Appendix 8.0
Energy Conversion

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Acronyms

ANL	Argonne National Laboratory
CO_2	carbon dioxide
FY	fiscal year
GIF	Generation IV International Forum
IC	interstage cooling
IH	interstage heating
IH/IC	interstage heating/interstage cooling
LFR	Lead-Cooled Fast Reactor
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
MW_e	megawatt electric
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

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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 more efficient and cost effective energy conversion technologies for Generation IV reactors. Energy conversion technologies that optimize the use of the thermal output of advanced reactors will result in more efficient and cost effective nuclear electricity, a key metric for determining Generation IV system viability. The cost of electricity from a Generation IV reactor is proportional to capital cost recovery and operating costs 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 cost for the more efficient power conversion cycle is 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 develop power conversion systems (PCSs) that maximize the power output of Generation IV reactors.

A8.1.1.1 Power Conversion Options for Advanced Nuclear Power Plants

The current suite of Generation IV reactors encompasses a wide range of thermal output conditions and the type of power conversion cycle that is most appropriate depends on these thermal characteristics—primarily outlet temperature, system pressure, and working fluid characteristics. The objective of the Generation IV Energy Conversion studies is to align reactor output with the most appropriate power conversion system to optimize the electrical output. The Generation IV Energy Conversion studies have focused on the PCSs for 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.
- Very-high-temperature reactor systems (i.e., the Next Generation Nuclear Plant [NGNP]) with an inert gas coolant at outlet temperatures up to 1,000°C.

A8.1.1.1.1 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, Brayton cycles using inert or other gas working fluids are considered the most promising power conversion approach.

A8.1.1.1.2 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.

A8.1.1.1.3 High-Temperature Helium Brayton Cycle Development. A smaller effort will address options for the NGNP to optimize efficiency and understand cost/efficiency trade offs. These studies are intended to provide a basis to evaluate future PCS design decisions for high-temperature Helium Brayton cycles for temperatures up to 1,000°C. The objective is to develop technology approaches for efficiency improvement with acceptable cost implications. Analytical studies will ultimately lead to scaling demonstration experiments to provide a validated technology basis for the high-temperature helium Brayton cycles. Although the ultimate measure of the viability of an advanced PCS is the cost of electricity generated, some increase in PCS capital costs can be cost effective if overall system efficiency is sufficiently increased.

A8.1.2 Overall System Timeline

The S-CO_2 cycle is applicable to several current Generation IV concepts, but particularly the SFR and LFR reactors. Development of demonstration reactor technology for transmutation and sustainable nuclear energy would be completed in the 2015 timeframe. One of the key considerations in the viability decision on these sustainable energy systems will be the efficiency and cost of the PCS. Energy Conversion R&D will need to provide information on S-CO_2 Brayton cycle cost and performance by that time to support this evaluation. Energy Conversion studies also need to address high-temperature Brayton cycle technology options for NGNP to support the evaluation and selection of proposed PCS designs. The stages of this assessment will be aligned with design stages of the NGNP.

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 to address viability issues and performance potential for S-CO_2 and Helium Brayton cycles.

2008–2011

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

2011–2015

- Construction and demonstration of pilot scale systems to confirm engineering approach and performance, and refine 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 for the next ten-year period 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. The objective for the NGNP power conversion studies will be the design of improved efficiency options for high-temperature Helium Brayton cycles.

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 fiscal year (FY) 2006 to 2015 time-period covers the key technology and demonstration issues for the S-CO_2 cycle. These studies will address S-CO_2 turbomachinery design—particularly the main compressor design—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, resolve materials and systems technology issues, and, ultimately, perform scaling experiments 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
2. Analytical studies of key cycle technology issues—turbine, compressor and heat exchanger designs, operation of the main compressor near the critical point of carbon dioxide (CO_2)
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, and control strategy investigation
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 (~100s kW)
6. Construction and operation of a pilot-scale S-CO_2 PCS to confirm performance and costs (~10's MW).

A8.2.2.2 Helium Brayton Cycle Development

The scope of the high-temperature helium Brayton cycle studies in the FY 2006 to 2015 period will cover the design and analysis of cost effective options for improved efficiency. Previous studies have identified interstage heating (IH) or interstage cooling (IC) configurations that result in higher efficiencies with acceptable increases in system complexity. Analytical studies will establish a baseline interstage heating/interstage cooling (IH/IC) configuration and preliminary turbomachinery and heat exchanger designs, and provide a basis for the design of small-scale experiments to demonstrate key technologies and system performance at a later stage. These studies will move forward at a rate consistent with available resources and will include the following elements:

1. Helium Brayton cycle design studies to identify improved efficiency options for full-scale systems
2. Analytical studies of key cycle technology issues—heat exchangers and ducting associated with IH/IC, turbine, compressor designs, and preliminary cost estimates
3. Design studies for small-scale heat transfer and fluid flow experiments for key components
4. Construction and operation of small-scale experiments for evaluation of component performance and system operation
5. Construction and operation of a pilot-scale helium Brayton cycle system to confirm performance and costs.

A8.2.3 Viability Issues

Brayton cycle systems and the sophisticated turbomachinery technology involved have been extensively developed for many commercial applications. The development of the split-flow S-CO_2 cycle and the high-temperature helium Brayton cycle strongly benefit from this extensive technology base. These advanced cycles also introduce additional technology issues that must be addressed.

A8.2.3.1 Supercritical Carbon Dioxide Viability Issues

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.

A8.2.3.2 High-Temperature Helium Brayton Cycle Viability Issues

Viability issues associated with high-temperature Helium Brayton cycles for high-temperature reactor systems are related to the very high temperatures proposed for these systems. The key issues include:

- Materials issues associated with operation at or above 900°C turbine inlet temperatures
- Design of high-temperature helium 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, but with 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, which focus on the development of more efficient PCSs that potentially have application to many large-scale power conversion options.

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 early stage, Energy Conversion research activities support the GIF advanced nuclear reactor development R&D projects in the PCS development.

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. There are continuing interactions with universities on the design of advanced high-temperature helium cycle options for NGNP.

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, France) is being pursued.

A8.3 HIGHLIGHTS OF ENERGY CONVERSION RESEARCH AND DEVELOPMENT

Energy Conversion research activities to date addressed three primary areas:

1. S-CO_2 system and component issues, design, and performance
2. High-temperature Helium Brayton cycle efficiency improvement
3. Advanced heat transport configuration options for NGNP.

A8.3.1 Supercritical Carbon Dioxide Brayton Cycle Research and Development Status

The S-CO_2 Brayton cycle has been the focus of Energy Conversion research for the intermediate temperature reactors (500 to 700°C) due to the potential for very high efficiency and very compact turbomachinery, which has the potential for reduced PCS capital costs. 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 MW_e 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 2006. 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.

A8.3.1.1 Supercritical Carbon Dioxide Layout Studies

Conceptual designs for a 300 MW_e S-CO_2 plant have also been 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 thermal conductivity of CO_2, resulting in relatively compact PCSs for S-CO_2 in comparison with similar sized conventional Rankine or supercritical 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.

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.

A8.3.1.2 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.

Initial work at ANL 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 MW_t (181 MW_e) LWR. 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—allow only part of the flow to go to the heat exchanger, decreasing the heat removal rate
- Turbine Inlet Throttle Valve—introduce a pressure drop before the turbine, reducing the pressure ratio available for the turbine
- Turbine Bypass—bypass flow to the turbine, increasing the flow rate through the compressors. Compression work increases relative to the expansion work
- Inventory Control—remove some portion of the CO_2 mass from the cycle, reducing pressure and S-CO_2 mass flow rates
- Flow Split Control—adjust the CO_2 flow split between the compressors, which could be used in conjunction with other strategies.

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. After using turbine bypass control over this regime, inventory control should be useful over a range of 50 to 90% load. Current calculations suggest that none of the remaining control strategies is capable of controlling the cycle from 50% load on down. Flow split control was considered to be useful in combination with other controls to extend their range. Analysis of S-CO_2 control strategies will continue to be a priority for FY 2006.

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.

A8.3.2 High-Temperature Helium Brayton Cycle Studies

High-temperature Helium Brayton cycle studies have examined the cost and efficiency implications of IH/IC modifications to the standard recuperated Brayton cycle. The added complexity results in some increased capital cost, but the efficiency improvements are significant and effectively leverage the cost of the nuclear system as well as the PCS. Observations from the current studies are summarized below.

A8.3.2.1 Efficiency Improvement from Interstage Heating/Interstage Cooling Modifications

For closed recuperated Brayton cycles, the use of multiple expansion and reheat stages can:

- Increase cycle efficiency by 8 to 12% over the single stage compression recuperated Brayton and 5 to 8% over the two-stage compression recuperated Brayton cycle (for the same turbine inlet temperature)
- Reduce the size of the input heat exchanger by 10 to 20%, the rejection heat exchanger by 15 to 25%, and the recuperator heat exchanger by a factor of 2
- Increase the PCS energy density by a factor of 1.5.

IH/IC modifications can more than make up for the 2 to 4% loss encountered when replacing a direct cycle with an indirect cycle. The approach adds complexity, but there are also compensating features, such as a reduced sensitivity to heat exchanger effectiveness in IH/IC systems, that may offset capital cost impacts.

A8.3.2.2 Engineering and Configuration Implications

Engineering choices (vertical versus horizontal, single versus multiple shaft, distributed versus integrated layout, working fluid choices) involve numerous trade offs, often interactive. Current Brayton cycle design studies have taken almost all of these paths at one point or another, and systems with similar efficiency and power density are possible with most of the major PCS design options. Maintenance implications, accessibility and reliability, etc. may end up being the differentiating considerations. 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. Some of the observations from this assessment of these factors include:

- Direct/Indirect—Efficiency loss can be 2 to 4%, depending on design, and the intermediate heat exchanger becomes a critical component at high temperatures. Maintainability is a key issue.
- Differences between helium and nitrogen working fluids were not considered critical for turbomachinery design. The primary difference is in the heat exchanger size to compensate for the lower nitrogen thermal conductivity.
- Nitrogen allows 3,600-rpm compressor operation at thermal powers at and below 600 MW_t, while helium compressors must operate at higher speeds requiring reduction gears, asynchronous generators, or multiple-shaft configurations. Turbomachinery tolerances for helium systems do not appear to be a key issue.

A8.3.2.3 Future Research and Development Directions

The specific R&D areas that need to be pursued to establish the technology base for future decisions include:

- Evaluation of the impact of dynamic head losses and recovery as a function of duct and nozzle design
- Detailed engineering designs for a reference system to compare to a current design recuperated cycle
- Confirmation of the reheat heat exchanger performance and cost
- Analysis of system transient response (start up, shut down, load rejection, accidents)
- Turbomachinery design studies (exit diffuser optimization, specific compressor and turbine designs for multi-reheat system conditions)
- Plans for small-scale experimental confirmation of system performance and transient response.

Technical risks can be mitigated by both engineering design choices and by initiating technology development or demonstration programs for key technology gaps. Horizontal, distributed systems could be envisioned that pose fewer technology issues—and provide nearer term solutions—with the possibility of some cost or efficiency impact. Mitigating risk through design choices or key technology development also implies early design studies to define those options and identify the key gaps.

A8.3.3 Advanced Heat Transport–Intermediate Loops

Coupling high temperature reactor heat sources to hydrogen production systems or advanced electrical generation requires both efficient heat transfer and in the case of hydrogen production, adequate separation of the facilities to assure that off normal events in the production facility do not impact the nuclear power plant. An intermediate heat transfer loop will be required for both hydrogen production and indirect electrical cycles. The proposed NGNP facility is a dual-purpose facility that demonstrates both hydrogen and efficient electrical generation. Later plants could be single-purpose facilities, but at this stage of development, both single- and dual-purpose facilities need to be understood.

Several possible configurations for an intermediate heat transport system that transfers heat between the reactor primary system and the hydrogen and/or electrical generation plant were evaluated, including both direct and indirect cycles for the production of electricity. Both helium and liquid salts were being considered as the working fluid in the intermediate heat transport loop. Thermal-hydraulic and cycle-efficiency evaluations of the different configurations and coolants estimated the sizes of components as an indication of the associated capital costs.

This phase of the study examined the use of a liquid salt as the working fluid in the intermediate heat transport loop for NGNP. The use of a molten salt working fluid results in an overall efficiency increase of 0.3 to 0.6% compared to low-pressure helium because of reduced pumping power. The study also observed that stresses in the hot leg piping and pressure heat exchanger tubes at operating conditions of 7 MPa and 880°C can be significant compared to allowable values. Reduced component thicknesses can be obtained by reducing the pressure of the intermediate heat transport loop, with some impact on the associated heat exchangers.

A8.4 PROJECT COST AND SCHEDULE

A8.4.1 Fiscal Year 2006 Project Budget

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 S-CO_2 cycle for intermediate outlet temperature Generation IV systems, and the evaluation and development of advanced technologies for performance improvement of high-temperature Helium Brayton cycles for very high-temperature Generation IV systems. The FY 2006 budget associated with these major activities is shown in Table A8.1.

Table A8.1. FY 2006 budget profile for Energy Conversion activities ($K).

Energy Conversion	FY-06[a]
Total	1,322

a. FY 2006 funding includes FY 2005 carryover funds.

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 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, and the evaluation and development of advanced technologies for performance improvement of high-temperature Helium Brayton cycles for very high-temperature Generation IV systems are summarized in Figure A8.1.

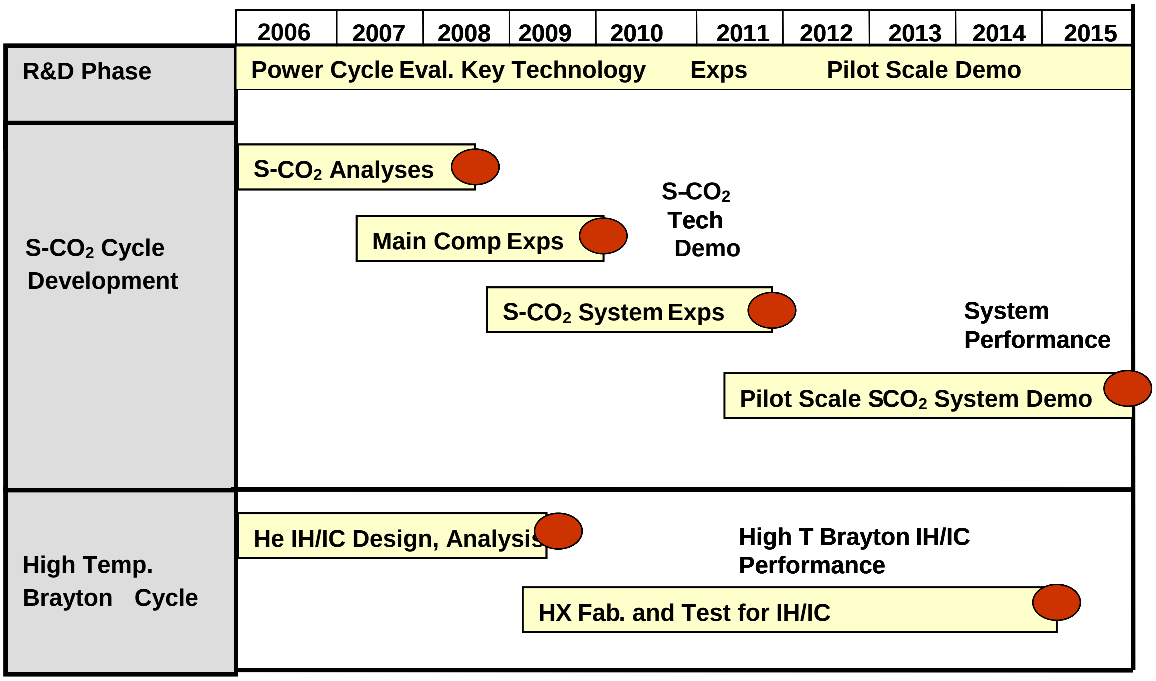

Figure A8.1. Schedule for Crosscutting Energy Conversion Research Activities

A8.4.3 Ten-Year 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 Helium Brayton cycles for improved system economics. The major milestones are summarized below.

FY 2006

- Complete assessment of S-CO_2 cycle key component designs, control strategies, and small-scale experiment designs needed to confirm technology issues
- Complete initial S-CO_2 heat exchanger experiments for precooler conditions
- Complete conceptual design for baseline IH/IC high-temperature Helium cycle.

FY 2007

- Complete design of a phased S-CO_2 small-scale test bed system to allow early testing of main compressor and subsequent testing of a full S-CO_2 system
- Construct 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.

FY 2009

- Complete $S\text{-}CO_2$ main compressor experiments
- Begin construction of turbine, recuperators, and balance of system for an $S\text{-}CO_2$ cycle small-scale demonstration loop (utilizes main compressor and alternator components developed in previous years).

FY 2010

- Complete construction of turbine, recuperators, and balance of system for an $S\text{-}CO_2$ cycle small-scale demonstration loop
- Begin initial small-scale $S\text{-}CO_2$ system experiments to demonstrate system operation, control strategies, efficiency.

FY 2011-2012

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

FY 2013-2015

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

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