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Alternatives to MARVEL Power Conversion – Comparison of Stirling Engine Thermal Efficiency and Design to other Power Conversion Cycles

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ABSTRACT

The Microreactor Applications, Research, Validation, and Evaluation (MARVEL) Reactor is a small liquid-metal thermal reactor that will be built at the Idaho National Laboratory to demonstrate design and operating processes for microreactors, microgrid integration, and process heat applications. Power conversion in the MARVEL design is provided by Stirling engines, which have disadvantages in nuclear environments. Compared to Stirling engine performance, some alternative power cycles can increase power production when coupled to a liquid-metal thermal reactor.

In this paper, the thermal efficiency of MARVEL's power production with Stirling engines is compared to the thermal efficiency of power production with MARVEL and alternative power cycles. Those cycles include a superheated Rankine cycle, open and closed Brayton cycles, and a supercritical carbon dioxide cycle. All cycles (except the Stirling engines) were modeled with an intermediate helium loop to meet MARVEL's principal design criteria.

All models are simple designs with conservative assumptions for consistent comparison. Detailed optimization will depend largely on reactor location and application, and the relative merit of each cycle is discussed for different environmental conditions. The study informs significant early decisions on power cycle design and economics for deployment of advanced microreactors as they move from theory and concept to execution.

Keywords: MARVEL, Stirling engines, alternative power cycles, thermal efficiency, comparison

1. INTRODUCTION

The Microreactor Applications, Research, Validation, and Evaluation (MARVEL) Reactor is a small liquid-metal thermal reactor that will be built at the Idaho National Laboratory to demonstrate design and operating processes for microreactors, microgrid integration, and selected process heat applications. MARVEL will produce 85 kW_{th} at nominal, hot full power, and transfer heat through four loops, each with an intermediate heat exchanger (IHX). Each IHX transfers heat to a secondary loop and then to a Stirling engine for power production. Each Stirling engine will produce approximately 5 kW_e, in this configuration for an approximate total of 20 kW_e. The motive force for the primary and secondary loops is natural circulation with eutectic sodium-potassium (NaK) and eutectic gallium-indium-tin (eGaInSn) coolants, respectively [1]. Thermal efficiency of MARVEL using Stirling engines is calculated in Equation 1.

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$$\eta_{th,\ Stirling} = (\sum W_{Stirling}/Q_{Reactor})*100 = 23.5\% \quad (1)$$

The thermal efficiency in Equation 1 reflects early single effects tests performed for MARVEL in which the secondary coolant was heated by combustion to MARVEL operating temperatures. Stirling engine power production was measured but the calculation does not account for the work required by the pumps in the Stirling engine cooling system.

The MARVEL Project completed 90%-final-design in September 2023. While they will be installed during construction per the 90% final design, Stirling engines have three limitations in this application.

1. The eGaInSn coolant is corrosive at MARVEL's operating temperatures and may cause early failure of the IHX tubes. The primary coolant boundary is protected from excessive corrosion in the IHX by a liner separating the eGaInSn from the primary coolant boundary, but the IHX tubes and their welds are exposed to eGaInSn. At operating temperatures above 400°C, 306H Stainless Steel (SS) and Haynes 230 – the principal alloys of concern – corrode at excessive rates. This likely limits the life of the Stirling engines at power and may severely limit the availability of the reactor.
2. The Stirling engines will be located close to the core and subjected to combined neutron and gamma radiation fields of several hundred rad/hour. Adjusting Stirling engine placement and adding shielding reduced early radiation field estimates, but without considerable redesign for radiation hardening, early failure of the Stirling engines is likely. Failure is not expected to be catastrophic but will significantly reduce MARVEL's performance, power production, and availability.
3. The air temperature in the ventilated space above the Upper Distribution Plenum is limited to a maximum of 120°C to prevent boiling in the Stirling engine cooling system. As a result, the differential temperature between the NaK and top plate of the Upper Distribution Plenum will cause the primary coolant boundary to exceed American Society of Mechanical Engineers (ASME) thermal stress and strain limits [2] unless MARVEL heating and cooling rates are severely limited. A full heat-up may take up to 48 hours.

Replacing the Stirling engines with a different power production cycle and raising the air temperature above the upper Distribution Plenum would eliminate these three limitations. Availability would improve as the time lost for replacements – due to corrosion of radiation-induced failure – would be reduced. Operational flexibility would improve as the time to heat and cool the reactor would be significantly reduced. However, the simplicity and compactness of the Stirling engines would be lost.

To provide a comparison, alternative power conversion systems that exploit MARVEL's relatively high reactor outlet temperature were modeled. Conservative parameters and well-established configurations are used as MARVEL's strategy for power conversion is to use "off-the-shelf" technology. That strategy is adopted here.

Thermal efficiency was optimized for each and compared to the Stirling engines as the primary quantified discriminator. A discussion of each system's merit regarding location and the effects of the environment on the thermodynamic parameters of each model is presented.

2. POWER CONVERSION MODELS

Four models were developed and analyzed in Aspen HYSYS ® Version 12.1 at steady state conditions using the Peng-Robinson properties package. The models incorporated the MARVEL 90% design for the primary coolant loop (PCS) and NaK coolant. NaK coolant properties were developed using a 22% Na, 78% K mixture of elemental components and validated against published properties [3]. By symmetry, modeling of only one primary loop and heat exchanger was needed to calculate thermal efficiency, which was calculated and compared to the original Stirling engine configuration with one fourth of the reactor heat, one loop, and one Stirling engine.

2.1. Models Set-up, Common Parameters and Assumptions

For all models, primary loop parameters were set as follows to match the MARVEL 90% final design [4].

- NaK mass flow rate = 1.49 kg/s
- Core Inlet temperature = 464C°C
- Core Outlet temperature = 533°C
- Heat Exchanger (hot side) differential temperature = 69°C

After establishing these parameters, the primary pressure was set at 2 atmospheres and the parameters were minimally adjusted to establish the transfer of 21.25 kW across the heat exchanger. These primary coolant loop settings were used for all flowsheets.

The eGaInSn secondary coolant was replaced by an intermediate helium loop to meet Nuclear Regulatory Commission (NRC) principal design criterion (PDC) 78. MARVEL adopted NRC Regulatory Guidance Criterion 78 for Primary Coolant System Interfaces without revision, which reads as follows [5].

> *When the primary coolant system interfaces with a structure, system, or component containing fluid that is chemically incompatible with the primary coolant, the interface location shall be designed to ensure that the primary coolant is separated from the chemically incompatible fluid by two redundant, passive barriers.*
>
> *When the primary coolant system interfaces with a structure, system, or component containing fluid that is chemically compatible with the primary coolant, then the interface location may be a single passive barrier provided that the following conditions are met: (1) postulated leakage at the interface location does not result in failure of the intended safety functions of structures, systems or components important to safety or result in exceeding the fuel design limits (2) the fluid contained in the structure, system, or component is maintained at a higher pressure than the primary coolant during normal operation, anticipated operational occurrences, shutdown, and accident conditions.*

Particular to MARVEL, the criterion provides guidance for the primary coolant system boundary in those cases where the secondary fluid is incompatible with NaK. To satisfy this criterion, a secondary loop with an inert gas – Helium – was chosen. The pressure of the secondary loop was chosen to be slightly higher than the primary pressure to meet the criterion, but less than one atmosphere higher to minimize the possibility of voids in the core in the event of an IHX leak.

The following power conversion units were modeled based on their potential to productively utilize MARVEL's high outlet temperature.

1. Superheated Rankine Cycle with Intermediate Helium Loop.
2. Closed Helium Brayton Cycle with Recuperation.
3. Open Brayton Cycle with recuperation and Intermediate Helium Loop.
4. Supercritical Carbon Dioxide Cycle with Intermediate Helium Loop.

Analysis was performed at steady-state, steady flow conditions for well-insulated processes. Variations in potential and kinetic energy were considered negligible. The following high-level assumptions were made for user-defined variables.

- Minimum heat exchanger approach temperature = 25°C.
- Minimum differential stream temperature for heat exchangers = 25°C.
- Minimum differential stream temperature for recuperators = 10°C.
- Pressure drops across heat exchangers = 2%.
- Adiabatic compressor efficiency = 85%.

- Adiabatic pump efficiency = 85%.
- Adiabatic turbine efficiency = 90% .
- Intermediate Loop Pressure set to approximately 220 kPa to minimize the effects of a tube leak on core neutronics (due to coolant voiding in the fuel).

2.2. Superheated Rankine Cycle with Feedwater Reheat and Intermediate Helium Loop

The Superheated Rankine Cycle (SRC) was set up using a reactor and primary loop with MARVEL's parameters. Heat transfer through an intermediate heat exchanger (IHX) mirrors the MARVEL design but the transfer of heat is to an intermediate loop with helium coolant, replacing the Stirling engines. The helium pressure in the IHX was set at approximately 220 kPa as assumed and loop performance optimized based on the helium compressor pressure ratio. The primary and intermediate loops in this model are used with minor variations in all subsequent models. The flowsheet for the SRC is presented below in Figure 1.

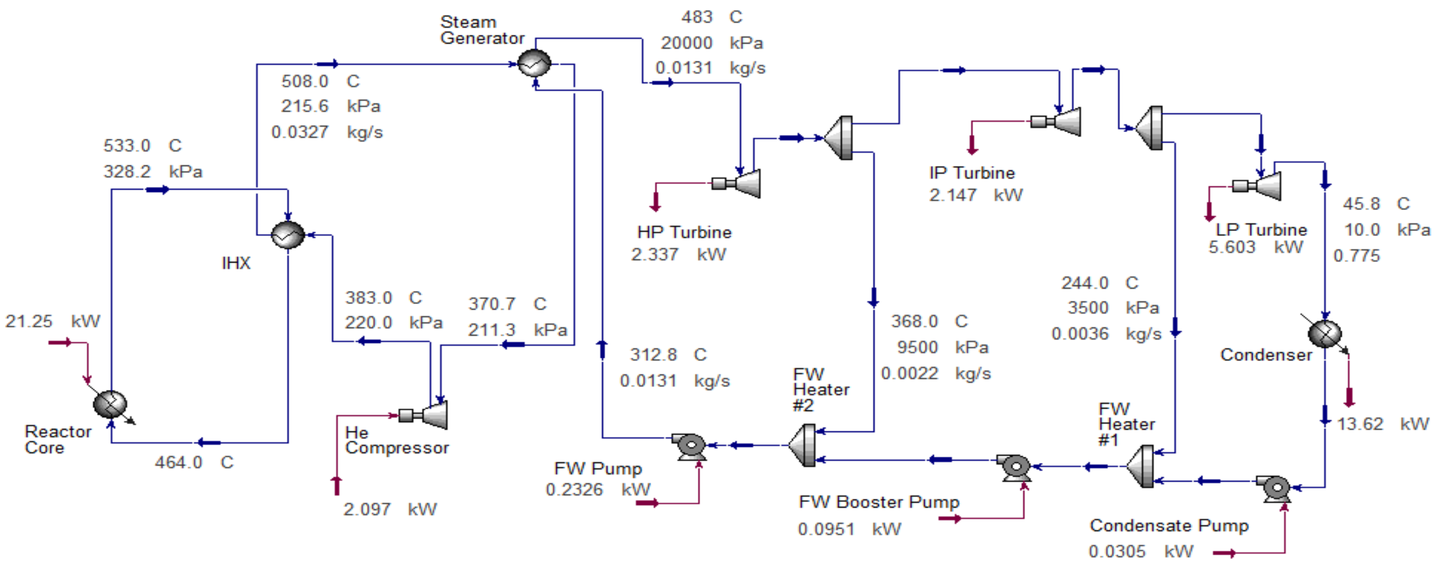

Figure 1. Superheated Rankine Cycle with Feedwater Reheat and Intermediate Helium Loop.

The SRC model adopts well-established Rankine cycle parameters and is optimized between steam pressure of 20 MPa and minimum condenser vacuum of 10 kPa. While SRCs exist that have steam pressures as high as 25 MPa, maximum steam pressure was limited to 20 MPa in the model to minimize material requirements imposed on the steam generator. Condenser vacuum of 10kPa approximates what can be reasonably achieved with common equipment [6].

Three turbines were modeled for ease of establishing a reheating leg off the discharge of each turbine which were connected to the suctions of three feedwater pumps. Rather than modeling a condensing heat exchanger, a simple cooler was used for heat rejection, as the geographical location and resulting heat sink temperature will factor heavily in selecting a heat rejection method. Heat rejection may vary across several methods from cooling towers to air cooled heat exchangers to cooling ponds and was judged to be more complex than needed for a simple feasibility study.

Power production was roughly balanced across the high-pressure, intermediate-pressure, and low-pressure turbines as a starting point. Steam pressures were iteratively reduced to increase power production while maintaining the stream in a superheated condition through the first two turbines. Steam quality was maintained above 75% at the exhaust of the low-pressure turbine at 10 kPa. These limitations were based on approximated values of the maximum vacuum that can be reasonably achieved in a condenser and the approximate quantity of water entrained in steam that can be withstood by turbine blades.

While steam temperature and pressure both significantly affected thermal efficiency, in the ranges analyzed, the steam temperature reductions had a larger impact. This is the largest and most complex system analyzed, and it will likely have the highest capital cost. Therefore, further work should include trade-offs of the complexity and cost of the Steam Generator and steam piping against the reduction in thermal efficiency as calculated in Equation 2.

$$\eta_{th,\,SCR} = (\sum W_{SRC}/Q_{Reactor})*100 = 36.10\% \quad (2)$$

Use of an intermediate helium loop eliminates or significantly reduces the issues introduced by the Stirling engines. Like the eGaInSn, it is chemically compatible with the NaK primary coolant, meeting the PDC. Helium is inert, which eliminates significant corrosion concerns in the IHX. The helium compressor does not have to be placed directly on top of the core and therefore, it will not be subjected to intense radiation fields. Neither will the compressor impose temperature limitations on air above the reactor core, reducing the temperature stresses in the Distribution Plenum. Conversely, thermal efficiency is reduced by introducing an additional compressor and heat exchanger. These advantages and disadvantages apply to all of the subsequent models.

Closed Helium Brayton Cycle with Recuperation

The closed helium Brayton Cycle model was set up with the same primary loop parameters as the SRC, but a helium turbine was inserted in the intermediate loop and a cooler added where the Steam Generator had been. A recuperator was added, at the turbine exhaust, to improve efficiency by recouping the heat in the turbine exhaust before heat is rejected in the helium cooler. The recouped heat is transferred back into the stream after compression and before the stream enters the IHX. The compressor inlet temperature was set to 35°C based on an achievable differential temperature across the cooler based and a rough approximation of groundwater temperature. It is also consistent with the physical constraints in the sCO_2 cycle. The closed helium Brayton cycle is presented in Figure 2.

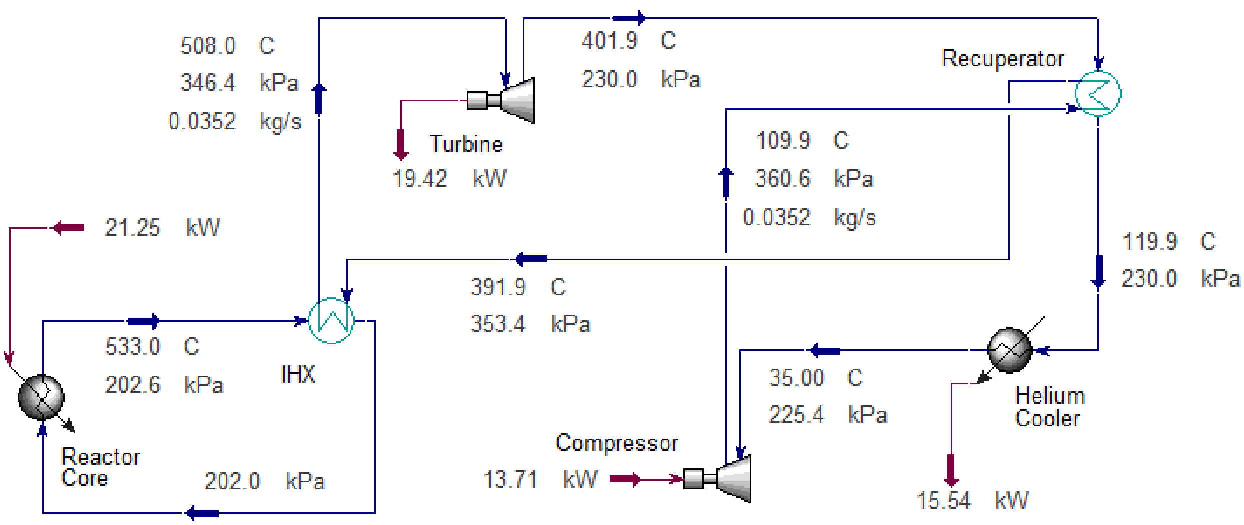

Figure 2. Closed Helium Brayton Cycle with Recuperation.

The closed helium Brayton cycle was optimized by varying the compression ratio across the helium compressor until maximum thermal efficiency was achieved using Equation 3.

$$\eta_{th,\ Closed\ He\ Brayton} = (\sum W_{Closed\ He\ Brayton}/Q_{Reactor})*100 = 26.87\% \quad (3)$$

Applications in the extreme north may use seawater or air as cooling mediums. Particularly in winter, when heating loads reach their peak, lower heat sink temperatures offer considerable advantage to thermal efficiency if they translate into the reduced temperatures within the power conversion system. Conversely, higher equatorial temperatures will penalize thermal efficiency as shown in Figure 3. These temperature variations had a negligible effect on the compressor pressure ratio.

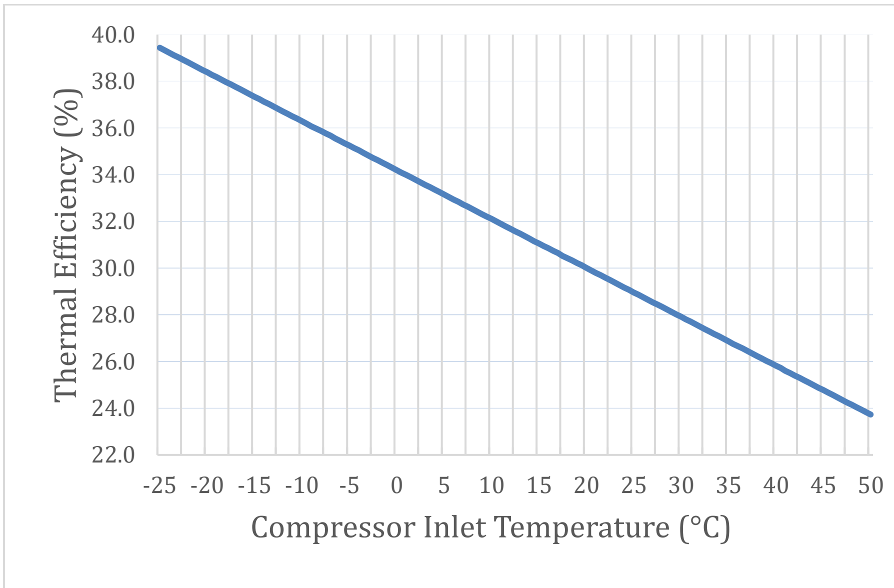

Figure 3. Thermal Efficiency versus Compressor Inlet Temperature for the Closed Helium Brayton Cycle with Recuperation.

2.3. Open Air Brayton Cycle with Recuperation and Intermediate Helium Loop

The Open-Air Brayton Cycle Model was set up using the same primary coolant loop and intermediate loop previously described. However, the Steam Generator in the intermediate loop is replaced by a helium-to-air heat exchanger (termed Brayton HX in the flowsheet). An air-driven turbine and air compressor are added in an open-air Brayton cycle and recuperation of heat between the turbine and compressor is added to pre-heat the air prior to introduction into the Brayton HX. The same general assumptions for differential temperatures (including the Recuperator), pressure drops, and component efficiencies are used. Ambient conditions for the air into Air Compressor were set at one atmosphere (101.3 kPa) and 20°C.

Optimization for this cycle was similar to optimization of the Closed Helium Cycle Brayton but using the pressure ratio across the air compressor. Manipulating the air turbine inlet pressure while the air compressor inlet pressure was held at one atmosphere effectively varied the pressure ratio. No adjustments were made in the intermediate helium cycle. The flowsheet is shown below in Figure 4.

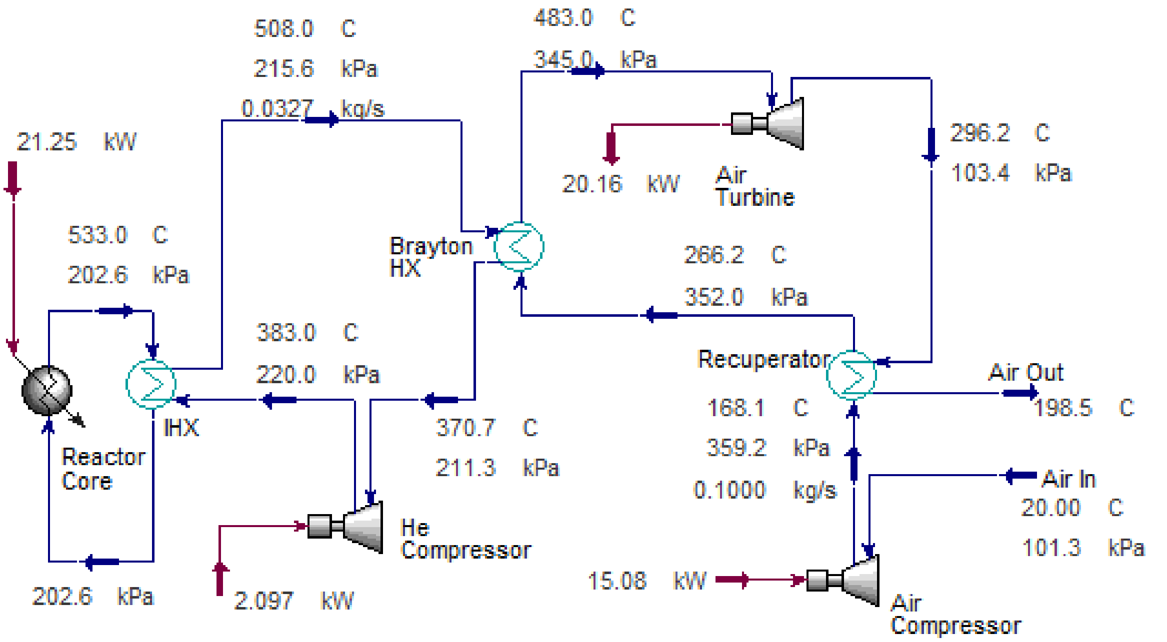

Figure 4. Open Air Brayton Cycle with Recuperation and Intermediate Loop.

Maximum thermal efficiency was achieved at optimal turbine inlet pressure of 345 kPa and resulting pressure ratio of 3.55. Air was discharged to ambient at 198.5°C and maximum thermal efficiency for these conditions was calculated using Equation 4.

$$\eta_{th,\text{ Open Air Brayton}} = (\sum W_{OpenAirBrayton}/Q_{Reactor})*100 = 14.07\% \quad (4)$$

Thermal efficiency drops because the air compressor takes 75% of the power produced in the air turbine to circulate air. The work required by the helium compressor in the intermediate loop remains about the same as for the SRC and subsequently modeled sCO_2 cycle but still contributes to the low thermal efficiency. As with the closed helium Brayton cycle, reducing the heat sink temperature (air temperature) improves thermal efficiency but not enough to make this cycle competitive. No further evaluation of the open-air Brayton cycle was performed.

2.4. Supercritical Carbon Dioxide (sCO_2) Brayton Cycle with Recuperation and Intermediate Helium Loop.

The sCO_2 model was set up using the same primary coolant loop and intermediate helium loop parameters previously described. An sCO2 recuperator was added, at the turbine exhaust, to improve efficiency by recouping the heat in the turbine exhaust before heat is rejected in the helium cooler. Recouped heat is transferred back into the sCO_2 stream after the stream is compressed and before it enters the IHX.

The flowsheet constraints were established between maximum system pressure of 20 MPa and conditions at the sCO2 compressor inlet dictated by the CO_2 critical point. Maximum pressure was limited to 20 MPa in the model to minimize material requirements imposed on the heat exchangers (similar to the SRC), consistent with published Department of Energy (DOE) sources for this type of power cycle [7]. The flowsheet is presented below in Figure 5.

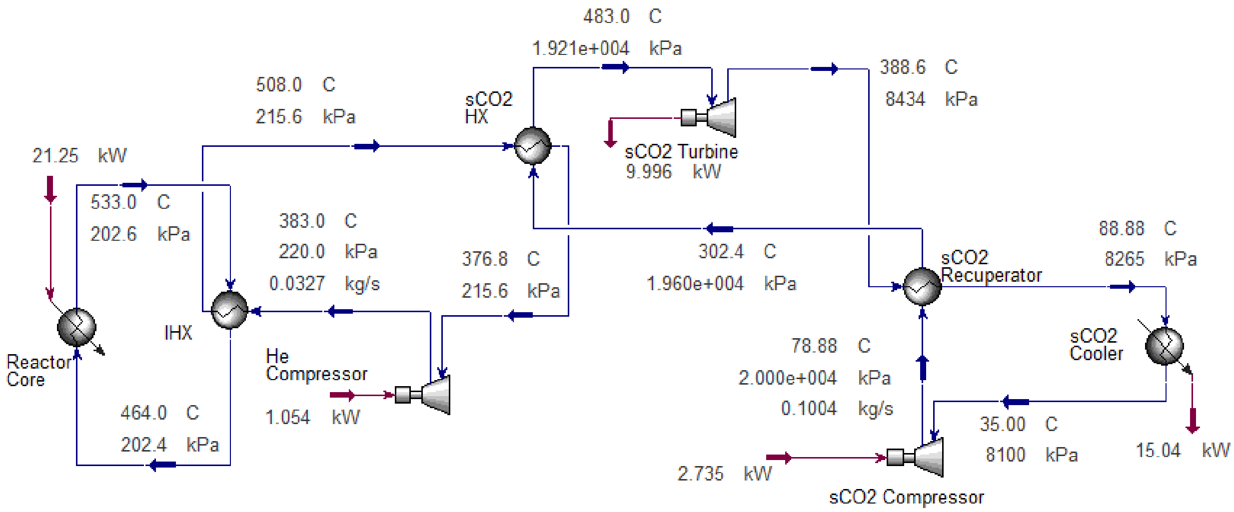

Figure 5. Supercritical Carbon Dioxide (sCO_2) Cycle and Intermediate Loop.

Conditions at the compressor inlet were originally set slightly above supercritical conditions (31.1°C and 7.38 MPa) to ensure the CO_2 behaves as a gas as it enters the compressor. Additionally, the recuperator reaches a constraint at approximately 7.4 MPa compressor inlet pressure because pressures below this cause the cold side pinch temperature to drop below 10°C. At compressor inlet temperature of 35°C, maximum thermal efficiency is reached at 8.20 MPa. However, there is liquid CO_2 in the compressor inlet at 35°C until pressure is reduced to approximately 8.17 MPa. Therefore, giving moderate operational margin, and considering 20 MPa the maximum system pressure, the system was optimized at 35°C and 8.10 MPa at the compressor inlet, resulting in a compression ratio of 2.47. Thermal efficiency was calculated for these conditions as shown in Equation 5.

$$\eta_{th,\,sCO2} = (\sum W_{sCO2}/Q_{Reactor})*100 = 29.21\% \quad (5)$$

Similar to the closed helium and open-air Brayton cycles, thermal efficiency is affected significantly by heat sink temperature and its effect on the sCO_2 compressor inlet temperature. A notable difference is that for the sCO_2 cycle, liquid in the CO_2 as temperature is reduced prevents the sCO_2 cycle from dramatic improvements in thermal efficiency as ambient air temperatures are reduced below approximately 10°C.

3. CONCLUSION

3.1. Summary Level Results

In all cases, the alternate power cycles eliminate or significantly reduce the issues associated with Stirling engines and eGaInSn secondary coolant. Like eGaInSn, helium is chemically compatible with the NaK primary coolant, and an intermediate helium loop design meets PDC 78. Corrosion concerns are addressed by using helium. The helium compressor can be placed away from the core and the reactor's intense radiation fields. This placement reduces the temperature-induced stress and strain on the Upper Distribution Plenum.

Thermal efficiency is improved by all alternate power cycles except the Open-Air Brayton cycle. Thermal efficiency is clearly highest in the SRC, followed by the sCO_2 and Closed Helium Brayton cycles. Thermal efficiencies for the Stirling engines and each alternative power cycle are presented in Table I below.

Table I. Thermal Efficiency for each Power Conversion Cycle.

Power Cycle	Stirling Engine	Superheated Rankine Cycle	Closed Helium Brayton Cycle	Open-Air Brayton Cycle	Supercritical CO_2 Cycle
Thermal Efficiency	23.5%	36.1%	26.9%	14.1%	29.2%

3.2. Additional Analysis

Equatorial locations or other factors that increase heat sink temperature can substantially reduce thermal efficiency in the sCO_2 and Closed Helium Brayton cycles. However, the thermal efficiency for the SRC is determined by water's saturation temperature in the condenser. While the vacuum in the condenser is affected by heat sink temperatures, it is less sensitive than the other cycles. For example, a 15°C increase in feedwater temperature more than doubles the condenser vacuum to 21 kPa but only results in a 1.8% decrease in thermal efficiency.

The Closed Helium Brayton cycle performance improves significantly when heat sink temperatures are reduced, which is desirable for Arctic locations and winter conditions in general. Reductions in heat sink temperature also improve the performance of the SRC because of the resulting drop in condenser saturation temperature and pressure. However, reductions in feedwater temperatures for extremely low ambient temperatures are limited by what can be reasonably achieved for condenser vacuum. Similarly, the lowest temperature inside the sCO_2 cycle (and hence, improvement in thermal efficiency) is determined by the critical point of CO_2. Pressure and temperature limits at the compressor inlet must be observed to prevent formation of liquid CO_2, which would damage the compressor. Therefore, extremely low heat sink temperatures won't substantially improve the sCO_2 cycle efficiency.

The Open-Air Brayton Cycle is the least efficient and its performance in cold weather does not improve enough to warrant continued analysis for this particular nuclear application. Similarly, improvement in thermal efficiency for the sCO_2 cycle due to colder ambient temperatures is limited. While promising, it is less technically mature than the other cycles and therefore not recommended for immediate further analysis.

Re-design of the MARVEL intermediate loop to accommodate other power conversion cycles is warranted. Although not chosen for evaluation here, re-design of the intermediate loop may include evaluation of NaK coolant because like helium, it satisfies PDC 78 and eliminates the corrosion, radiation damage, and temperature limitations associated with intimate placement of Stirling engines. It provides some advantages relative to helium, including:

1. higher thermal efficiency due to better heat transfer properties.
2. elimination of potential voiding in the core in the event of a leak to the primary.
3. simpler and smaller IHX design would.

NaK's reaction with water in the event of a steam generator leak is its notable disadvantage as an intermediate coolant. Double-walled components to address the industrial hazard would increase cost and reduce performance. Additionally, a NaK-cooled intermediate loop could not be used directly for the Closed Brayton cycle and a tertiary loop would be needed for that power conversion system.

3.3. Recommendations

Cost, performance, and flexibility comparisons of helium and NaK in an upgraded intermediate loop, followed by detailed design and fabrication, could be finished prior to MARVEL startup. Therefore, two actions are recommended.

1. Initiate conceptual design of an upgraded intermediate loop for MARVEL. Early focus in the design should include trade studies of intermediate coolants and heat exchangers. The design should focus on enabling the SHR and Closed Helium Brayton cycles and allow for testing selected process heat applications.
2. Refine analyses of the SRC and Closed Helium Brayton cycle models to better determine which set of locations and conditions favor which power cycle. Integrate a microgrid into the MARVEL thermodynamic systems models and perform similar analyses for selected heat applications.

3.4. Conclusion

It was concluded that of the cycles analyzed, the Closed Helium Brayton cycle is the best choice for deployment in Arctic and cold weather applications. The Superheated Rankine cycle is the best choice for deployment in equatorial and hot weather applications. Further feasibility and trade studies are warranted to provide better data regarding which of the recommended power cycles fit best for likely deployment locations and conditions.

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REFERENCES

[1] D. Gerstner and Y. Arafat, "MARVEL 90% Final Design Report, INL/RPT-23-74280," Idaho National Laboratory, Idaho Falls, 2023.

[2] American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code (ASME BPVC.III.5-2021 Subsection HB Subpart B),* New York City: ASME, 2021.

[3] O. J. Foust, Sodium-NaK Engineering Handbook Volume I, New York: Gordon and Breach, Science Publishers, Inc., 1972.

[4] C. Parisi, "RELAP-3D Thermal-Hydraulic Analysis of MARVEl Microreactor Final Design," Idaho National Laboratory, Idaho Falls, 2023.

[5] NRC , *U.S. Nuclear Regulatory Commission Regulatory Guide 1.232, Revision 0,* 2018.

[6] Babcock and Wilcox Company, "Chapter 2, Thermodynamics of Steam," in *Steam, its Generation and Use Edition 41*, Barberton, OH, Babcock and Wilcox Company, 2005, pp. 2-19 - 2-21.

[7] Department of Energy, "Quadrennial Technology Review 2015, Chapter 4: Advancing Clean Electric Power Technologies," U.S. Department of Energy, Washington D.C., 2015.