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NASA GRC's Closed Brayton Power Conversion Capabilities

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Abstract

NASA Glenn Research Center (GRC) has a rich history of closed Brayton technology developments that expands decades. Technology maturation efforts have led to advanced hardware prototypes, internally developed system models, and robust supporting infrastructure. The integration of these elements has enabled a growing ecosystem of closed-Brayton space power capabilities, which continues to evolve through ongoing development activities. This ecosystem demonstrates the potential to enable technology readiness assessments, inform future mission formulation and execution, and advance the current state of the art.

Keywords: Nuclear, Brayton, Power, Space

1. Introduction

NASA GRC's Brayton cycle expertise and capabilities expand all the way to the days of when it was called the Aircraft Engine Research Laboratory (AERL)[1]. During this era, the AERL tested the nation's first turbojet and ramjet engines in an altitude wind tunnel. After World War II, the laboratory spent the next decade immersing itself into compressor, turbine, and high temperature material research, which has led to much of the current open and closed Brayton technology development. Open cycle Brayton power conversion systems are a close relative to the closed cycle Brayton power systems that are currently being studied for nuclear space power applications. The thermodynamic cycle is similar for both, involving compression, heat addition, expansion, and heat rejection. The main difference lies in the thermal source, heat sink, and how the working fluid is handled.

In an open cycle, air is drawn from the atmosphere and compressed so that it can be mixed with the fuel and burned for combustion. During combustion, the fluid's temperature, volume, and enthalpy increase to provide the necessary energy to drive the turbine. Afterwards, hot gases are expanded by the turbine and are accelerated to produce thrust. For the open cycle, the primary heat source is derived from combustion and heat rejection is accomplished via sinking heat into the exhaust stream.

In a space-based closed Brayton cycle, the working fluid would be comprised of an inert gaseous mixture, typically helium-xenon (HeXe), that will recirculate continuously throughout the power system. In a non-ideal case, the working fluid flows through the inlet of the compressor at low pressure and moderate temperature. At the compressor outlet, the HeXe fluid has been compressed non-isentropically raising both temperature and pressure. After leaving the compressor exit, the fluid mixture enters a counterflow heat exchanger called the recuperator. Here, in the cold-side of the recuperator, the relatively cool fluid is preheated by the turbine's exhaust stream while also experiencing a pressure drop due to passage friction and geometry. Leaving the recuperator, the fluid flows into the reactor's heat exchanger, where it absorbs heat at nearly constant pressure as it reaches turbine inlet temperature. Through the turbine, the hot, high pressure fluid expands as it converts thermal and pressure energy into mechanical shaft work. The shaft work drives both the compressor and alternator to re-pressurize the working fluid and to produce electric power, respectively. Three phase, alternating current (AC) will be provided by the alternator. The expanded HeXe mixture is now in a relative low pressure and low temperature state when compared to its pre-turbine phase. In contrast to the post-compressor phase, the fluid is at a low pressure and high temperature state. In this high thermal energy phase, the fluid re-enters the hot side of the recuperator and transfers heat to the cold counter stream that left the compressor.

This thermal exchange increases system efficiency by recycling heat instead of wasting it. Before the working fluid transfers its final waste heat energy to the radiator, it goes through a heat sink heat exchanger. As the working fluid traverses the heat exchanger, both its temperature and the radiator heat loads are reduced. Finally, after leaving the heat sink heat exchanger, the HeXe fluid reaches the compressor inlet and the cycle restarts.

Understanding of prior Brayton research and its underlying thermodynamic principles is of critical importance for the continued advancement and reliable operation of future nuclear closed Brayton power systems. From the 1960s to the early 2000s, NASA GRC engaged in three crucial projects that led to the successful demonstration of closed Brayton hardware. These efforts included the adaptation of aeronautically derived models and the establishment of infrastructure to support space-based testing. This paper provides a detailed discussion of these foundational hardware, modeling, and infrastructure developments, followed by an assessment of their current status and maturity.

2. Previous Hardware: Power Brayton Systems

Space power Brayton systems offer several significant advantages, including high efficiency, operational lifespan, scalability across missions, and continuous steady power output. Recognizing these benefits, NASA GRC initiated closed Brayton development in the early 1960s, with ongoing advancements continuing to the present day. Brayton Rotating Units, Solar Dynamic Brayton, Jupiter Icy Moons Orbiter, and a Barber Nichols contract were four principal activities that led to the development of three historical pieces of working Brayton hardware: Brayton Rotating Unit (BRU), Mini-BRU, and the Dual Capstone Brayton Test Loop. Numerous reports describe hardware testing, modeling methodologies, and supporting infrastructure used to assess each power conversion system [2–9]. Therefore, this section will not provide exhaustive detail on each element but instead it will highlight important aspects and their current status.

2.1 Brayton Rotating Unit

From 1968 to 1978, four BRU units were fabricated by Allied Signal (previously known as AiResearch), and tested at NASA GRC. As a result of varying charge pressure, units were designed for 2.25 to 10.5 kWe operation. A cycle map for a 6 kWe operating condition is shown in Figure 1 and referenced by [10]. A HeXe molecular weight (MW) of 83.8 g/mole was chosen as a result of optimal power output due to higher aerodynamic turbine and compressor performance [11]. Each Brayton turbine, alternator, and compressor (TAC) assembly consists of a radial centripetal turbine, a radial centrifugal compressor, and a Rice-Lundell alternator. The alternator operates at 36000 rpm and it is liquid cooled by Dow-Corning 200 fluid (DC 200). Furthermore, a gas-to-gas recuperator and a gas-to-liquid (DC 200 fluid) sink heat exchanger were built as one unit to enhance BRU performance [12]. A total of 38,000 hrs without degradation was shown for the BRU-2 unit. As of today, the BRU has been decommissioned, with only the TAC remaining as a display item. However, comprehensive research reports and technical schematics continue to be accessible to support future designs and analytical efforts.

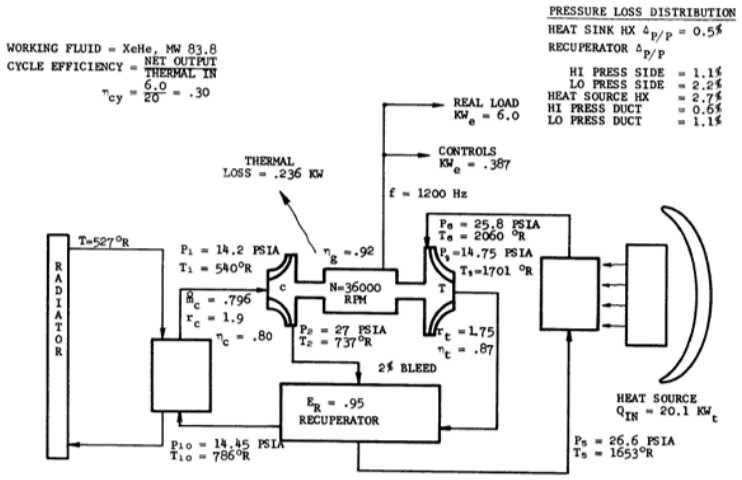

Figure 1: Final cycle map for 6 kWe operating conditionn.

2.2 Mini-BRU

Initial Mini-BRU manufacturing and research was conducted between 1974 to 1978. This lower power producing system was also manufactured by Allied Signal. The Mini-BRU was developed to demonstrate high cycle efficiency, up to 30 percent between 0.5 to 2.1 kWe. Similar BRU components were incorporated in the TAC assembly, utilizing HeXe with a molecular weight (MW) of 83.8 g/mole. Instead of using liquid cooling for the alternator, internal stator cooling via compressor discharge gas flow was used. In 1996, the Rice-Lundell TAC was replaced by a permanent magnet (PM) TAC [13] for a Solar Dynamic Flight Demonstration activity. Both of the Rice-Lundell and the PM TACs were operated at 52,000 rpm. Additionally, the Mini-BRU's recuperator, a counterflow, plate-fin heat exchanger, was engineered to surpass the thermal performance of the BRU, achieving an effectiveness of 97.5 percent. An image of the Mini-BRU's cycle map is shown in Figure 2[14]. Worthy of note is the 2 kWe system's integration with a Xenon ion thruster. The ion propulsion hardware used was an engineering model of the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR). Successful completion of this test provided critical advances in nuclear electric propulsion (NEP) development. The closed turbo machine is currently still available for testing and reconfiguration. TAC components, heat exchangers, and cooling methods can be altered to support higher power Brayton scalability, reliability, and compatibility with advanced power architectures.

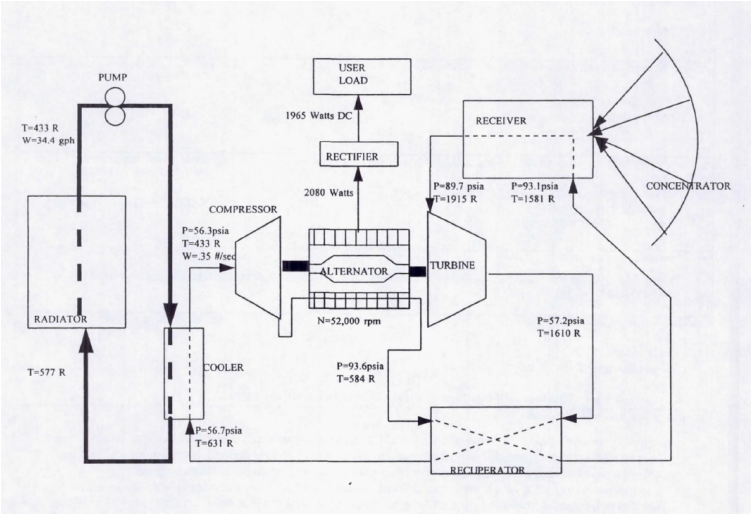

Figure 2: Mini-BRU cycle schematic.

2.3 Dual Capstone Brayton Test Configuration

During 2006-2007, two commercial open-cycle Capstone C30 Microturbines, made by the Capstone Turbine Corporation, were modified by Barber-Nichols for dual closed Brayton. An image of the Dual capstone configuration is shown in Figure 3[15]. The combustor in the open cycle Capstone C30s was replaced by a single shared electrical resistance heater, which resulted in common nitrogen gas inventory for the dual Brayton units. Similarly, the atmospheric exhaust of the original units was replaced by a gas-to-water cooler which diverts the flow to the compressor inlet and closes the cycle loop. The combined power output of the 90 krpm units was 20 kWe. TAC components include a radial turbine, centrifugal compressor, and PM alternator. Unlike the BRU and Mini-BRU, the TAC assembly features a distinct layout wherein the alternator is positioned downstream of the compressor. This strategic location maintains the alternator's temperature relatively low during operation. Since single Brayton architectures have been deeply researched at NASA GRC, dual Brayton behavior needed to be assessed to understand future mission redundancy requirements for Fission Surface Power (FSP) and NEP systems. Steady-state studies were performed at equal and unequal shaft speeds for heater exit temperatures of 840-950 K at speeds of 50-90 krpm. Results from this research demonstrated that units were sensitive when running at unequal shaft speeds, which was a result of decrease in mass flow due to working fluid redistribution [15]. Furthermore, more experimental testing of various starting scenarios revealed that maintaining a constant shaft speed consistently led to lower motoring energy consumption compared to the constant motoring power mode for a defined thermal load. Sequential start up, initiating one power unit and allow-

ing it to reach power generating conditions prior to engaging second power system, was observed to further decrease motoring energy required for a prescribed heater power input. Insights gained from this research offer the potential to rework how redundancy is conceptualized and integrated into future missions. At present, Dual Capstone Brayton power system has been discarded and only one C30 Microturbine is located at GRC. There are also reports available via NASA Technical Reports Server (NTRS).

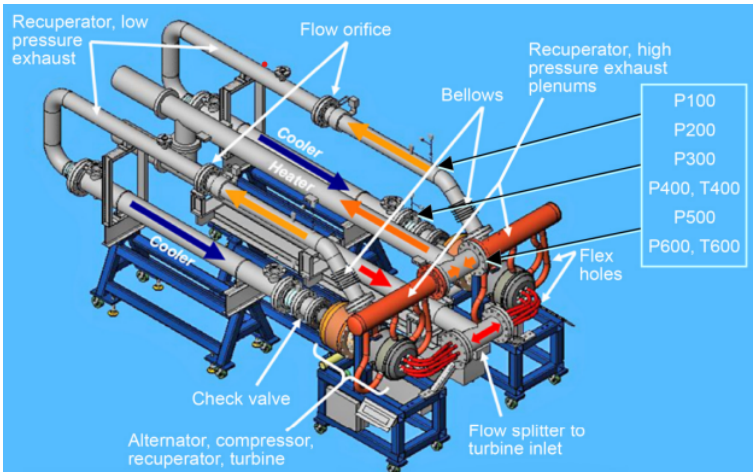

Figure 3: Dual Capstone Test Configuration.

3. Previous and On-Going Modeling

Closed cycle Brayton modeling is crucial to understanding the fundamental phenomena, performance analysis, and optimization design, particularly when direct observation during testing is impractical or infeasible. NASA GRC has a plethora of modeling software at its disposal for modeling Brayton systems but only a few will be described due to constraints imposed in paper length.

3.1 Numerical Propulsion System Simulation (NPSS)

The Closed Cycle Engine Program (CCEP), an early FORTRAN-based analysis tool for closed Brayton cycle systems, represents one of NASA's foundational efforts in Brayton cycle modeling. CCEP evolved from the earlier NASA Navy Engine Program (NNEP), which later transitioned into the NASA Engine Performance Program (NEPP). Both CCEP and NEPP were written in FORTRAN. They are modular systems that allow the user to build systems models by defining the connections for the 0-D components. For CCEP, these components include compressors, turbine, ducts, reactors, radiators, heat exchangers and pumps. The model performs an overall systems analysis to conserve energy and mass based on the performance of the individual components. These components are the classic 0-D/1-D elements. They take the input port conditions and transform them into the output condition based on the component performance. For example, the compressor will determine the exit conditions based on the input fluid conditions, pressure ratio, and efficiency to determine the output conditions. The heat exchanger elements will break the components up into several sections and perform a 1D heat exchanger analysis. All the other elements perform the same 0-D/1-D classic calculations. Elements also perform a preliminary weight and size calculation. The CCEP computational algorithms have been transferred into the NPSS environment.

NPSS is the current state of the art tool being used to model thermodynamic system performance. NPSS had already been used as a replacement for NEPP. Since CCEP was a derivative of NEPP, creating a derivative of the CCEP elements was straightforward. Figure 4 demonstrates an integrated development environment (IDE) example of NPPS closed Brayton model using previous CCEP ideology.

The CCEP-based NPSS library has been used to model the system power for Jupiter Icy Moon Orbiter (JIMO). The purpose of the JIMO mission was to provide a high-power source on a probe to power powerful instruments that would be sent to Jovian system. The JIMO power source was a nuclear powered Brayton system.

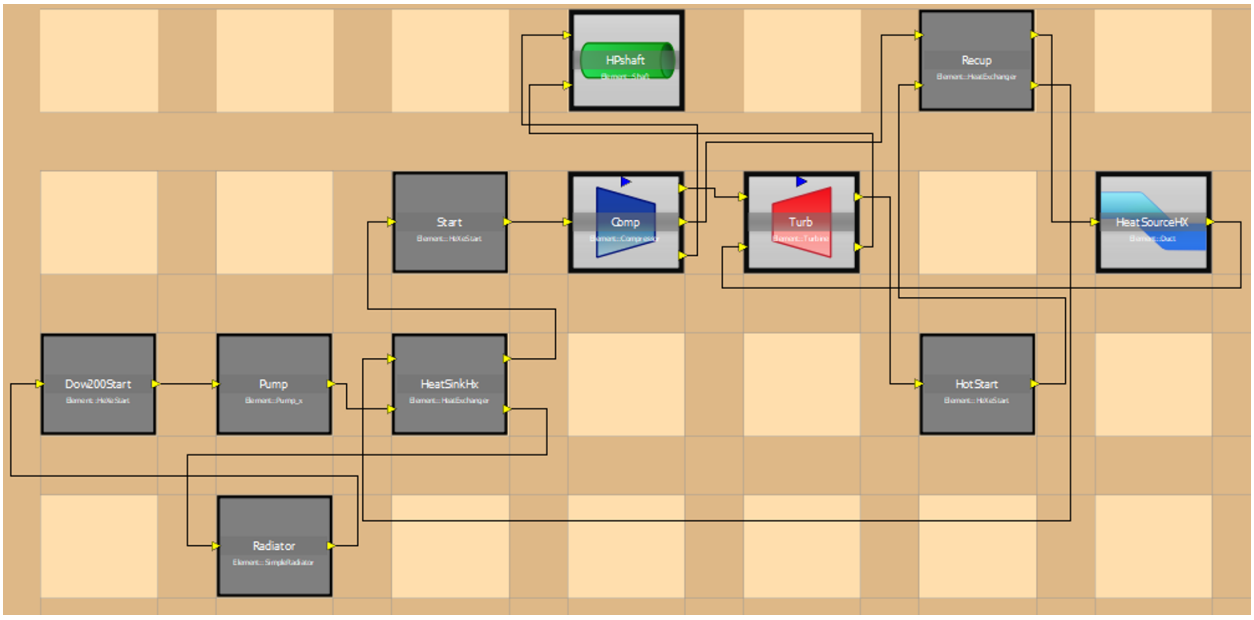

Figure 4: IDE example of a close Brayton model in NPSS.

In addition, the CCEP based libraries were used to support the work done by Clough [16] to model a bimodal Nuclear Thermal Rocket (BTR). For a bimodal NTR, the reactor provides high levels of power for the propulsion mode and then low levels of power for the vehicle during the mission. The system for the power model is a Brayton conversion unit similar to what was proposed for JIMO. The Clough report provides detailed information on the methodologies used to determine the individual component's performance. Figure 5 represents an artist interpretation of the JIMO concept.

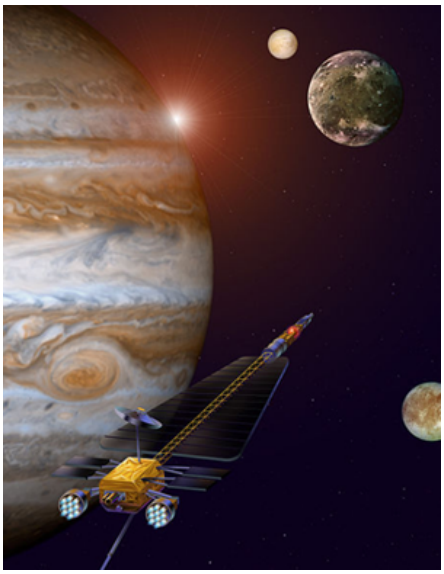

Figure 5: JIMO concept.

For future work, NASA GRC is working to modernize the existing sizing and performance algorithms present in the various current analysis packages. This task involves ensuring that the 0-D/1-D calculations will be used to represent what the current view is for the performance of these components. This work mainly involves working on the efficiency and sizing/weight correlations. NASA GRC is also working to combine this capability with the openMDAO

optimization package, enabling the developed designs to be refined to minimize overall goals, such as weight and size. For the turbomachinery elements (compressor and turbine), the work will be done by expanding the OTAC analysis package to include current loss models as well as updated weight and sizing calculations. For the thermal elements (the heat exchangers, radiator, reactors), work is being done to create Python-based analysis packages. The overall system balance will be controlled by an NPSS model running lower fidelity pure 0-D calculations. Consistency between the more complex tools and the simplified 0-D elements will be maintained using a nested solver approach, shown in Figure 6, that has proven to be successful in the aeropropulsion industry.

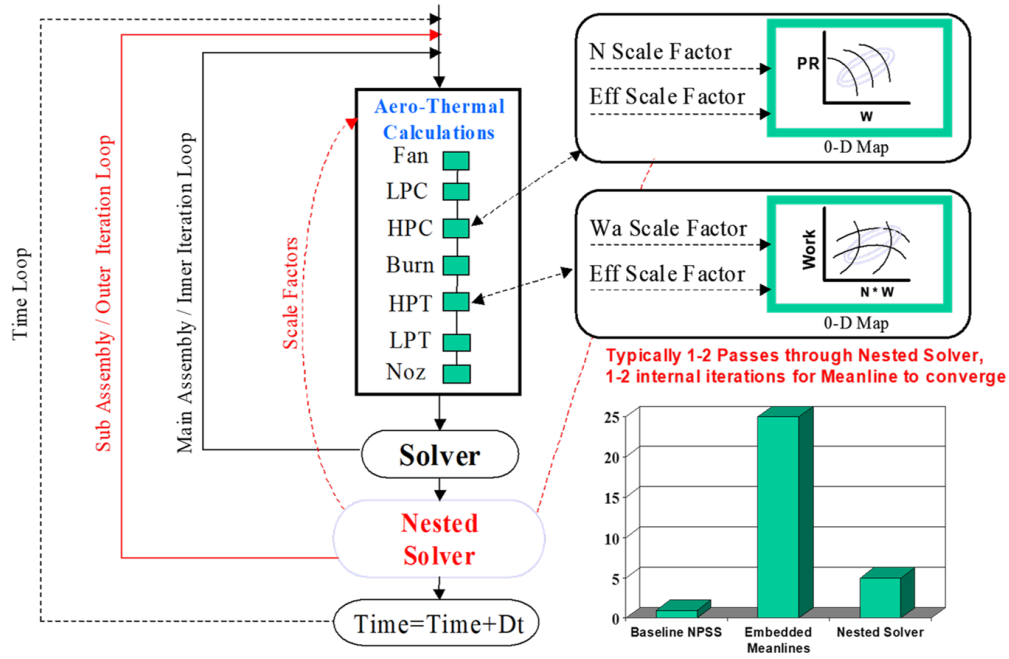

Figure 6: Example of NPSS nested solver approach.

A final note: Experts at GRC are familiar with many developer environments. One of the real values of this work is developing, refining and validating the algorithms. Once that is done, the calculations can be moved between different modeling environments.

3.2 Computational Fluid Dynamics (CFD)

At NASA Glenn Research Center's Thermal Energy Conversion Branch, the capabilities exist to perform Computational Fluid Dynamics (CFD) analysis of Brayton cycle components. Ansys products, which include pre- and post-processing software tools along with the CFD solver Fluent, are used to perform 3-D simulations of various Brayton cycle turbomachinery geometries. Simulations can be 2-D or 3-D, single- or multi-stage, steady and transient. The Ansys products are installed on a 32-processor Microway computer workstation running an Ubuntu Linux operating system. Recently, 1.5 stages of a bi-directional turbine have been selected for investigation [17], to increase understanding and possible future use in a Brayton based power generation device. A turbine baseline geometry is shown in Figure 7 and preliminary calculations were performed using this geometry. Smaller parametric simulations are also performed to develop a strategy to modify the blade profiles, before generating a new 3-D geometry.

An inlet and exit plenum was added to the 1.5 stage turbine geometry with stations defined. This modification to the turbine geometry is shown in Figure 8. The simulation is operated by setting rotor wheel speed, inlet temperatures and pressures, and other relevant parameters. Turbine power, efficiency, flow coefficient, and reaction rate are some of the predicted parameters used to uncover the ideal operating range and the related flow physics that could influence the need for turbine blade profile adjustments. A known bi-directional turbine geometry is used as a starting point for the numerous simulations that follow. Figures 9 and 10 show some of the prediction results that are produced by the simulations and post-processed. CFD generates a lot of predicted results that can be used to interrogate and better understand the flow physics connected to the geometry.

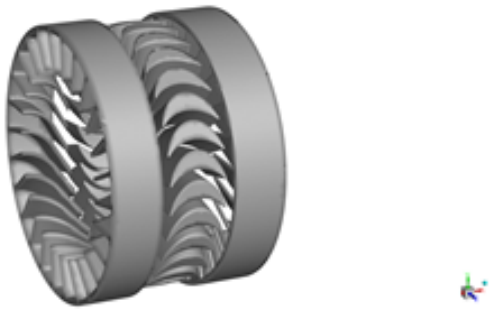

Figure 7: Fluent baseline turbine geometry.

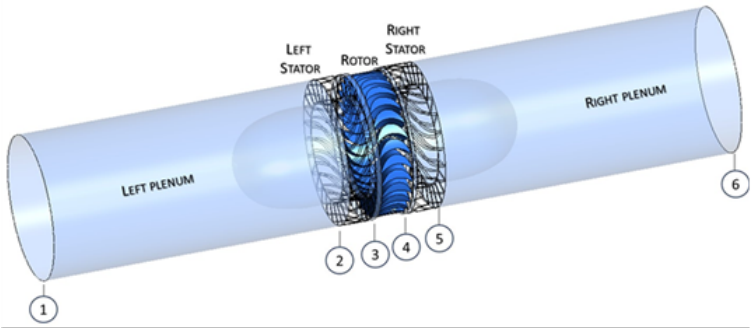

Figure 8: Bi-Directional turbine plenum.

4. Infrastructure for Future Brayton Testing

As interest in Brayton research continues to rise, and the development and delivery of closed cycle Brayton systems are increasingly brought to NASA GRC, the demand for sustained investment in testing capabilities and infrastructure improvements becomes critical. For decades, engineers and researchers in the Stirling Research Laboratory (SRL) have successfully tested and validated many smaller power class systems (e.g., Stirling engines and generator concepts) [18]. This expertise in testing smaller systems matched with the growing need for more testing spaces has captured the interest of project planners to invest in renovating an existing room at GRC into a developmental testbed for higher power closed-Brayton systems. Currently, design work for this room is underway to enable up to four independent test articles to be tested within a 28 x 28 x 12 ft laboratory space, see Figure 11. In addition, the lab can accommodate a test article with heater power and cooling needs of 500 kW and 400 kW, respectively. The new lab space will be designed with modularity and scalability in mind, allowing the four test stations to be combined into one large station for increasing power requirements. By combining existing long-duration testing knowledge with Brayton expertise, the engineers and technicians of this new laboratory will be capable of running validation tests on various subsystems to continue research and ultimately increase the overall TRL of closed cycle Brayton systems.

In addition, infrastructure exists for the testing of high speed rotatory devices. The laboratory contains an underground metal pit, with reinforced concrete walls above ground. It was previously named ”the spin pit,” which was used to test flywheels rotating at 60 krpm. Currently, there are plans to test closed Brayton alternators at close to similar speeds. This lab also allows compressor and turbine tri-hub burst failure testing.

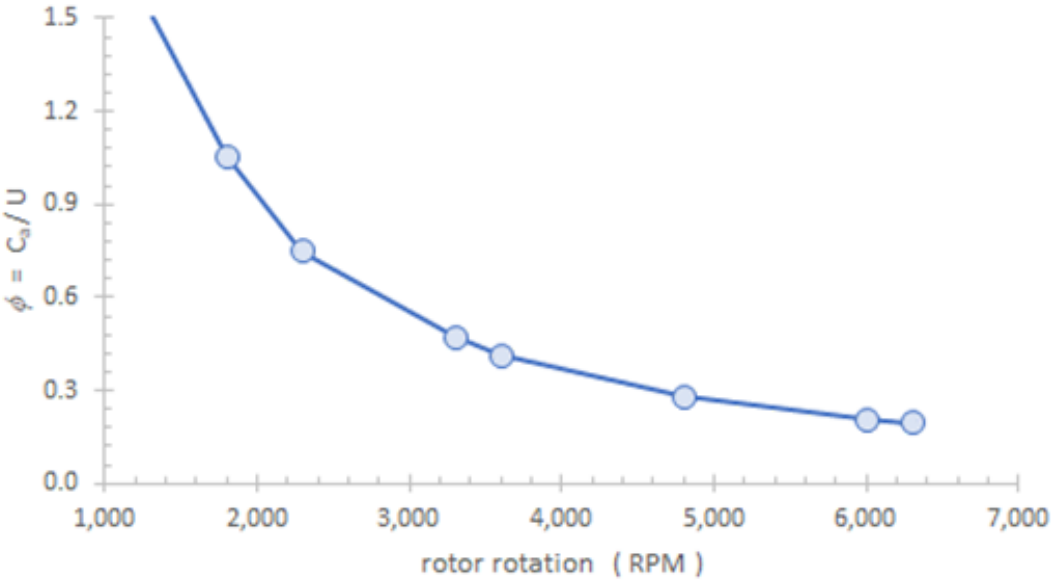

Figure 9: Flow coefficient prediction.

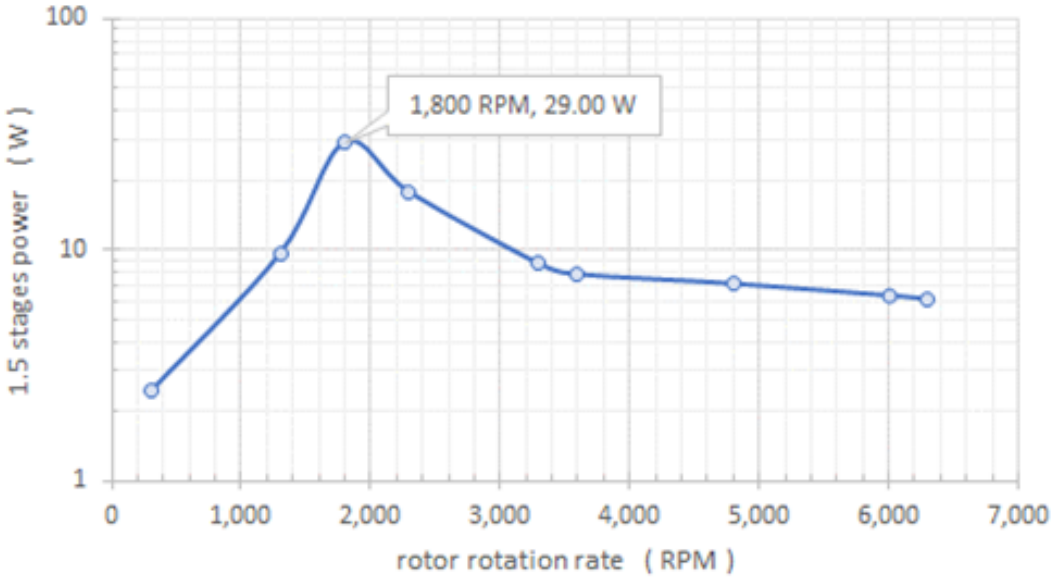

Figure 10: Turbine power prediction.

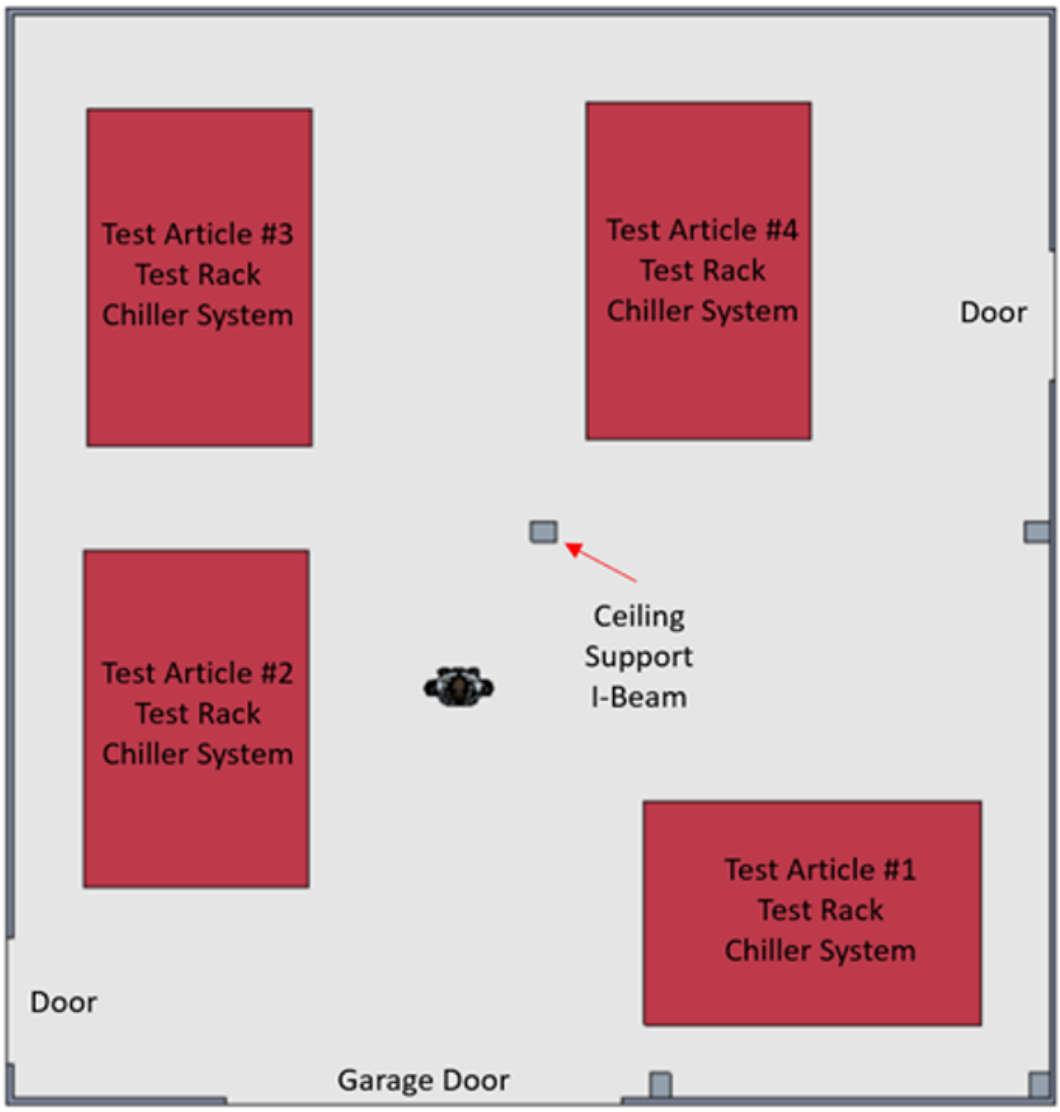

Figure 11: Concept Floorplan for the Higher Power Closed-Brayton Laboratory

5. Conclusions

NASA GRC's long term investment in closed Brayton cycle technology has brought to life a strong ecosystem of advanced hardware prototypes, verified system models, and continuous infrastructure development. This synergy of hardware, modeling, and infrastructure development not only demonstrates the maturity of space power conversion systems, but also provides a pathway for a thorough technology readiness assessments and mission planning. As development continues, GRC's work positions closed Brayton systems as a cornerstone for future exploration, enabling reliable, efficient power for lunar and Mars bases, and deep-space propulsion. This is accomplished by utilizing state of the art technology, so that GRC can ensure that space power capabilities evolve in step with the current customer need.

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