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Systems Engineering Model for ART Energy Conversion[1]

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Systems Engineering Model for ART Energy Conversion

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Abstract

The near-term objective of the EC team is to establish an operating, commercially scalable Recompression Closed Brayton Cycle (RCBC) to be constructed for the NE - STEP demonstration system (demo) with the lowest risk possible. A systems engineering approach is recommended to ensure adequate requirements gathering, documentation, and modeling that supports technology development relevant to advanced reactors while supporting crosscut interests in potential applications. A holistic systems engineering model was designed for the ART Energy Conversion program by leveraging Concurrent Engineering, Balance Model, Simplified V Model, and Project Management principles. The resulting model supports the identification and validation of lifecycle Brayton systems requirements, and allows designers to detail system-specific components relevant to the current stage in the lifecycle, while maintaining a holistic view of all system elements.

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Executive Summary

The mission of the Energy Conversion (EC) area of the Advanced Reactor Technology Program is to commercialize the supercritical carbon dioxide (sCO_2) Brayton cycle for advanced reactors and to support the Supercritical Transformational Electric Production (STEP) program. The cross-cutting nature of STEP (bringing together DOE NE, EERE, and FE towards the common goal of commercializing Brayton systems) highlights the potential of several Brayton applications beyond ART's reactor focus. A roadmap for the commercialization of Brayton systems outlines the need for a comprehensive approach that supports scalable and reconfigurable solutions to support the development of the technology, while maximizing resource utilization and knowledge sharing, and reducing rework across applications.

The near-term objective of the EC team is to establish an operating, commercially scalable Recompression Closed Brayton Cycle (RCBC) to be constructed for the NE - STEP demonstration system (demo) with the lowest risk possible. A systems engineering approach is recommended to ensure adequate requirements gathering, documentation, and modeling that supports technology development relevant to advanced reactors while supporting crosscut interests in potential applications.

A holistic systems engineering model was designed for the ART Energy Conversion program by leveraging Concurrent Engineering, Balance Model, Simplified V Model, and Project Management principles. The resulting model supports the identification and validation of lifecycle Brayton systems requirements, and allows designers to detail system-specific components relevant to the current stage in the lifecycle, while maintaining a holistic view of all system elements. The complexity of Brayton systems highlights the need for a systems engineering modeling tool to support components requirements management, with the potential to scale to multiple applications. This report describes the use of systems engineering modeling to document, analyze, design, and validate detailed component and full lifecycle system requirements.

Nomenclature

ARC	Advanced Reactor Concepts
ART	Advanced Reactor Technologies (Office of)
ASMR	Advanced Small Modular Reactor
CBC	Closed Brayton Cycle
CE	Concurrent Engineering
CoP	Community of Practice
CRADA	Cooperative Research and Development Agreement
CTE	Critical Technology Elements
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy (Office of)
EFFBD	Enhanced Functional Flow Block Diagrams
FBO	Federal Business Opportunity
FE	Fossil Energy (Office of)
HTR	High Temperature Recuperator
MBSE	Model Based Systems Engineering
NE	Nuclear Energy (Office of)
NGNP	Next Generation Nuclear Plant
PMO	Project Management Organization
R&D	Research and Development
RCBC	Recompression Brayton Cycle
RD&D	Research, Development and Deployment
sCO2	Supercritical Carbon Dioxide
SFR	Sodium Fast Reactor
SME	Subject Matter Expert
STEP	Supercritical Transformational Electric Power Generation
STP	Standard Temperature and Pressure
TRL	Technology Readiness Level
WFO	Work for Others

Introduction

Sandia's Brayton team mission states that "by the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550°C 10 MWe R&D demonstration sCO2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology." In support of the mission, this systems engineering plan for energy conversion was undertaken to formally apply systems engineering in the identification and retirement of technical risks, in a phased approach that supports a successful launch of the sCO2 Brayton Cycle demonstration.

Specifically, Sandia's team utilizes Technology Readiness Levels (TRLs) to assess the readiness of systems components, estimating the technology maturity of Critical Technology Elements (CTEs) in the program. A roadmap for the commercialization of the technology has been created; it highlights several potential applications for Brayton technologies, and also defines the path for a technology demonstration that is both scalable and reconfigurable to support the multiple applications. A systems engineering approach is recommended to ensure adequate requirements gathering, documentation, and modeling that supports technology development while maximizing knowledge transfer and validation across multiple applications.

Project Scope

The scope of this systems engineering effort to support Brayton technology development is to:

- Develop a systems engineering model for sCO2 Brayton systems that supports the reconfigurable and scalable need for variability across potential applications, maximizing the potential for cross-application knowledge sharing and requirements validation.
- Select a systems engineering modeling tool that will enable the Brayton team to support the initial planning for a sCO2 Brayton demonstration facility, identifying CTEs, specifications, and requirements. The tool must be able to be flexibly refocused for subsequent projects (such as different heat sources) while maximizing the input and knowledge already developed during the initial planning stage.
- Gather component and systems requirements to populate the tool in support of a 550°C 10MWe demonstration. This is expected to be an ongoing effort that will keep team members updated on the status of component TRL and progression, leveraging resources from past and ongoing projects.

Background

DOE-NE ART, STEP and sCO2 Crosscut

Two programs within the DOE Office of Nuclear Energy (NE) are involved in R&D efforts towards sCO2 Brayton Cycle energy conversion:

The Supercritical Transformational Electric Power (STEP) program, cosponsored by the offices of Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency and Renewable Energy (EERE), is a crosscut that seeks to facilitate the commercialization of sCO2 technology. Its mission is to reduce the technical barriers and risks to the commercialization of the sCO2 power cycle. The goal of STEP is to work with industry to develop and mature the technology at the pilot scale in order to facilitate commercialization.

The Office of Advanced Reactor Technologies (ART) sponsors research, development, and deployment (RD&D) activities through its Next Generation Nuclear Plant (NGNP), Advanced Reactor Concepts (ARC), and Advanced Small Modular Reactor (ASMR) programs to promote technical, economic, environmental, and safety-related advancements of innovative Generation IV nuclear energy technologies. One of the efforts supported by ARC is exploration and development of a supercritical CO2 Brayton thermal cycle for diverse reactor applications that couple nuclear reactors to power generation with improved conversion efficiency and reduced plant size [1].

The crosscut's Supercritical CO2 Technology Team (Tech Team) is charged with using a collaborative approach to develop and facilitate commercialization of sCO2 energy conversion technology, spanning several potential applications beyond ART's reactor focus. The crosscut is structured around a common goal of establishing a 10 MWe scale STEP facility for evaluating power cycle and component performance over a range of operating conditions, capable of supporting the diversity in potential target applications. This condition requires the exploration of system solutions that are reconfigurable and scalable to fulfill diverse target applications.

sCO2 Brayton Systems

Supercritical carbon dioxide is a fluid state of carbon dioxide where it is held at or above its critical temperature and critical pressure. Carbon dioxide usually behaves as a gas in air at standard temperature and pressure (STP), or, when frozen, as a solid known as dry ice. If the temperature and pressure are both increased from STP to be at or above the critical point for carbon dioxide, sCO_2 can adopt properties midway between a gas and a liquid. In this state, it can be used efficiently throughout the entire Brayton cycle [2].

A closed Brayton cycle (CBC) recirculates the working fluid, and the turbine exhaust is used in a recuperating heat exchanger to heat the turbine feed. A "supercritical cycle" is a closed Brayton cycle in which the working fluid (sCO_2) is maintained near the critical point during the compression phase of the cycle.

Brayton benefits

The key property of the fluid near its critical point is its higher gas density, closer to that of a liquid than of a gas, allowing for the pumping power in the compressor to be significantly reduced, which in turn increases the thermal-to-electric energy conversion efficiency [3]. The resulting higher conversion efficiency (up to 50%) translates into increased production of electricity for the same thermal input.

High pressure in the supercritical cycle and the resulting low volumetric flow rate allow for a significant reduction in the overall footprint of the power-conversion system, when compared to the same power output of a steam-Rankine cycle. This in turn allows the heat-rejection heat exchanger and turbine to be smaller than for similar power output steam-Rankine systems.

The benefits can further translate into lower installed costs [4]. In general, increased efficiency represents increased output for the same thermal input, regardless of the thermal source (natural gas, nuclear, solar, or coal). Where fuel costs are a significant portion of overall costs (coal and natural gas fired plants), the benefit is reduced fuel costs. Where capital investments are high (nuclear and concentrating solar power), the benefit is increased output for the initial investment. In addition, the sCO_2 Brayton cycle greatly reduces fresh water consumption, due not only to increased efficiency, but also to the fact that the heat rejection temperature is significantly higher than for steam-Rankine systems, allowing for considerable heat rejection directly to air.

Other benefits include environmental improvement from greenhouse gas reduction, and dry cooling, making the system suitable for arid environments.

Commercial applications

sCO_2 Brayton power cycles provide potential solutions to a wide variety of power-generation applications. Nuclear power, concentrated solar thermal power, fossil fuel boilers, geothermal, and shipboard propulsion systems are considered favorable applications that could replace traditional steam Rankine cycles [4]. Table 1 describes applications that may be relevant to Brayton cycle commercialization efforts.

Table 1: sCO2 potential applications and configurations.

Application	**Motivation**	**Size [MWe]**	**Temperature [C]**	**Pressure [MPa]**
Advanced Reactor Designs (Includes Sodium and High Temp Reactors (gas, molten salts)	Efficiency Size Water reduction	10 – 300	350 – 800 +	20 - 35
Small Modular Reactors	Compact size Dry cooling			
Gas Turbine Bottoming		10	Low Temp	
Shipboard Propulsion	Efficiency Size	10 – 100	500 - 1000	35
Shipboard House Power	Efficiency Size	< 1 – 10	230 - 650	15 – 35
Waste Heat Recovery	Efficiency Size Simple cycles	1 – 10	< 230 - 650	15 - 35
Concentrated Solar Power	Efficiency 50% Size Dry cooling	3	700	35
Geothermal	Efficiency	1 – 50	100 - 300	15
Natural Gas fuel cycle, targeting distributed energy	Dry cooling	1-25	750	42
Fossil Fuel (indirect heating)	Efficiency Water reduction	300 – 600	550 - 900	15 – 35
Fossil Fuel (direct heating)	Efficiency Water reduction facilitates CO2 capture	300 – 600	1100 - 1500	35

Achieving a specific system design for the demo is a critical step. In order to advance component readiness, it is necessary to define the specific application, configuration and characteristics desired for the demo. Such system characterization is needed to gather full system requirements and lifecycle specifications.

Primary design criteria include:

- Heat source characteristics (temperature, available heat energy, primary heat source, waste heat stream)
- Conversion cycle configuration (simple or recompression)
- Conversion cycle specifications (electrical power output, pressure ratio, maximum temperature)
- Other significant features (dry/wet cooling, grid connectivity, normally on/off)

It is important to note, in Table 1, how size, temperature, and pressure vary based on specific applications. These ranges highlight a need to develop tools that facilitate scalable and reconfigurable strategies, instruments and tools to technology development.

System components

Brayton systems are formed by multiple components, each with its own functions, requirements and characteristics. For successful technology development, each component must be developed to adequately safe levels, and the interaction between the components also must be understood, modeled, and developed to specifications. Figure 1 shows the components of this complex system of systems. Each of these components is defined below.

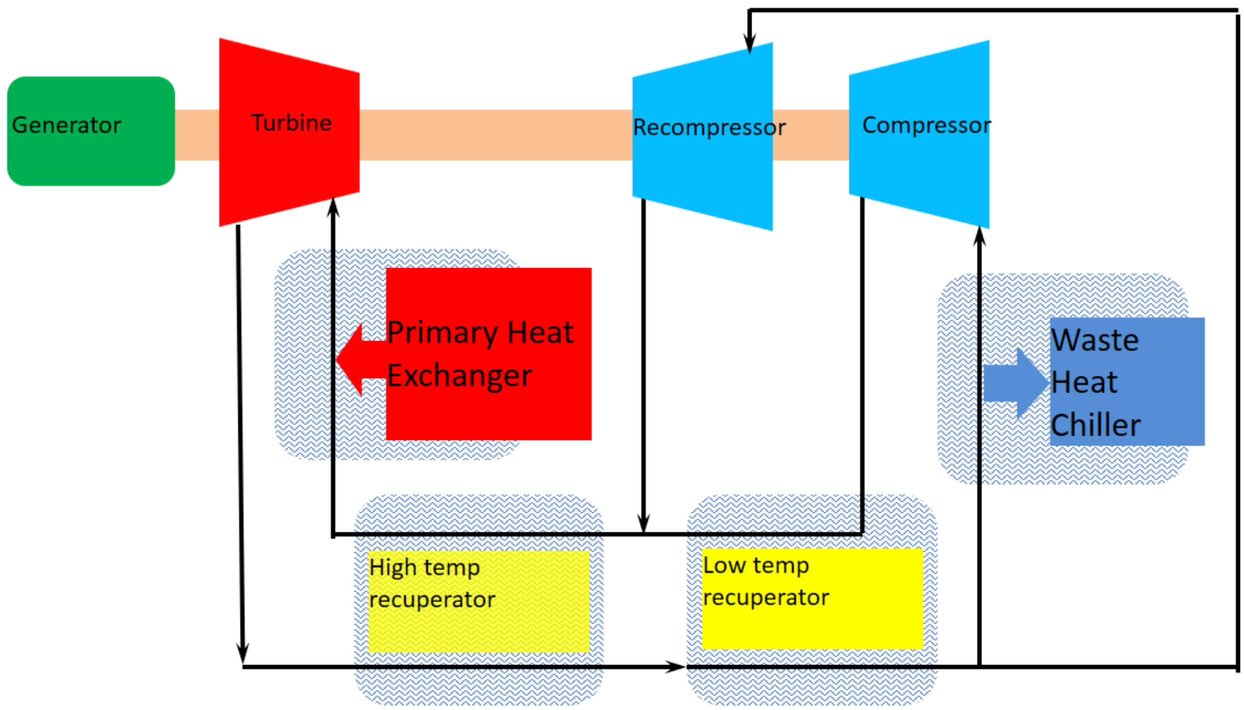

Figure 1: Recompression Closed Supercritical CO2 Brayton Cycle schematic diagram.

- **Compressor** is a mechanical device that increases the pressure of a gas by reducing its volume. A simple closed Brayton cycle includes a single stream of process fluid, so compression work is accomplished by one or more compressors in series.

- **Generator** converts mechanical energy to electrical energy in the form of alternating current. A commercial RCBC can conceivably use an alternator to provide starting power during power-up and then to convert excess shaft power to electrical power. A more likely scenario separates these functions into a starting motor and a generator.

- **Turbine** is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor.

- **Primary Heat Exchanger** is used to transfer heat between a primary heat source and the power cycle sCO_2 working fluid. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils, and air flows past the coils, which cools the coolant and heats the incoming air.

- **Recuperator** is a special purpose counter-flow energy recovery heat exchanger positioned within the supply and exhaust air streams of an air handling system, or in the exhaust gases of an industrial process, in order to recover the waste heat.

- **Waste Heat Chiller** is a heat rejection system used to maintain the thermodynamic operating point of the cycle. This technology is very well understood, with a variety of configurations in use since heat engines were first used.

Technology readiness levels

The ultimate goal of the development of sCO_2 is technology transfer and commercialization. To achieve this, it is necessary to define and measure the requirements for a safe and secure transfer and commercialization of technology. The focus of component readiness is to retire risks of system components individually, to increase the probability of a successful demonstration of the potential and viability of the technology at commercial levels. Sandia's sCO_2 team utilizes Technology Readiness Levels (TRLs) to assess the readiness of system components.

"Technology Readiness Levels (TRLs) are a method of estimating technology maturity of the Critical Technology Elements (CTEs) of a program during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. [5]"

Based on the DOE's TRL definitions, an important consideration in increasing technology readiness above TRL 4 is that "validation … should also be consistent with the requirements of potential system applications." The sCO2 Sandia team proposes that for testing TRL4 or above "the application-specific product must have been chosen and its design specified so that component configuration and any system integration is relevant." Sandia continues to gather TRA information, having completed a review on September 13, 2016 to assess the current TRL of components for small applications. The TRL levels identified are best-estimate assessments based on team practice, knowledge, and expertise for an RCBC cycle [6].

Path to Commercial Applications

Sandia has developed an integrated proposal for the critical phases of technology development: why they are needed, what testing must be accomplished, and considerations for the supporting facility [7]. Brayton testing must take into account that the power cycle is a complex system-of-systems, where successful commercialization will result in replacing a mature technology application.

Technology roadmap

A technology roadmap was created to support the development of sCO_2 Brayton systems through commercial applications. The roadmap is divided into interim stages aligned with phases of technology development. Figure 2 illustrates the interim stages of the roadmap, leading up to a commercialization goal. This staged approach develops technology by focusing on specific requirements so that the scope, milestones, actions and timelines can be focused by short-term objectives. The characteristics that define each stage are shown below.

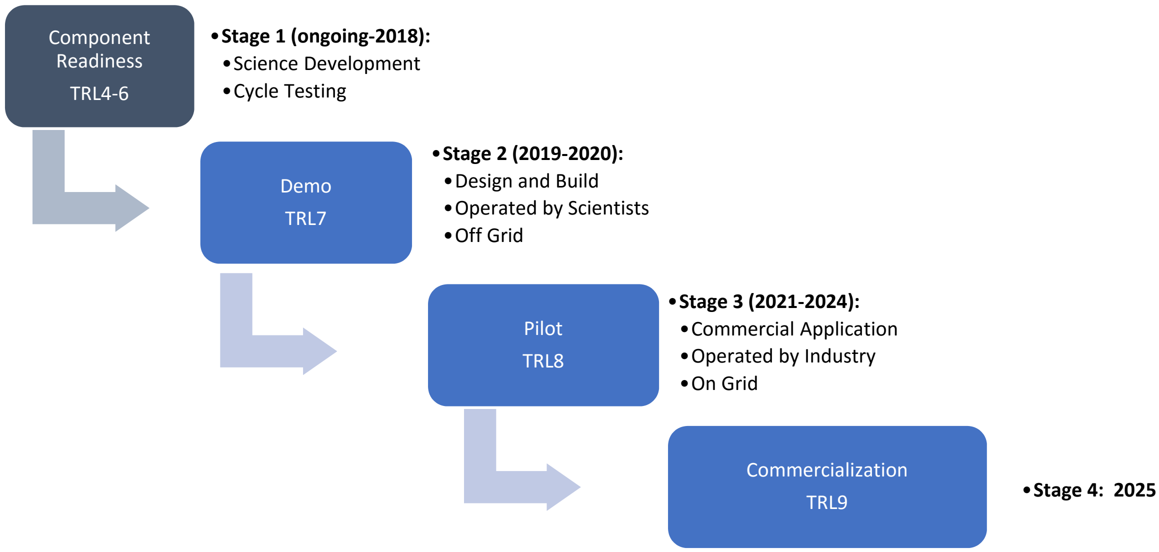

Figure 2: Roadmap stages for sCO2 commercialization.

- **Component Readiness:** Sandia has been working on sCO_2 science development since 2007. Previous work has included development of the Supercritical CO2 Brayton Cycle test-loop, controls, testing, and model validation. This stage includes all the previous work done in the technology and components, reaching a readiness level that is considered adequate for the demonstration scale. To demonstrate readiness for commercialization, it is necessary to achieve commercial scale configurations that facilitate the retirement of risks associated with sCO_2.
- **Demonstration (proof of concept):** The RCBC TA has limitations that make it impossible to demonstrate commercial scale. The demonstration aims to establish a 10MWe RCBC 550C facility capable of showing that the technology is as close to commercial scale as possible, considering actual applications of the system. However, the demonstration will not be connected to the grid (although it can include simulation of the scenario) and is expected to be normally "off." The demonstration would be capable of being turned on for multiple days at a time, allowing experiments to explore the system effects on the environment.
- **Pilot:** The Pilot phase would take the demonstration application and configuration even closer to commercial scale. It is expected that the Pilot would be connected to the grid and will be normally "on," operating for a minimum of 1000 hours. However, it would still be a research facility operated by engineers and scientists.
- **Commercial:** The main differentiator between the demonstration phase and reaching commercial scale is that during the commercial phase the operation of the facility is transferred and fully owned by industry.

Continuing technology development activities

In support of the DOE crosscut team, Sandia's activities include researching technology readiness, working with an array of organizations to improve component readiness, and testing integrated systems. This work is fully described in the DOE-NE Preliminary Roadmap to Product Commercialization [8]. Examples of such activities include:

Component Development Activities
Reaching out and engaging industry through the Federal Business Opportunity (FBO)/Cooperative Research and Development (CRADA) process creates industry interest by providing a pathway to address technical risk, to attain a better understanding of industry needs, and to consolidate information at the national laboratory advancing the development process of energy conversion systems.

Collaborations and Partnerships
Using FBO announcements to ensure fairness of opportunity, Sandia engaged with over twenty potential commercial partners, yielding nine competitive proposals in the areas of bearings, seals, and systems. Collaborative partnerships are on track to advance the technology readiness of sCO2 Brayton power cycle bearings and seals by the end of FY18.

Collaborations also include R&D work with alternative energy for DOE-EERE.

Materials
To achieve the greatest efficiencies, sCO2 Brayton systems must perform at high temperatures (>700°C turbine inlet). In this regime, material performance has not been proven. It is necessary to establish component materials requirements for commercial scale system components, and to identify the materials that will satisfy those requirements during the lifetime of a commercial system. Sandia has developed a program to identify and mitigate materials concerns.

Systems Engineering

System Definitions

A **system** is a set of interacting or interdependent components that form a complex whole.

A **subsystem** is a system in itself and a component of a larger system. It is formed by a set of components or elements.

A **component** is a set of elements that together form a functional part of the system.

An **element** is the smallest defined system unit that can be characterized by requirements and validated during testing.

A **function** is a task or work to be performed by a system, component, or element.

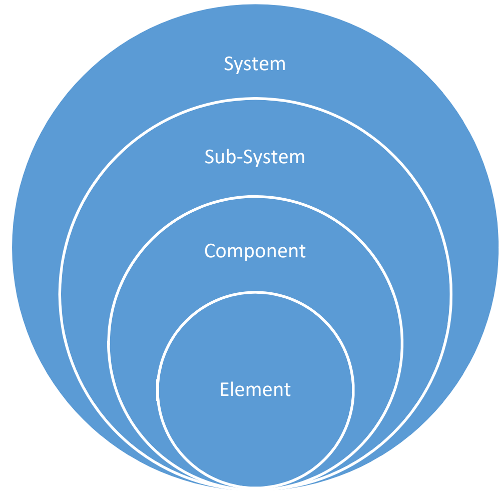

Figure 3: System definition hierarchy.

System boundaries help define the scope of the system and determine what components and functions are part of the system, and which are environmental factors.

Why Systems Engineering?

Brayton as a system-of-systems

A system is a set of components or elements that work together to accomplish a common purpose, where any change is likely to reverberate through the system and impact the outcomes. A systems analysis provides the opportunity to clearly define the requirements of each element and understand the interactions between elements, so that changes and related impact can be understood, managed and controlled. Systems engineering creates and executes an interdisciplinary process to ensure that customer and stakeholders needs (requirements) are satisfied in a high quality, trustworthy, cost-efficient and schedule compliant manner throughout a system's entire life cycle [9].

As previously stated, sCO_2 Brayton systems are a complex system-of-systems. Components and component development is only one (critical) aspect of the system that must be thoroughly considered for the successful application of the technology. A full systems engineering model of Brayton systems would detail not only the specifications that define each component and their criteria for success, but also outline how components integrate and interact with each other; how the system integrates with the facility; how the facility integrates with the human factor, tools, and the environment; and how the entire technology integrates with the energy industry, customers, and commercial stakeholders during the lifecycle. Figure 4 illustrates a simplified Brayton system, where elements include components, management and planning, integration and controls, facilities design and operations, and applications to customer, to name a few.

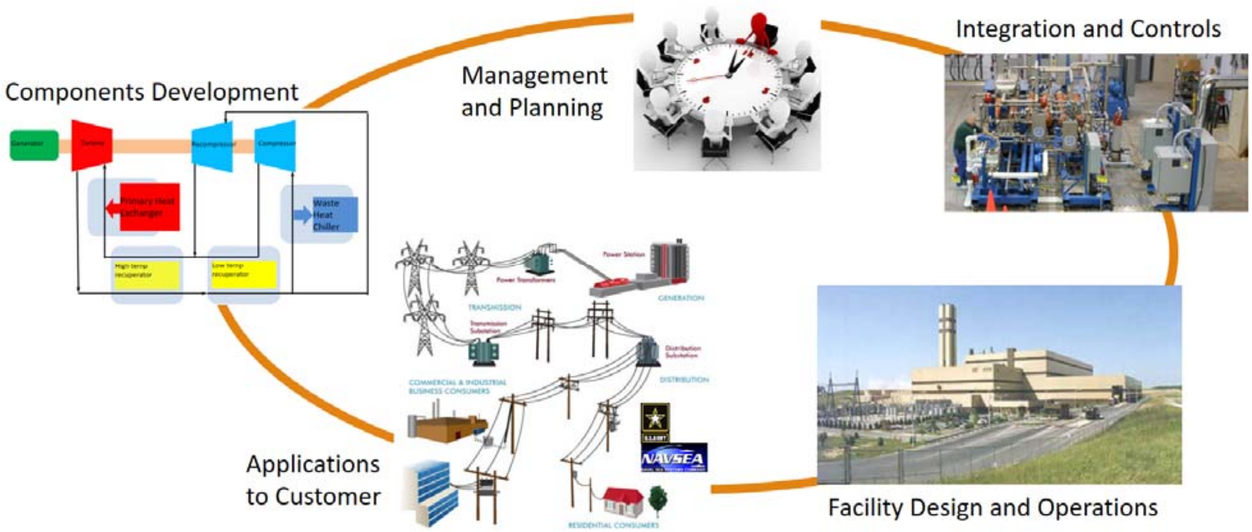

Figure 4: Commercial Brayton systems elements.

The complexity of the system requires a holistic systems view that supports the technology lifecycle, while allowing for strategic breakdown of each system component to be characterized and defined by its requirements. This project proposes an integrated systems model to support both holistic and detailed systems analysis and design. The integrated model draws from various industrial and systems engineering theories, detailed in the following sections.

Concurrent engineering for multifunctional design process

Concurrent Engineering (CE) is a systematic approach to the integrated design of products that replaces the traditional, lineal product development process with one that highlights early, concurrent consideration for every aspect of a product's development process. The CE approach requires the creation of a multifunctional team tasked with defining system requirements for each functional area. This multifunctional team is formed by experts from every stage of the product lifecycle, which allows designers visibility of full lifecycle requirements to incorporate them early in the design process, thus reducing the need to retrofit or reengineer after much work has been completed.

Several key principles to consider when applying concurrent engineering to support Brayton technology development include:

- Primary factors for success are setting and analyzing goals, directing and controlling integration, and fostering communication [10].
- Multifunctional teams, concurrency of product/process development, integration tools, information technologies, and process coordination are among the elements that enable CE to improve performance [11].
- Focus on the optimization and distribution of resources during the design and development phases ensures an effective and efficient development process [12].

- Systematic implementation of CE involves process, people, tools and technology, organizational support, metrics, buy-in, and benefits and barriers to success [**Error! Reference source not found.**].

CE was in its origins envisioned for *short life-cycle products*. The traditional product development cycle for which concurrent engineering was originally envisioned follows the product from design to sales and distribution, with limited consideration for operation and continued maintenance of the "outcome" of the design. These factors need to be considered when applying concurrent engineering to Brayton technology development.

Balance model for (holistic) work design

The Balance Model for Work Design provides foundations to support a holistic view of the system through its lifecycle. It was originally conceived within the human factors discipline as a means of evaluating on-the-job stress and identifying strategies for stress reduction [14]. It has since been developed into a more generalized tool to visualize the complexities of any work system.

The model suggests that every work system is defined within 5 core areas (which the Balance Model calls *elements*), and that a change in any of these areas will have consequences and will bring additional changes to each of the other areas. Early assessment of the resulting changes allows designers to identify required adjustments and propose solutions prior to implementation in order to support the stability of the system, allowing them to view the interaction within elements as a potential path to balance effects.

The five areas of the work system include the people that act and interact with the system, the tasks performed, the tools and technologies used, the environment within which the system operates, and the organization that defines and controls the system:

- **Tasks** – define all the activities that need to be completed, building up to the outcome of the system. One or several system outcomes must be identified, providing the scope of analysis. For each outcome, a process and interim stages of the process are then considered. The analysis of each process provides the individual stages or actions that are completed during the execution of work.
- **Tools and Technology** – considers all the instruments utilized during the execution/completion of work. This includes the degree of automation and reliability in the technology, and the availability, complexity, and performance of the tools/instruments/controls.
- **Environment** – describes all surrounding characteristics within which the work system operates. These variables are normally defined for physical climatology and geographical environments, but can also relate to social and political environments that affect the system.
- **Organization** – includes policies, procedures, rules and guidelines put in place to regulate the work system, such as broad characterizations of the organizational structure, and detailed procedures for escalation, maintenance, emergency response, operations, etc.

- **People** – considers all personnel and staffing needs, and their intrinsic characteristics. The analysis defines the roles and responsibilities of each job, what the staffing needs are for every task, and the profiles of people relevant to the system, including individuals internal and external to the system (operators, management, customers, investors, community observers, etc.).

For the Brayton system, the Balance Model would describe the inputs across any stage of technology development through commercialization, and define "work" as the function (process or action) that is conducted to transform inputs into outputs. Therefore, inputs are the five work areas and output is the product generated by the system (see Figure 5).

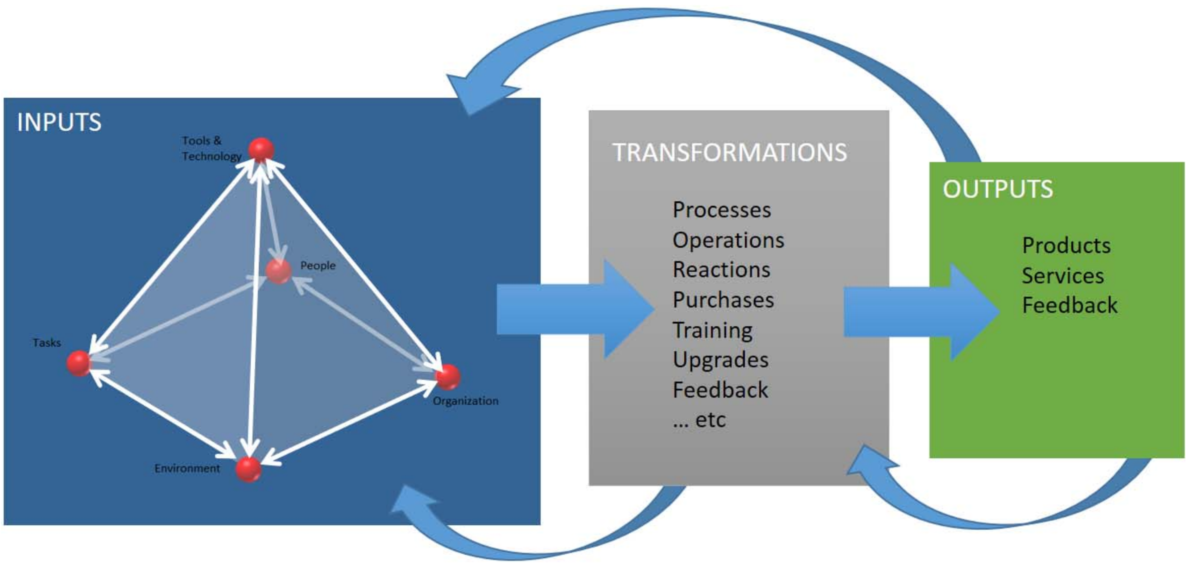

Figure 5: Applied Balance Model for holistic Brayton systems design.

Model-based systems engineering for requirements management

Model-based systems engineering redefines requirements engineering into two parallel types of activities:

- **Requirements Management** describes the needs and conditions to develop a product by categorizing stakeholder requirements as capabilities and characteristics of the system, where capabilities reflect functions or behaviors desired by stakeholders and characteristics reflect system attributes or properties.
- **Architecture and Design** describes the process by which the stakeholder requirements are turned into a system concept, and system requirements are implemented into system and sub-system architecture.

A requirements management approach provides a consistent and traceable method to produce and manage requirements documentation, enabling the assessment of requirements modification by analyzing the impact of any changes prior to making them. It also enables a methodical approach to verify that requirements are met by the design, and demonstrate how components meet system requirements. This approach also provides access to traceability from stakeholder expectations to system and component requirements, and links to testing activities and the resulting data supporting that verification.

The V Diagram [15] is commonly used to define, integrate, and validate requirements. It provides a framework for systems thinking that warrants identifying the need and its requirements as the first step of the process, followed by translating that knowledge into the model of a system that meets those needs, and lastly, validating that what has been built in the model meets those needs. This model supports the detailed development of requirements by breaking down the system and sub-systems into corresponding components and other lower-level elements, and the interactions between these elements.

The V Diagram includes verification and validation plans (Figure 6) that connect the requirement definition and validation across the system lifecycle:

- **System Validation** is the confirmation, through objective evidence, that the system will perform its intended functions. A validation plan is a set of actions used to check the compliance of any element with its purpose and functions. These actions are planned and carried out throughout the life cycle of the system.
- **System Verification** is a set of actions used to check the correctness of the full system. Verification is the confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. These actions are planned and carried out throughout the life cycle of the system.
- **Sub-System and Component Verification** is verification of the correctness applied to any sub-system and components, including documents, services, tasks, etc. in accordance with its purpose and functions.

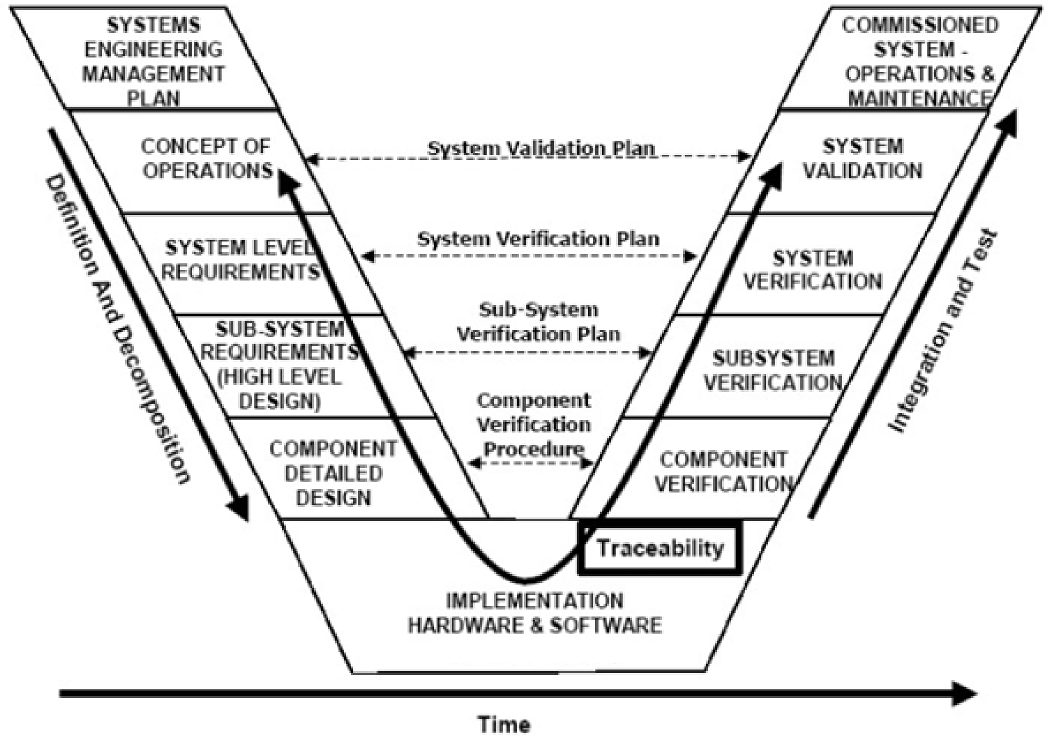

Figure 6: Systems engineering V Diagram.

The process to develop requirements by breaking the system elements down into components and sub-components is described in Figure 7. The initial stage involves the development of program input criteria, which is defined by the mission objectives and derives into high level, baseline requirements. The second stage is the identification and analysis of requirements, which seeks to identify operational, functional, performance, and design requirements for each sub-system, consistent with top-level requirements, and decomposes them into sub-system requirements to sub-system components and lower-level elements. The last stage performs the functional analysis and allocation of the requirements into the specific tasks or functions of the components. Throughout this entire process, it is important to pay at least as much attention to the interfaces between elements as to the elements themselves, and to address all lifecycle issues up-front during design.

The current scope of this report encompasses the development of program input and requirements analysis. The second stage is expected to be an ongoing iterative effort based on the contribution of stakeholders into the concurrent engineering team. The last stage, to perform functional analysis and allocation, is expected to be achieved once a target application is defined.

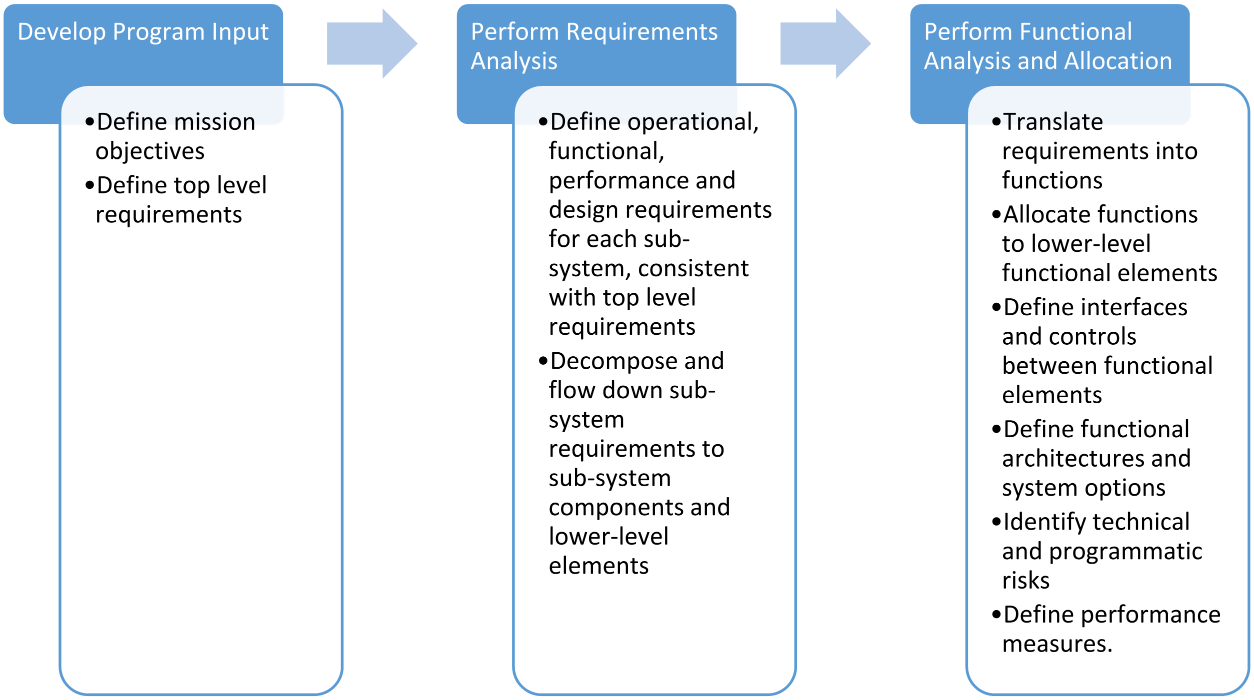

Figure 7: Requirements identification stages.

Application to Brayton Technology Development

Integrated Systems Engineering Model

The systems engineering model developed for ART energy conversion integrates Concurrent Engineering, Balance Model, Simplified V Model, and project management principles into a *Reinforced V Diagram*. The resulting model (Figure 8) supports the identification and validation of Brayton systems requirements by allowing designers to detail system-specific components relevant to the current stage in the lifecycle, while maintaining a holistic view of all system elements.

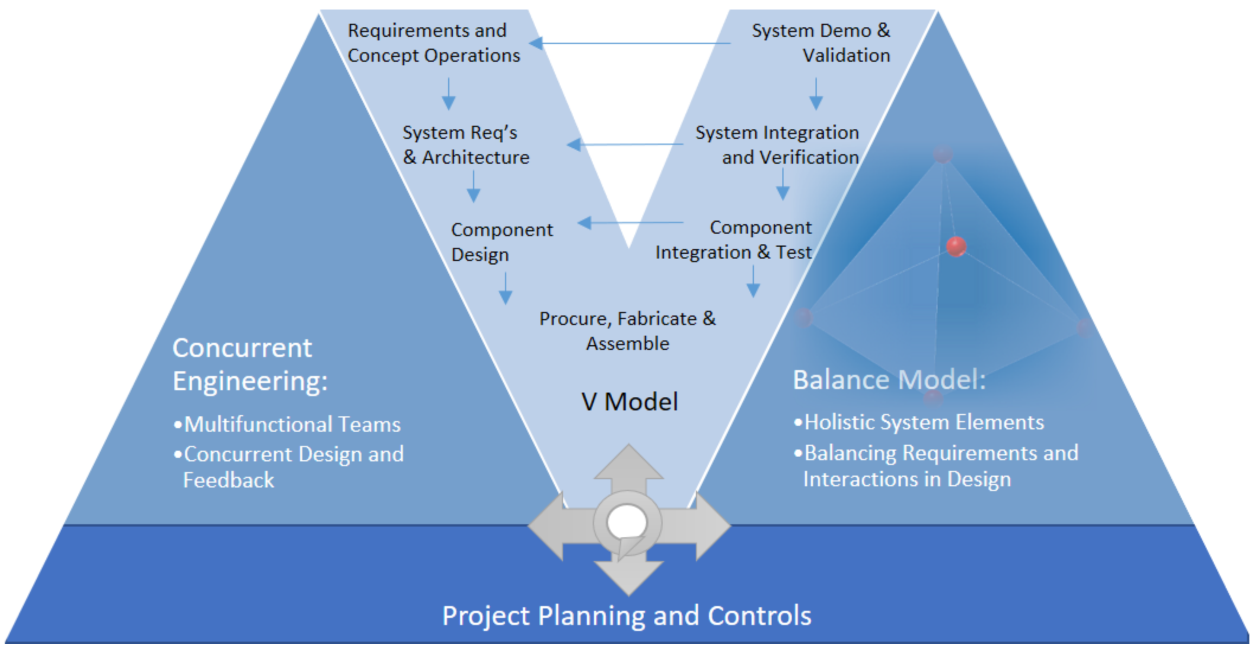

Figure 8: Reinforced V Diagram.

Through this model, Concurrent Engineering principles are used to outline the multifunctional nature of the effort, defining the team with relevant membership that represents the technological and scientific community, the development lifecycle (which includes management and operations), and stakeholder interests through the technology commercialization goal. The CE multifunctional team is tasked with concurrent verification of the relevance and impact of requirements as the Brayton system progresses through its development stages. Integrated feedback supports team discussion to reach cohesive solutions that addresses requirements and validation needs from all functional areas while being cost-effective, safe, and relevant to the system's long-term goals.

The Balance Model guides the multi-functional team to define a holistic system and supports the development of important baseline requirements that outline the impact of system outcomes. During systems definition and requirements gathering, this approach supports a comprehensive strategy that addresses definition across the 5 work system elements. During the design and validation stages, this approach supports designers in addressing component and system concerns by evaluating alternatives and solutions from all system elements and ensuring that any consequent effects are identified and assessed.

The V Diagram supports the effort to focus on the immediate and most current stage of the technology development process, without losing sight of the relationship, interaction, and impact of preceding and subsequent design stages. It allows the teams to focus on detailed requirement definitions and validation testing in accordance with defined metrics. The V Diagram also calls for the creation of a systems engineering requirements management tool that supports modeling of requirements for multiple applications, developing the potential for a scalable and reconfigurable solution that extends beyond the primary application selected.

Systems engineering and project planning are complementary disciplines that support the full-fledged management of complex projects. While systems engineering focuses on the strategic identification of requirements and breakdown of tasks to fulfill those requirements, project planning and controls ensure that resources are available for the successful completion of those tasks through project success (Figure 9). Through the process, project management supports schedule and resource allocation, monitoring project progress, controlling project risk, and retaining stakeholders' engagement.

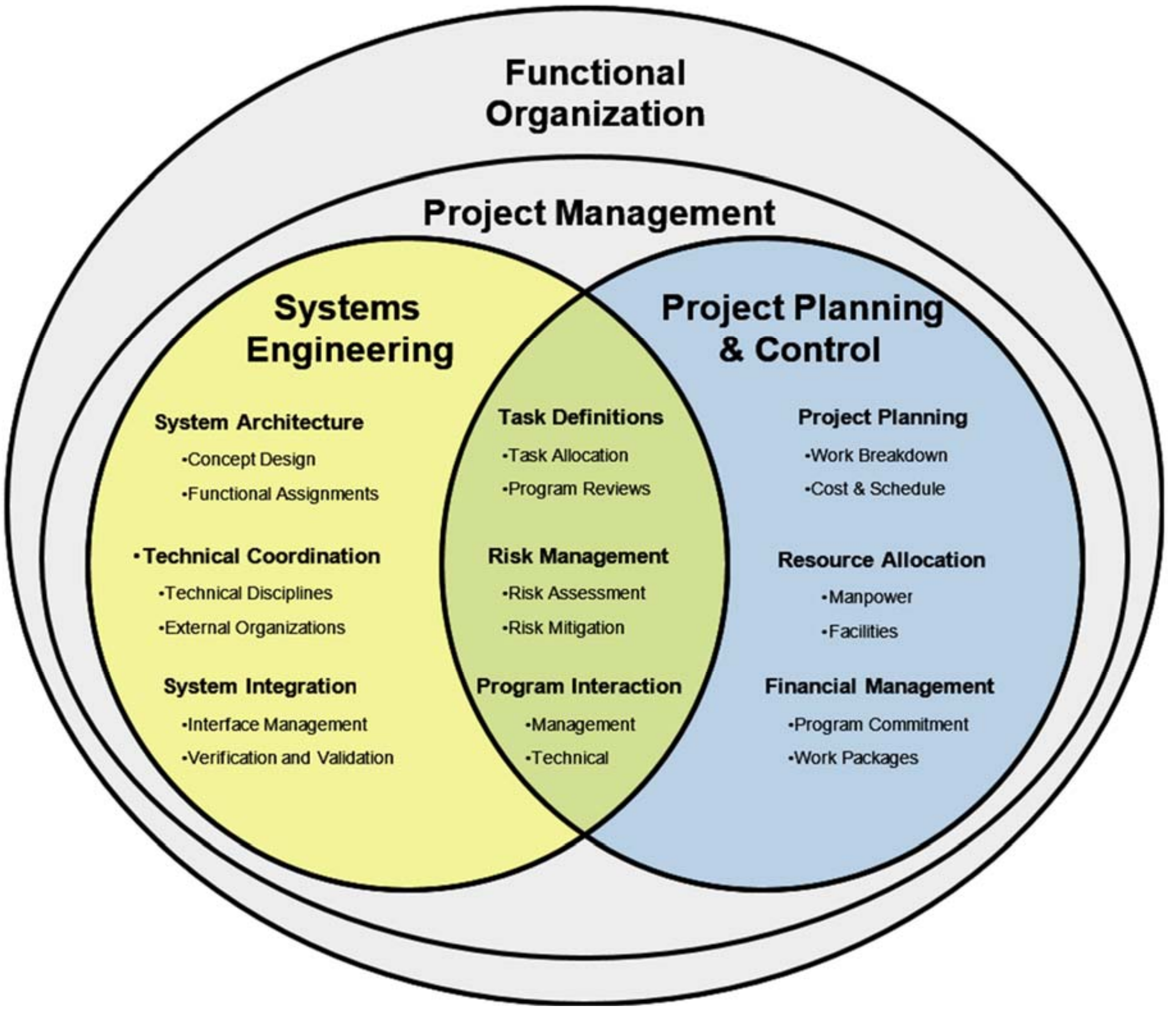

Figure 9: Systems engineering and project planning.

Sandia implemented a comprehensive project management approach for the sCO2 Brayton Program that considers the complexity of Brayton systems, the relatively early stage of technology development (in assessing component readiness), and the long-term goal of technology commercialization. A program structure was developed to highlight functional areas of technology development and their progression, allowing for their targeted development while maintaining an integrated view of the program towards the common goal. This structure collocates systems engineering and project planning (Figure 10) to consistently manage requirements, risk, and resources, and their impact throughout the program.

A program manager and project manager have been designated within a Project Management Organization (PMO) structure with specific roles to define and manage procedures pertaining to scope, schedule, cost, risk, quality, requirements, records, and change control management. Work package managers have been identified as principal investigators and deputy project managers within each focus area.

Focus Area	Sub-Area	Objectives
1 Management and Integration		
Includes the identification and support of program variables for successful sCO2 commercialization, such as roadmapping, systems and concurrent engineering, TRL management, system metrics and economic market assessment.		
	1.01 Roadmap	Develop and manage integrated roadmap for STEP
	1.02 System Engineering	System Requirements for SFR RCBC, CSP and Fossil Heat Recovery
	1.03 Economics	Cross-cutting Economic Model Identifying Value Engineering Opportunities
	1.04 Administration	Office Administrative tasks to support Brayton mission
2 sCO2 Materials Development		
Identification/ validation of materials that will satisfy the performance requirements for each component in a commercial scale system, using commercial purity grade sCO2.		
	2.01 Materials support for a future commercial scale sCO2 power system	Integral component to the system development efforts in Sandia-NM, providing timely materials analyses support / troubleshooting & evaluating the performance of materials used in piping, heat exchangers, and bearings for S-CO2 systems.
	2.02 Development of NE-Focused sCO2 Structural Materials Consortium and Experimental Program	Identify and Resolve structural materials issues involved in the development of S-CO2 energy conversion systems for Advanced Nuclear Reactor Technologies
3 Commercial Component Development		
Facilitate commercialization of domestic heat exchanger, Turbomachinery, Cycle Development, Bearings and Seals technology and other components and systems.		
	3.01 Turbomachinery Development	sCO2 Turbine designs: RCBC Turbo Machinery Design for full system analysis at 550C
	3.02 Compressor	sCO2 Compressor Designs: 1MW 550-700 C, 5.5 Kg/sec Turbo Compressor Tested
	3.03 Recuperators	sCO2 Recuperator Designs
	3.04 Bearings	Bearing design and qualification for sCO2 service
	3.05 Seals	Seal design and qualification for sCO2 service
	3.06 Piping and Casting	High Temperature/Pressure piping and castings for sCO2 Service
	3.07 Primary Heat Exchanger	Development of Primary Heat Exchanger for sCO2 System efficiency
	3.08 Heat Rejection	Low cost heat rejection for maximum net conversion efficiency
	3.09 Valves	Flow control valves for high mass flow rates fo sCO2
	3.10 Instrumentation	Unique Instrumentation for commercial use on a power plant
	3.11 Generation & Grid	Power Generation to meet dynamic conditions for grid integration without reactor impact
4 System Integration		
Facilitate the integration of materials, components and programmatic research into commercially viable Brayton system applications, including prototyping, commissioning and piloting operations.		
	4.01 Prototype Systems	Development of Process, O&M, and Maintenance Protocols
	4.02 System Commissioning	Commissioning of full system for commercial applications and deployment
	4.03 Pilot Operations	Operations monitoring when Candidate 10 MWe system is fielded.
5 Development Platform Operations and Maintenance		
Upgrade and maintain the Development Platform (DP) with new subsystems and upgraded infrastructure, including spare parts inventory to ensure continued DP operational readiness.		
	5.01 Operations 5.02 Maintenance 5.03 Infrastructure	Upgrade and maintain the Development Platform (DP) with new subsystems and upgraded infrastructure, including spare parts inventory to ensure continued DP operational readiness.
6 sCO2 Brayton Cycle Research and Development		
Advanced Development of Brayton Engines exploiting the benefits of Supercritical Fluids, Compact Heat Exchangers, and associated cycle variations with a goal of clean coal power production.		
	6.01 Advanced Cycle Configurations 6.02 Advanced Heat Exchangers 6.03 Advanced Heat Rejection 6.04 Advanced Supercritical Fluids 6.05 Crosscut Collaborative Research	Advanced Development of Brayton Engines exploiting the benefits of Supercritical Fluids, Compact Heat Exchangers, and associated cycle variations.

Figure 10:Sandia's sCO2 Brayton Program structure.

Programmatic input – Mission and objectives

Programmatic criteria are needed to guide the baseline requirements of the systems engineering model. Based on ART and STEP common goals, Sandia developed the following Brayton mission:

"By the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology."

The technology roadmap that supports this mission further specified the following objectives:

- Ensure component readiness for the successful launch of sCO_2 Brayton Cycle demonstration for NE applications, supporting the mission.
- Support the development of a system that is re-configurable and scalable, allowing the testing of commercially attractive configurations and system components that can be transferred to industry.
- Establish the foundations for successful commercialization of the technology inclusive of elements that enable means to increase the reliability and resiliency of electric power systems.

These criteria can be qualified within the 5 elements of the work system (Table 2) to identify the key membership of the multifunctional concurrent engineering team, which will then define baseline systems requirements and system boundaries needed to apply detailed requirements management.

Table 2: Programmatic input as work system criteria.

People	Sandia stakeholders Industry stakeholders NE stakeholders Commercial stakeholders
Organization	Commercial application Industry NE
Tools and Technology	550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System Re-configurable Scalable
Environment	Foundations for successful commercialization Inclusive of elements that enable means to increase the reliability and resiliency of electric power systems
Tasks	Energy conversion Fully operational facility Identification and retirement of technical risks Testing of system components Testing of commercially attractive configurations

Building a multi-functional team

The multi-functional team advocated within concurrent engineering models is based on collaborative partners that work together towards a shared outcome.

The team must have three key attributes:

- The ability to successfully address the inherent uncertainties of innovation;
- The ability to represent a broad range of professional skills, including engineering, science, marketing, manufacturing, operations, emergency preparedness, and industry regulations;
- Most of those involved will be professional knowledge workers; that is, individuals whose main responsibility and asset is knowledge, such as engineers and scientists.

The Brayton CE team must be composed of experts representing every functional area of the product lifecycle. In general, membership should represent each of the criteria identified within the work system elements and can be expanded as the technology progresses to incorporate changes in scope and detailed definition as needed. To accomplish a successful design, it is necessary to bring together representatives of potential application as well as experts from all areas of the technology life-cycle. This includes the regulatory environment, Brayton developers, and energy providers. The best approach is to form this team at the early design stages because such collaboration is difficult to accomplish in the late stages due to too much detailed engineering that would need to be redone.

Team members may be identified as:

- *Designers* – those addressing technical and regulatory requirements pertaining to technology or industry regulations. Examples include laboratory personnel, technicians, scientists, engineers, and designers; or
- *Advisors* – those providing feedback on the validity of assumptions and representing the interests of the government, the business, or potential applications. Examples are policy makers and lobbyists, business and strategy representatives, manufacturers, suppliers, and scientists.

In this environment, each of the expert representatives holds equal ranking roles work to achieve a common goal. As the design then evolves, each of the representatives has knowledge and appreciation of the requirements and impacts of the others. This allows discussion, informed decisions, and effective compromise. The program and project managers work as subject matter experts (SMEs) within the CE team to complete the requirements-gathering documentation, including requirements definition and analysis. This stage allows the CE team to identify whether additional team members need to be incorporated into the project and to identify the constraints.

To support this effort, Sandia has been working on stakeholders' engagement through several means, including the execution of CRADA, FBO, and WFO projects, support for DOE's Brayton Industry Week, and planned development for a Brayton Community of Practice (CoP).

Baseline system requirements and boundaries

The first task of the CE team is to establish baseline requirements that support program mission and objectives. The following initial baseline requirements are derived from programmatic criteria with a focus on STEP-NE goals:

The Brayton System to be developed will:
• Fulfill the demands/requirements for which it is built
• Be an economical and functional alternative when compared to the best existing alternative
• Meet regulatory requirements
• Support cost efficiency during the lifecycle
• Show flexibility in design, to allow for scalable and reconfigurable applications

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These baseline requirements will guide the application of systems engineering to a Brayton technology solution. However, much more detail is needed to model the requirements of a Brayton system. While the ultimate goal is the commercial application of the technology, the current scope should focus on component development for a successful technology demonstration. Given the current stages of technology development and the diversity in potential applications, it is critical to define boundaries to define the system and its environment.

Guided by the roadmap, which focuses on a **sodium fast reactor (SFR) sCO_2 RCBC** demonstration test, the system boundaries can be defined as shown in Table 3.

Table 3: System model boundaries.

	BOUNDARY	COMMENTS
SYSTEM CONFIGURATION	Size: 10 MWe Temp: 550˚C Pressure: 20-35 MPa	The near-term objective is to establish an operating, commercially scalable RCBC demonstration system with the lowest risk possible.
APPLICATIONS	Sodium Fast Reactor RCBC	Exploration and development of sCO_2 Brayton thermal cycle for applications that couple nuclear reactors to power generation with improved conversion efficiency and reduced plant size, supporting NE-STEP goals.
COMPONENTS	Compressor Generator Turbine Primary Heat Exchanger Recuperators Waste Heat Chiller	Includes all sub-components and sub-system controls, interfaces, and interactions, such as materials development for bearings and seals, valves, and interaction between components and sub-components.

	ENVIRONMENT	COMMENTS
LIFECYCLE STAGES	Component Readiness (TRL 4-6) Demonstration (TRL 7)	The currents scope focuses on component readiness with view to design and build an off-grid demonstration to be operated by scientists.
COMMERCIALIZATION	Operating Commercially Scalable Reconfigurable	As applicable to system lifecycle and crosscut target applications.

Further system specifications are needed to ensure that the system can “fulfill the requirements for which it is built,” and in many cases these are dependent on the target application. Based on this criteria, the Brayton System Diagram (Figure 11) was defined to establish temperatures and pressures for the components of the SFR application of a 10 MWe, 550C sCO2 RCBC Brayton system. This system is based on conservative assumptions, including 80% efficient compressors and 1% pressure loss in each component.

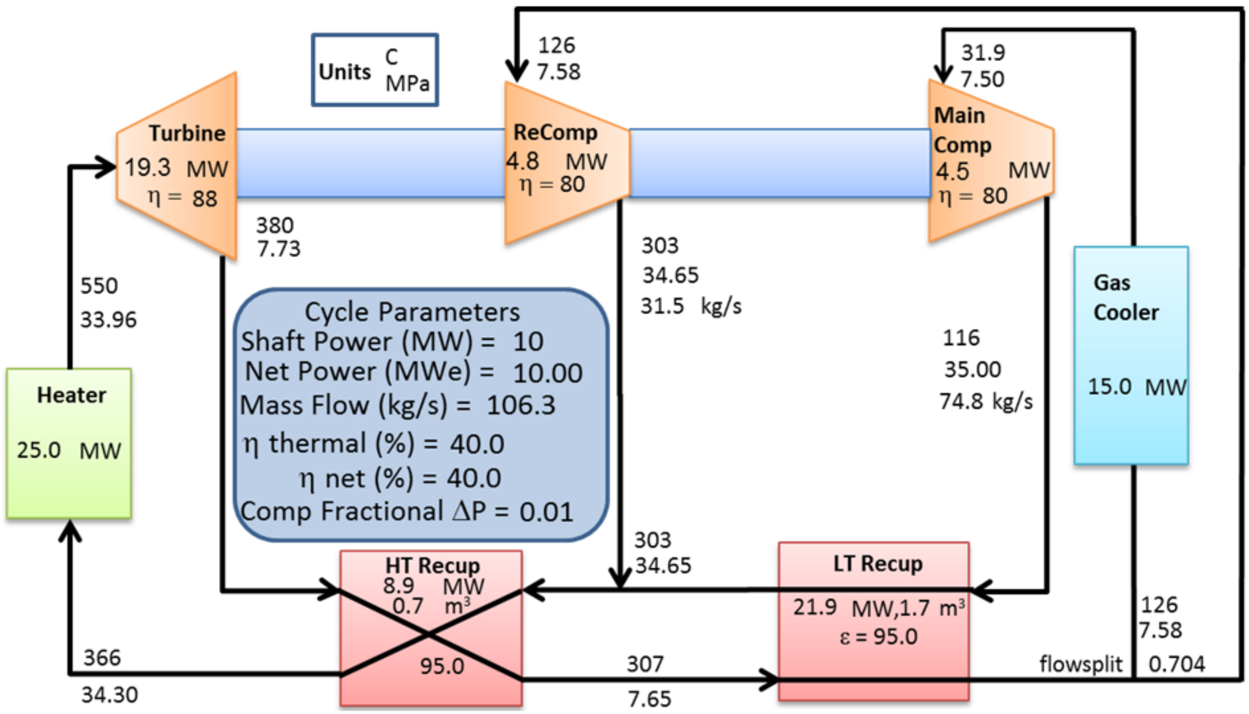

Figure 11: Brayton System Diagram specifications.

In addition, performance and lifecycle specifications for the sodium fast reactor, such as those in Table 4, may be needed to clearly define the requirements of the Brayton system as a component of the reactor.

Table 4: Example of performance and lifecycle specifications to define reactor system requirements.

Performance Specifications	Life-Cycle Specifications
Energy generation	Maintenance
Output	Expected life
Refueling	Regulations
Technology	Personnel
Safety	Output-throughput demand
Security	Decommissioning
Operations	

It is precisely because this extensive and time-consuming process is dependent on applications, and the variety of applications for the Brayton system can be so broad, that one of the baseline requirements is to show flexibility in design, in order to allow for scalable and reconfigurable applications of the system.

Since the systems engineering Brayton requirements model includes exploring reconfigurable and scalable considerations, a holistic representation of requirements is needed for specifications that may or may not vary according to application. The high-level focus areas defined in the Brayton Program structure (Figure 12) can provide the foundation for holistic modeling.

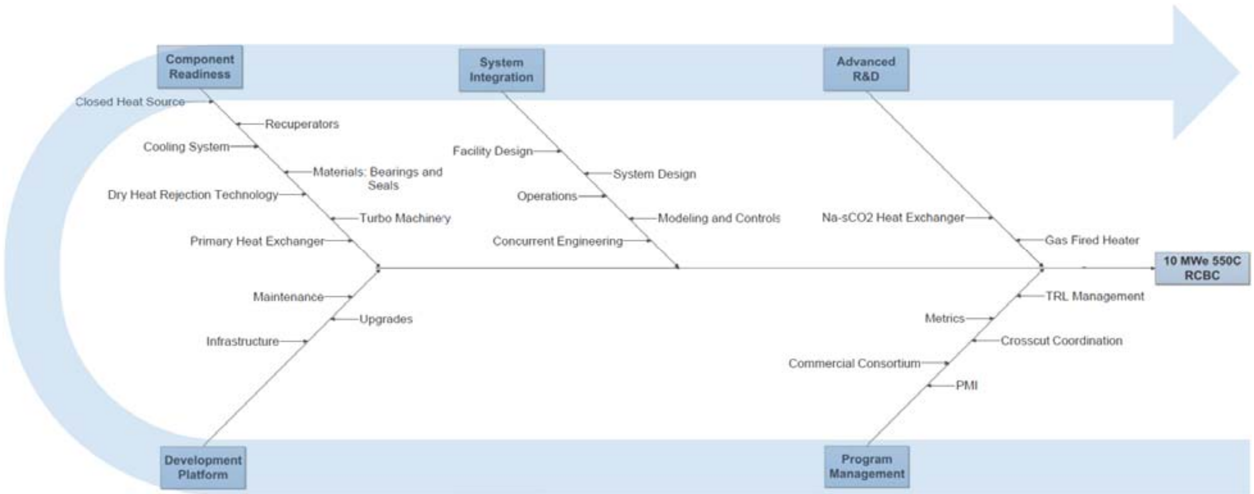

Figure 12: Brayton Program structure.

Figure 13 shows how this approach allows the designer to focus on the specifications of a particular area, while maintaining the holistic systems view, taking as an example the High Temperature Recuperator (HTR), which is one of the two recuperators identified for Component Readiness development.

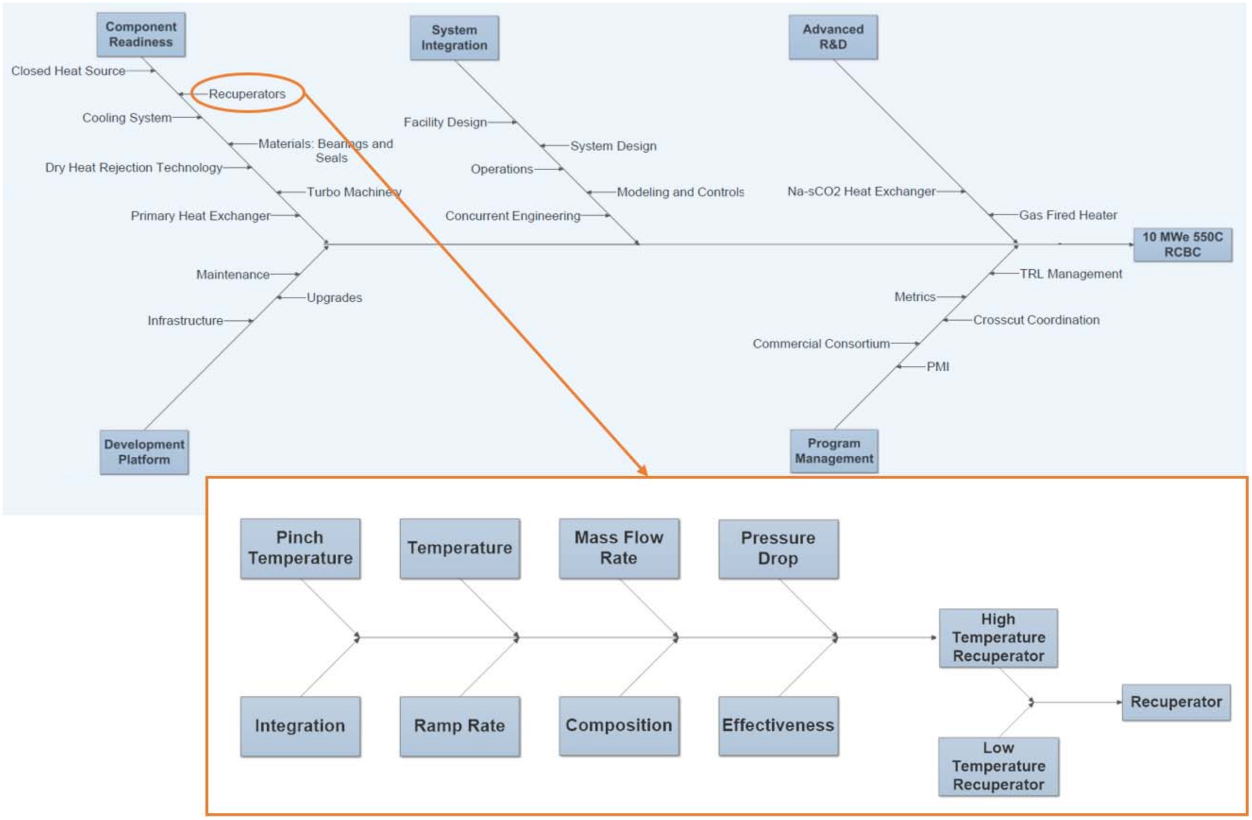

Figure 13: High Temperature Recuperator requirements outline.

Requirements and validation criteria must also be documented for each design element. A useful definition of requirements must ensure that they are unambiguous, correct, verifiable, and design independent (meaning they should not impose an implementation approach, solution, or technology). Table 5 shows an example of a requirements breakdown exercise as applied to the High Temperature Recuperator, including areas where specific requirements are still unknown.

Interactions within element specifications, and between elements, sub-components, and components must also be documented to ensure that they are reflected in the model, as these are critical for cross-component design and systems balancing. The complexity of the system, components, sub-components, and interactions highlights the need to utilize a Model Based Systems Engineering (MBSE) tool to support detailed requirements modeling.

Table 5: Sample requirements breakdown for High Temperature Recuperator.

Component	Specification	Requirements	Validation Criteria
High Temperature Recuperator	Temperature (K)	The sCO2 RCBC High Temperature Recuperator shall have a Hot Inlet Temperature of 680K or less.	K ≤ 680 hot inlet
	Temperature (K)	The sCO2 RCBC HTR shall have a Hot Outlet Temperature of 506K or greater based on efficiency.	K ≥ 506 hot outlet
	Temperature (K)	The sCO2 RCBC HTR shall have a Cold Inlet Temperature of 486K or greater.	K ≥ 486 cold inlet
	Temperature (K)	The sCO2 RCBC HTR shall have a Cold Outlet Temperature of 634K or greater.	K ≥ 634 cold outlet
	Pinch temperature	The sCO2 RCBC HTR shall have a pinch Temperature of 20 degrees C (293.15K)	K = 293.15 pinch
	Mass flow Rate	The sCO2 RCBE HTR shall have a mass flow rate of 50kg/s each side or greater.	≥ 50kg/s each side
	Pressure drop	The sCO2 RCBE HTR shall have a pressure drop (expected performance) of 1%.	Pressure drop = 1%
	Effectiveness	The sCO2 RCBC HTR shall have an effectiveness (NTU method) of 90% or better.	Effectiveness ≥ 90%
	Composition	The sCO2 RCBC HTR shall be made of materials that handle the temperature and pressure requirements as defined by the system model.	Materials that can survive 680K
	Thermal cycling	Thermal cycle requirements consistent with required capacity factor in operation.	> 90% capacity operations
	Ramp rate	Commensurate with startup and shut down of the heat source.	Startup ≤ 2 hrs Shutdown ≤ 2 hrs
	Integration	Interfacial connections are consistent with reconfiguration principles of the cycle.	Commensurate with ASME code requirements for welded junctions

Selection of a Systems Engineering Tool

Systems engineering based on document control (such as the requirements shown in Table 5) is prone to human error. The V Diagram calls for extensive documentation from identification to validation of requirements. This complexity calls for specific tools capable of ensuring proper updating and traceability of system requirements, interactions, and validations [15].

An assessment of Model Based Systems Engineering (MBSE) tools was undertaken to select a software-based tool appropriate for the Brayton program. To qualify for review, tools had to be available to industry and supported within Sandia National Laboratories. The focus was on tools that could provide near-term requirements management, and scale to meet program needs at the demonstration and commercialization phases. The immediate need was for a software platform that could quickly meet requirement technical readiness level evaluations and be scalable to the pilot-test and higher temperatures. The model-based tool search began with delineating the capabilities required by the Brayton team (Table 6).

Table 6: Initial tool criteria.

Capability	Considerations
User-friendly interface	Easy installation, access, and usability for the entire team.
Accessibility	Team access, commercial partners access, security, other?
One-stop shopping, SE from concept to grave	Everything located in one place, document archiving (retention), other?
Import/Export to other applications	Excel, PowerPoint, other?
Cost	Shared/individual license, cost per license, amount of training required, and cost of training.
Requirements Management	Traceability, version control, gaps, TRL.
Long-term scalability and modularity	Ability to reconfigure components and requirements into multiple project configurations simultaneously. No repetition of requirements/data entry for new projects.
Support/Tech support	Tool supported by Sandia? Support provided by supplier?
Security and backups	How is the security of the tool tested/validated with Sandia's security requirements? If cloud-based, what is the reliability and availability? Encryption? Etc.
Software training	Is there training available to learn the software tool?
Ease of configuration or customization	Is the tool customizable at all? Would changes be required by the supplier or can we manage the technology?
Provide a platform for Risk Management	Consistency in risk management and promoting use in project management.
Prepare for and conduct stage gate reviews	Objectively validate technology maturity to customers.
Prepare and execute TRL checklists	Consider viable interest, intent or commitment to transition.

Live software tool demonstrations were set up for the leading options to aid in the selection process. The following software tools were evaluated:

- Cradle – Requirements tool from 3SL (requires Vdot). Used for requirements capture, management and publishing.
- Vdot – Process and program management tool from ESI Group (requires Cradle). Used for project execution, process visibility, information flow, task automation, and team management.
- TPMM – Technology Program Management Model, a SharePoint solution set from the US Space and Missile Command.
- Astah – Architecture modeling tool which supports object-oriented software design.
- Doors – Dynamic Object Oriented Requirements System, a requirement management tool.
- Genesys – Model-centric system modeling tool with enterprise ready architecture from Vitech.

A review of Sandia's existing systems engineering resources and lessons-learned narrowed the list of possible MBSE tools to Astah SysML and Genesys. Cradle, Vdot, TPPM, and Doors were removed from consideration based on software interface complexity, cost, and significant training requirements.

Astah SysML

Due to the analysts' previous knowledge and familiarity with the technology, Astah was selected for initial system architecture development and requirements management. Astah SysML is a lightweight and user-friendly tool that allows modeling and analysis of complex systems.

Astah uses SysML, a general-purpose graphical modeling language, for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures and facilities. Astah SysML is a common language uses by mechanical, electronic, and software engineers to design safe, complex systems architecture diagrams swiftly, with intuitive interface design.

Figure 14 shows the Project View that provides an overview of the whole project in a tree structure, and enables you to navigate between the diagrams.

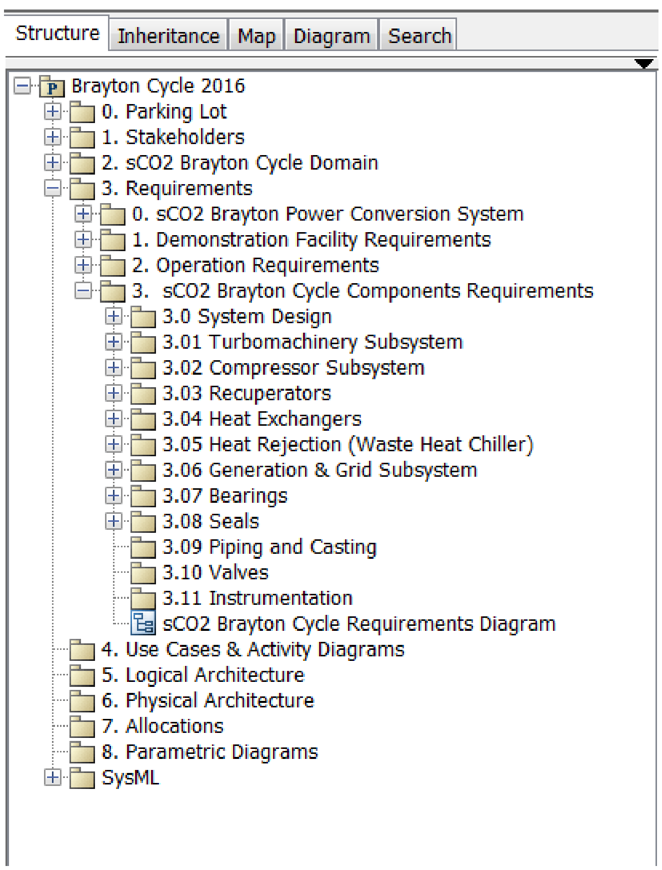

Figure 14: Astah Project View.

Although preliminary assessment of the tool suggests that it meets all the capability needs, it is possible that as the program develops it may be necessary to use a more robust software platform.

Genesys MBSE

The Genesys MBSE platform provides improved capabilities and functionality. Genesys is not intuitive, however with a four-day training class provided by Vitech, general application of the software can be performed. Using Genesys for the Brayton program would provide significant benefits associated with requirements determination from originating documents, integrated system behavior, interface modeling, and artifact generation (Genesys-created reports). In addition to importing existing system requirements from Microsoft-based documents, Genesys can search the documents for user-defined key words such as shall, should, needs to, etc. and pull them into the requirements hierarchy while maintaining traceability to the original document (original stakeholder). Genesys can create all the necessary diagrams to represent the system, including system behavior diagrams (which show what a system does or appears to do without regard to how it does it). Once Enhanced Functional Flow Block Diagrams (EFFBDs) are created, functions within the model can be simulated to determine model validity, and the results analyzed. At any stage of system model development, Genesys Report Writer can generate area-specific (requirements, risk, function, integration) or complete system reports.

Genesys licensing is more expensive and use of the application requires training for consistent and effective use. Not all Brayton team members would need to work within Genesys. The ease with which content can be shared outside of the model makes limited users a common and practical solution. Long term it is a more effective MBSE tool and its use would benefit the Brayton program.

Requirements for sCO2 Brayton Systems

Developing program input

A basic system architecture was created in Astah, based on high-level structural architecture and high-level requirements, from the following reports:

- Level 3 Milestone Report: Technology Roadmap for Energy Conversion Maturation, Work Package [8].
- Level 2 Milestone Report: Supercritical CO2 Power Conversion System (10MW Class) [16].
- Level 3 Milestone Report: M3AT-16SN1902013: Compact sCO2 Heat Exchanger Development.
- *Supercritical Co2 Brayton Cycle Program*, Quantigy, January 2016 [17].
- *System Definition: 10 MWe Supercritical Carbon Dioxide Recompression Closed Brayton Cycle Demonstration Power System, Physical and Procedural Components*, Quantigy, January 2016 [18].

Figure 15 summarizes the high-level sCO2 Brayton Conversion system requirements that will be decomposed and allocated to specific subsystems and components. The high-level system begins with the definition of requirements based on two system criteria established by the Sandia Brayton mission:

1. To establish an operational sCO2 Brayton power conversion system; "…shall develop…a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System."
2. That such system will have low risk; "…will allow the systematic identification and retirement of technical risks and testing of components…"

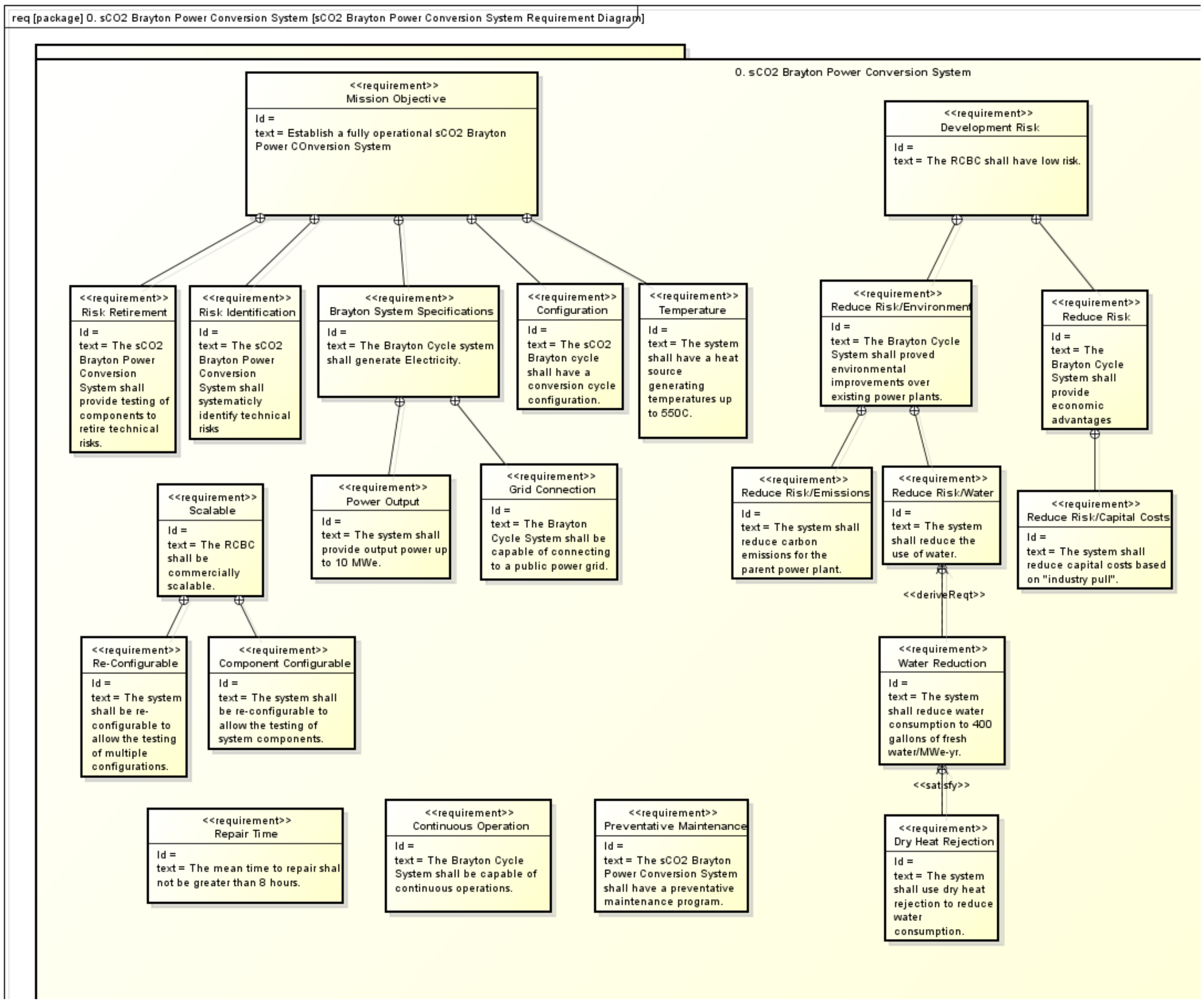

Figure 15: sCO2 Brayton Conversion system requirements diagram.

To facilitate further requirements gathering, it is necessary to identify the system stakeholders that must provide input and output criteria for the system. The Concurrent Engineering team must seek out and have representation from each stakeholder group to ensure a holistic model is designed for the system. Figure 16 summarizes the active and passive role of stakeholders based on the nature of their role during system requirements definition, providing input and/or output criteria (Table 7).

Table 7: System stakeholders I/O.

Inputs		Inputs and Outputs
City planners	Security	Brayton System owners
Environment	Testers	Industry partners
Installers		Operator
Local residents		Sponsors/Customers
Manufacturers		Utilities
Regulators		

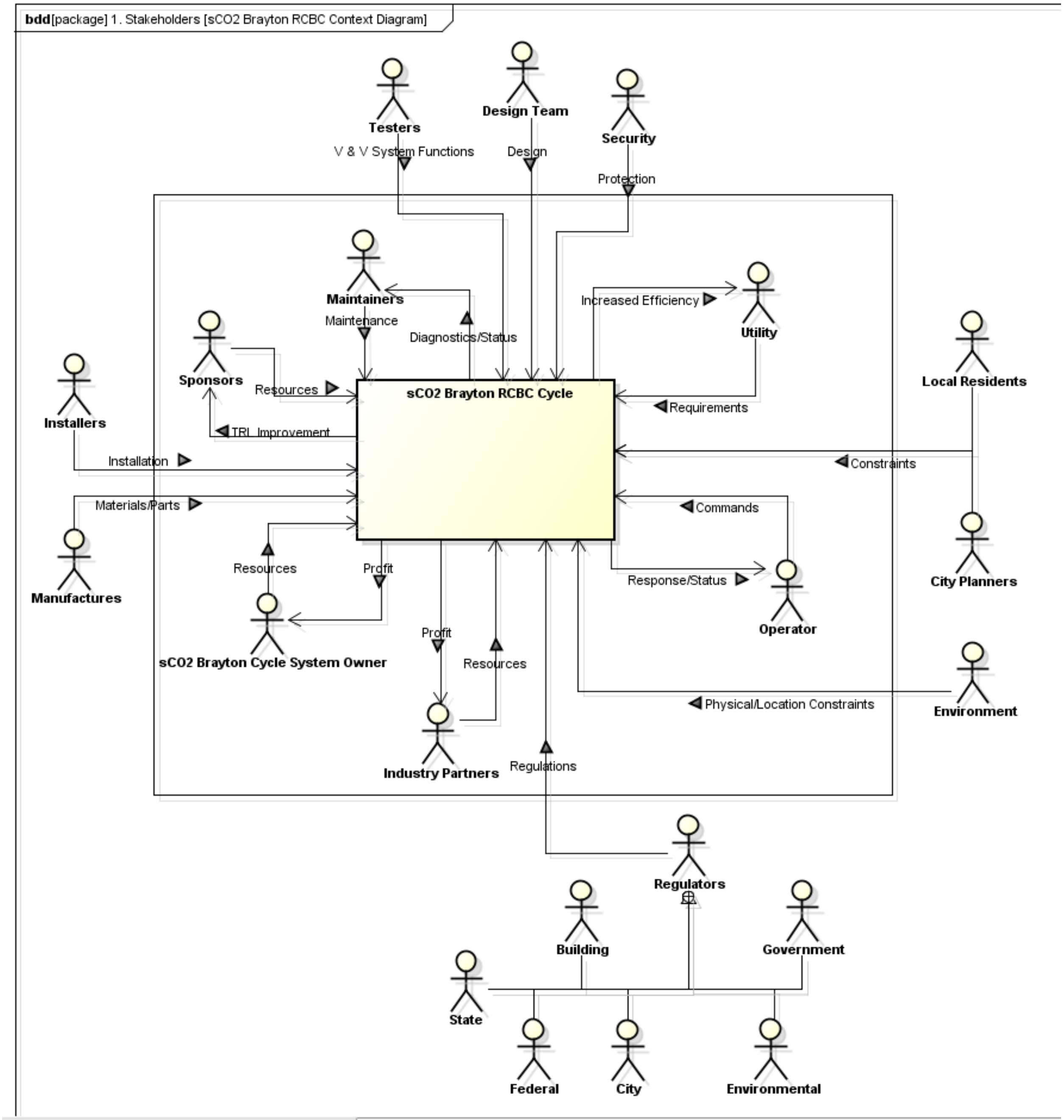

Figure 16: sCO2 Brayton RCBC Cycle stakeholders diagram.

Performing requirements analysis

As previously stated, requirements gathering for the Brayton system is dependent on stakeholders' involvement and the target application for the system. The current status of technology development generates a major focus on requirements analysis for components development. This process is still ongoing, but Figure 17 shows a preliminary view of the Astah model within the sCO2 Brayton Cycle subsystems. For better visibility, Figure 18 zooms in on the subsystems view contained in the pane seen on the right side of Figure 17.

The use of the MSBE tool allows the designer to adopt a holistic systems lifecycle view at any point during the design process, documenting requirements as soon as the information is available, and ensuring that connections and relationships are updated as needed. To demonstrate this functionality, while the current focus of this effort is on component development due to the status of the technology, some Operations (Figure 19) and Facility (Figure 20) requirements have already been documented. This allows for the holistic lifecycle view of the system from the beginning.

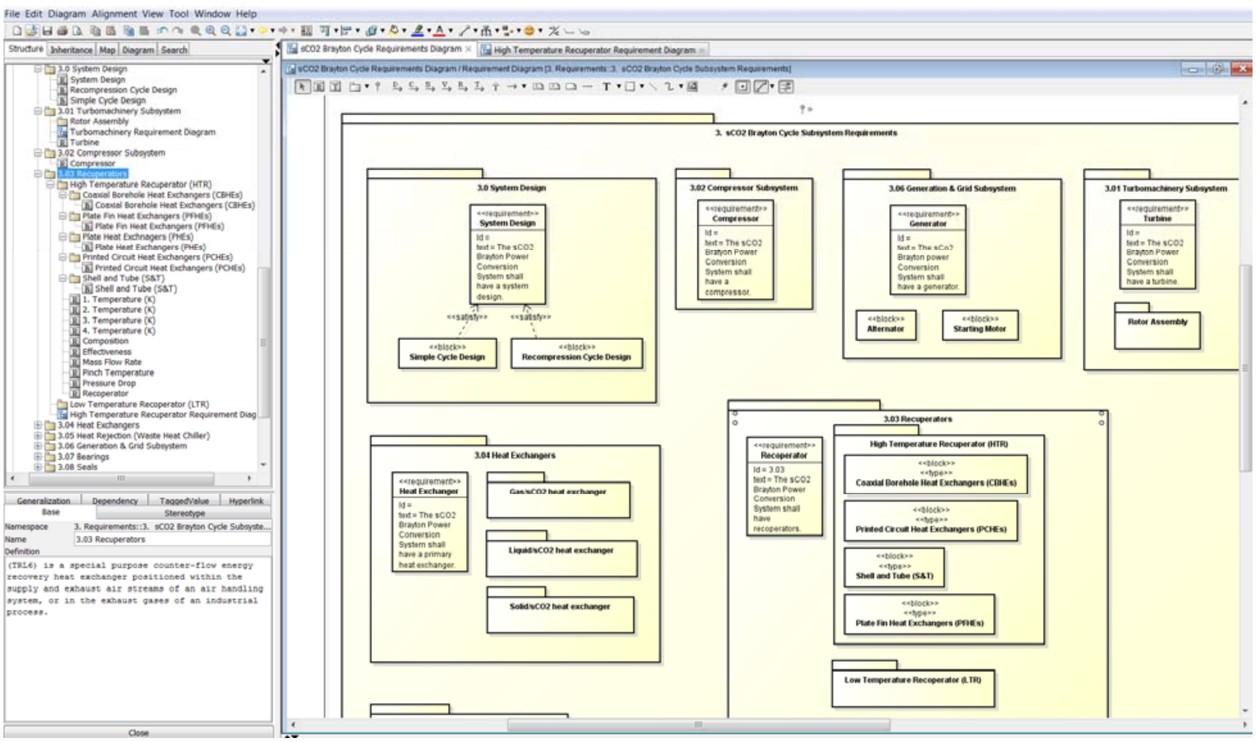

Figure 17: Astah preliminary sCO2 Brayton Cycle system.

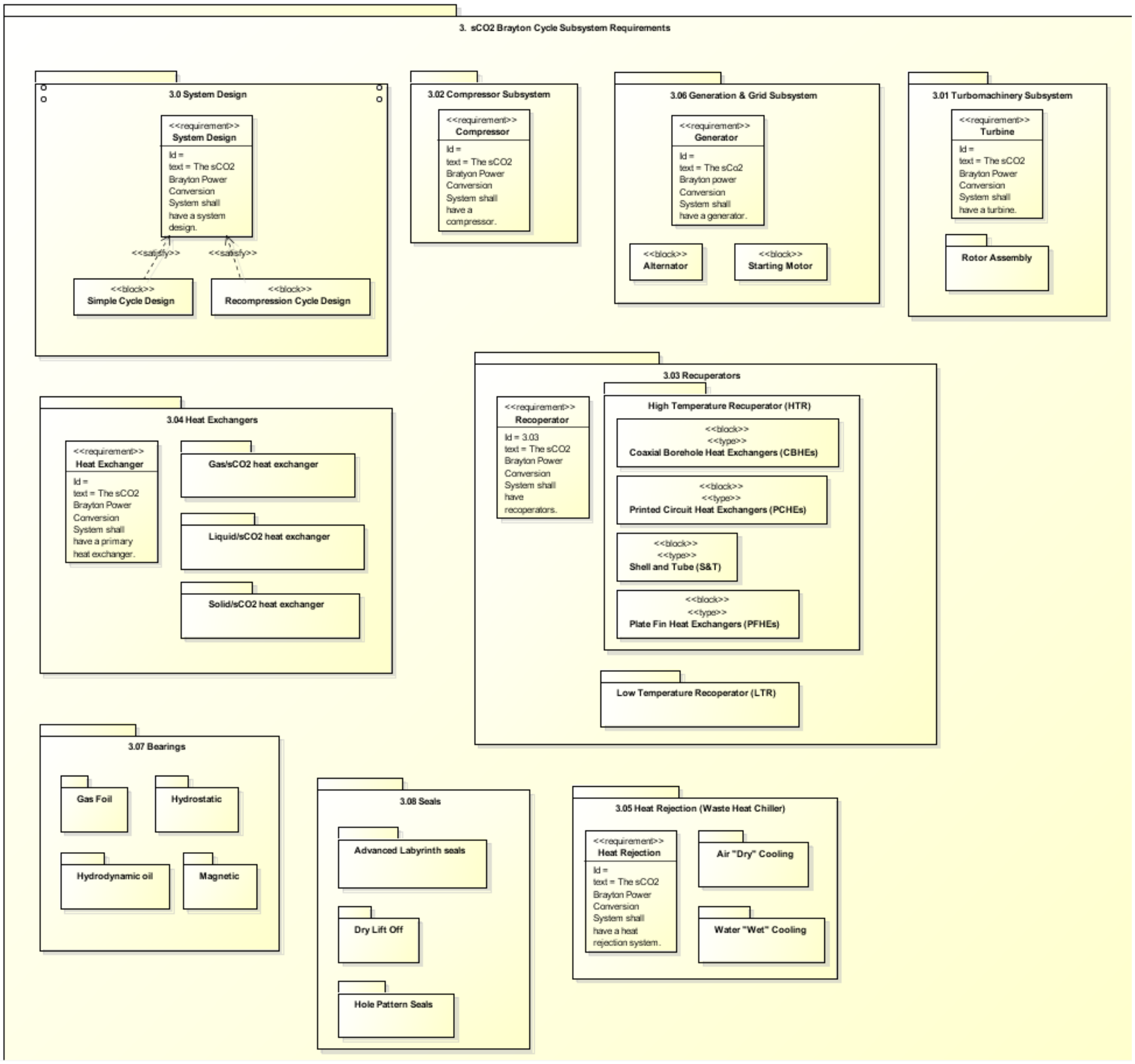

Figure 18: Astah preliminary sCO2 Brayton Cycle system (zoom).

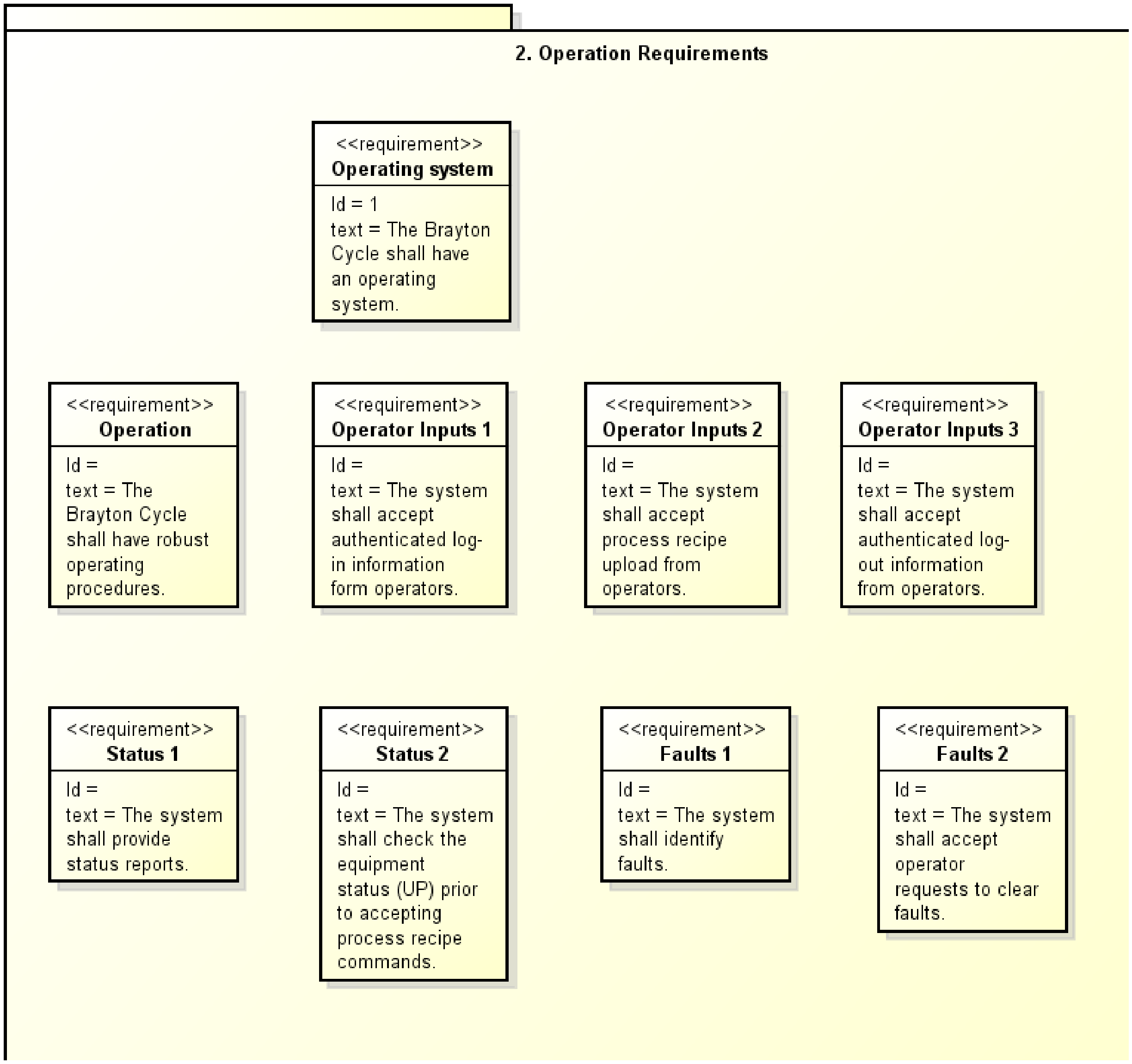

Figure 19: Preliminary Operations high-level requirements.

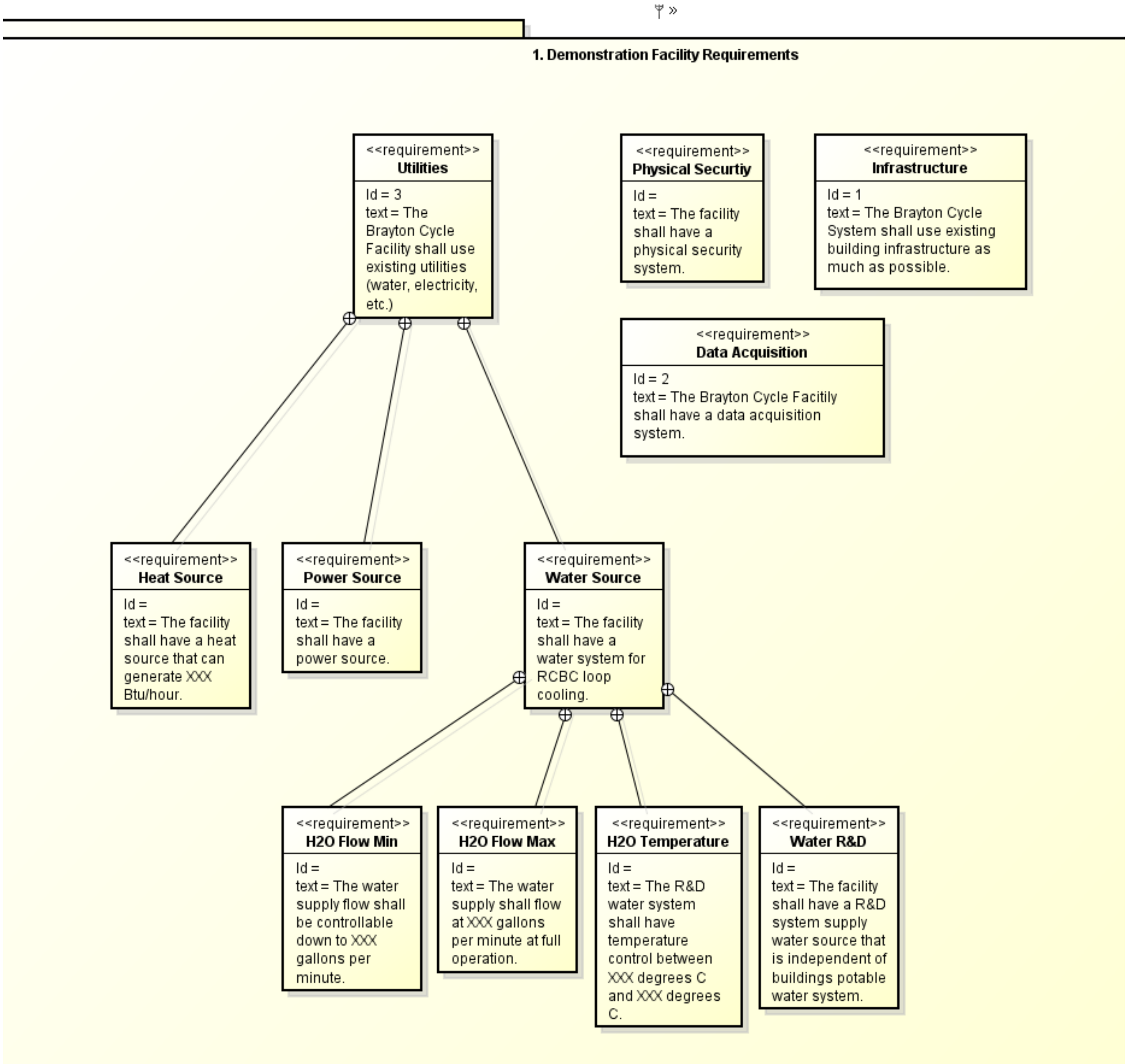

Figure 20: Preliminary Facility high-level requirements

Requirements documentation for recuperators

For consistency, recuperators are selected as an example to illustrate the requirements documentation process. Figure 21 shows that when "3.03 Recuperators" is selected (highlighted blue), the definition of *Recuperators* and the current TRL level is provided underneath. Figure 22 zooms in on the recuperators package, outlining the types of high temperature recuperators that are or may be capable of meeting the requirements. Figure 23 details the High Temperature Recuperator requirements.

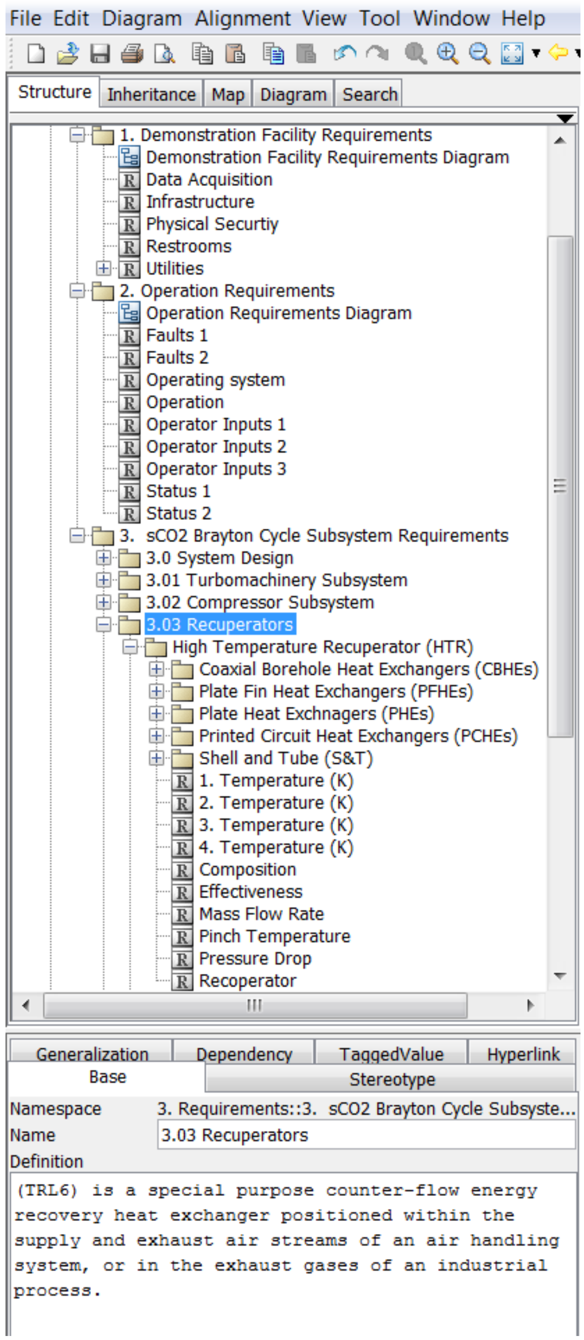

Figure 21: Focus on recuperators (menu).

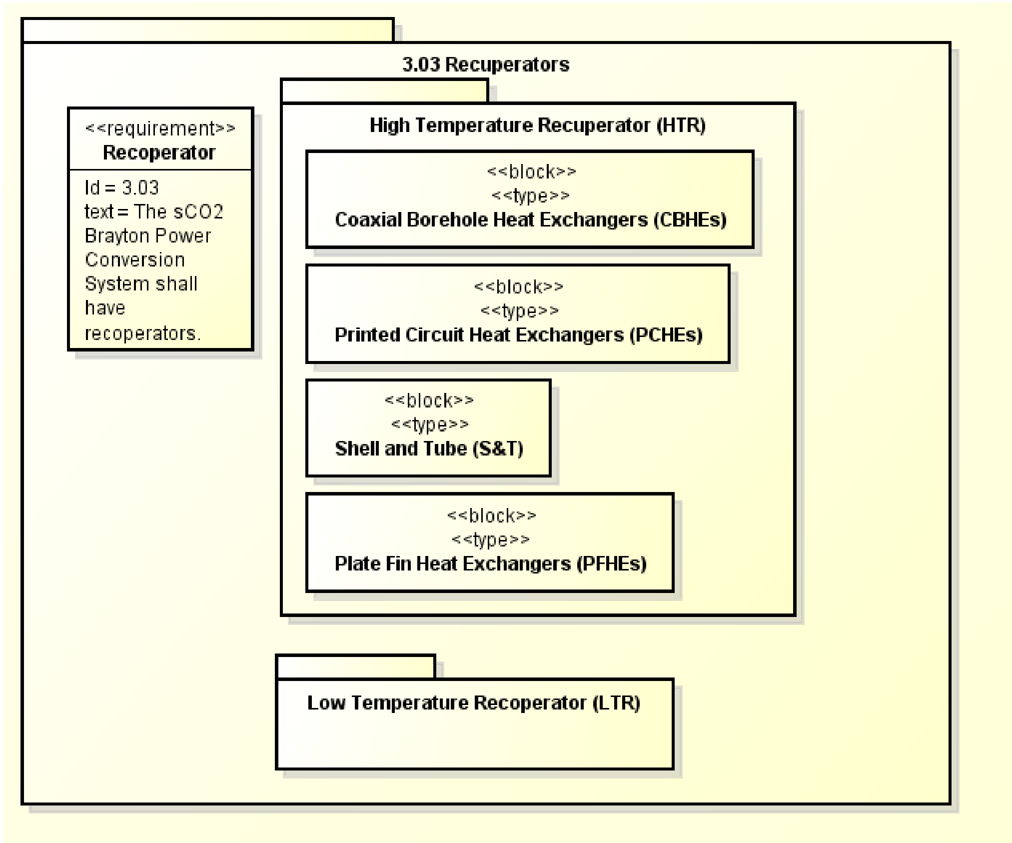

Figure 22: Focus on recuperators (model).

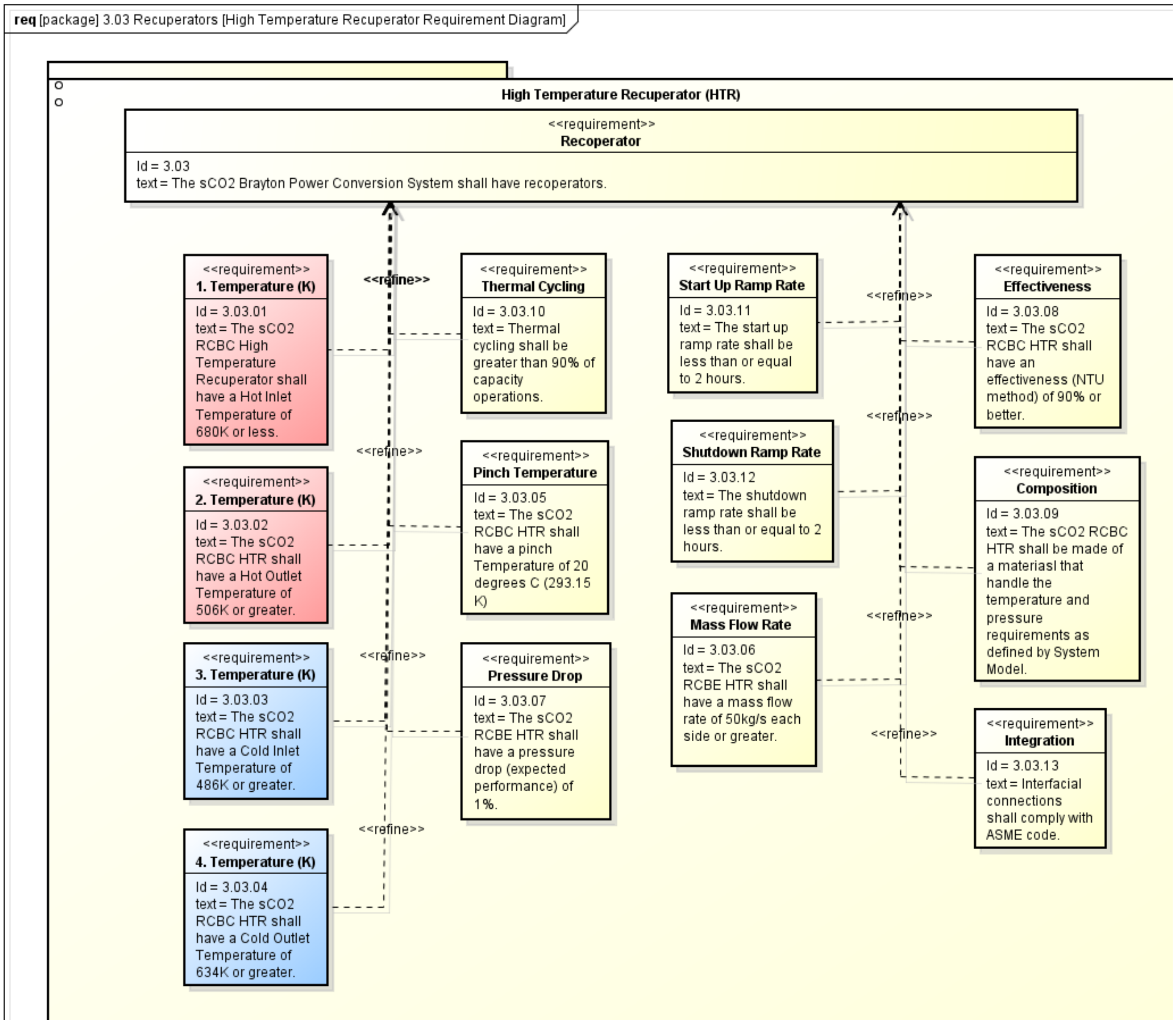

Figure 23: High Temperature Recuperator requirements.

Conclusions

The broad applicability of Supercritical CO2 Brayton Cycle technology to a variety of heat sources, and benefits such as higher plant efficiency, reduced fuel and water consumption, smaller size, and environmental improvement make Brayton cycles an attractive alternative for energy conversion. DOE's ART and STEP Programs are interested in developing its capabilities by supporting a demonstration to reduce the technical barriers and risks to the technology commercialization, while encouraging collaboration among the offices and with industry.

Because of the complexities of Brayton systems, its components and sub-components, and the variety of potential applications, a systems engineering approach is recommended to manage technology development, and documentation, verification, and validation of targeted requirements. This approach enables strategic requirements management with the potential to validate requirements across multiple applications, maximizing resources optimization and reducing duplication of efforts.

A systems engineering approach that is grounded in holistic systems design, including developing the full system lifecycle through concurrent engineering, balancing and interaction of work system elements, and comprehensive project planning and controls, is recommended. This document proposed a *Reinforced V Diagram* for the gathering, development, and validation of requirements that is supported by established theory and practice. Requirements modeling through systems engineering calls for a comprehensive set of requirements for the Brayton system and its subsystems. This report encompassed the development of program input and initial requirements analysis. The requirements analysis stage is expected to be iterative based on the contribution of stakeholders to the concurrent engineering team.

A systems engineering modeling tool is needed to support this effort. After analyzing multiple tools, Astah was deemed the best alternative. At the time of this report, formalized requirements gathering and development of the Astah model is underway. The initial requirements reported and modeled to demonstrate the application of systems engineering were sourced from previous milestone reports that have been developed in the course of component testing for technology readiness, and through engagement with multiple sCO2 Brayton technology partners.

While key requirements for the development of the NE-STEP sCO2 Brayton systems goals include reconfigurable and scalable capabilities, many detailed component and lifecycle specifications are still needed to accurately track technical readiness levels to specific applications. A comprehensive systems engineering model, including functional analysis and allocation of requirements, can only be established once the initial target application is agreed upon.

Continued systems engineering and requirements modeling for sCO2 Brayton systems will include the pursuit of detailed requirements for a defined application, development of user cases for the Brayton system, and adding specifics on component requirements to Astah or another MBSE tool, tracing the physical architecture to a logical architecture, and developing a verification and validation plan for the requirements.

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