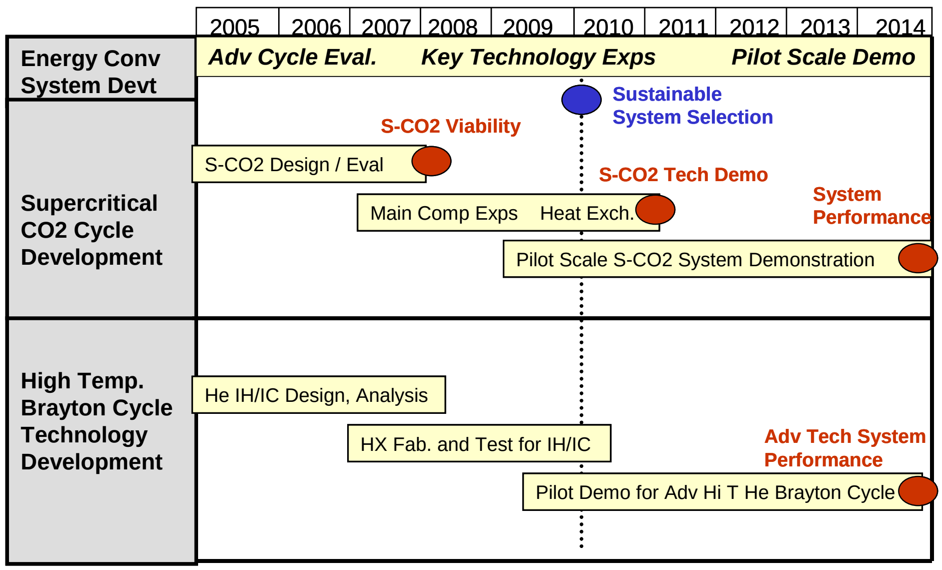

Figure A8.1. Schedule for Crosscutting Energy Conversion Research Activities

A8.4.3 10-yr Project Milestones

The major milestones for crosscutting Energy Conversion research activities are the stages of demonstration of power conversion cycle performance for sustainable nuclear energy systems, and the demonstration of advanced technology for high temperature He Brayton cycles for improved system economics. The major milestones are:

FY 2007

- Complete assessment of supercritical CO_2 cycle to confirm viability for intermediate temperature Generation IV reactor systems.

FY 2010

- Complete demonstration of key technologies (main compressor, high effectiveness heat exchangers/recuperators, and control algorithms) for supercritical CO_2 cycles operating at temperature range of selected Generation IV sustainable nuclear energy system

FY 2014

- Complete pilot scale demonstration of S-CO_2 cycle to confirm performance and operational characteristics.

- Complete pilot scale advanced technology demonstration of efficiency improvements for high temperature He Brayton cycles.

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