

Design of a CO₂ Makeup System for a Nuclear sCO₂ Brayton Cycle on Mars and Analysis of Its Impact on Net Power Output

Gwanwoo Park^a, Seongmin Son^{a*}

^aDepartment of Convergence & Fusion System Engineering, Kyungpook National University

^a 80, Daehak-ro, Buk-gu, Daegu, Republic of Korea

*Corresponding author: seongminson@knu.ac.kr

***Keywords:** Supercritical carbon dioxide, Leakage makeup, In-Situ Resource Utilization (ISRU), Mars Atmospheric Acquisition and Compression (MAAC)

1. Introduction

Supercritical carbon dioxide (sCO₂) Brayton cycle is a strong candidate for compact space-surface nuclear power systems [1]. However, long-term operation requires replenishment of CO₂ that leaks across the system boundary and cannot be recovered. Because the Martian atmosphere contains approximately 95.4% CO₂ by volume, it can serve as an in-situ source of working fluid. Its low surface pressure of approximately 0.6–0.8 kPa, however, necessitates additional processing before the captured CO₂ can be utilized. For example, the Mars In-Situ Propellant Production Precursor (MIP) adopted a zeolite 13X temperature-swing adsorption pump for CO₂ capture and was designed to increase the pressure to approximately 0.109 MPa (815 Torr) by heating the adsorbent bed [2,3]. Because MIP was developed for the canceled 2001 Mars Surveyor Lander mission, its performance was not demonstrated on Mars. Subsequently, MOXIE demonstrated atmospheric intake on Mars, with its compressor processing approximately 55 g/h of Martian atmosphere as part of the oxygen-production process [4]. However, strategies for replenishing unrecoverable CO₂ leakage during long-term operation have received limited attention. Therefore, the objective of this study is to evaluate the required makeup capacity and the associated energy penalty. A relevant precedent can be found in Mars in situ resource utilization systems developed to produce oxygen from atmospheric CO₂. These systems also faced the challenge of acquiring CO₂ from the low-pressure Martian atmosphere and adopted an adsorption-based approach for CO₂ capture and initial pressure elevation. Building on this approach, the present study assumes an additional multistage compression process and evaluates its applicability to supplying makeup CO₂ to an sCO₂ power system.

Three leakage scenarios are established using leakage data from a closed helium–xenon (He–Xe) Brayton rotating-unit design, and a corresponding in situ resource utilization process is designed to compensate for the working-fluid losses. A safety-factor concept is also applied to maintain sufficient margin from the solid-CO₂ region, and the power requirement of the makeup system is estimated. The objective is to estimate the associated energy requirement of makeup process demand and

assess its magnitude relative to the net power output. Formal process optimization is beyond the scope of the present conceptual screening study.

2. Methodology

The system boundary governing internal working-fluid circulation and external leakage extends throughout the primary reactor system and the secondary power conversion system. It encompasses the reactor heat exchanger, recuperator, cooler, turbomachinery, piping, inventory tank, and feed pump. Working fluid retained within the system and fluid that is recovered and reused are excluded from the leakage inventory. External leakage includes losses resulting from imperfect sealing or unrecovered discharge through valves, welds, flanges, penetrations, instrumentation, and unrecovered flow paths. Large-break accidents are excluded from the design basis of the replenishment system for normal plant operation. The total annual working-fluid loss within this system boundary is expressed by Eq. (1)

$$M_{\text{loss}} = \lambda M_0 + M_{\text{op}} + M_{\text{vent}} \quad (1)$$

Where M_{loss} is the total annual CO₂ working-fluid loss (kg/year), λ is the annual fractional leakage rate across the system boundary (year⁻¹), and M_0 is the initial CO₂ inventory (kg). M_{op} and M_{vent} represent the annual operational loss and the annual intentional or non-recoverable venting loss (kg/year), respectively. In the present screening analysis, M_{op} and M_{vent} were assumed to be zero to isolate the effect of boundary leakage. Therefore, Eq. (1) is simplified to $M_{\text{loss}} = \lambda M_0$. Leakage rates expressed as %/year were divided by 100 before being used as λ . An initial CO₂ inventory of $M_0 = 1,000$ kg was adopted as the baseline condition, and a historical He–Xe closed-Brayton rotating-unit design was used as an engineering analog for leakage screening [5].

Table 1. Annual He–Xe analog leakage scenarios relative to the total CO₂ inventory [5]

Leakage Scenario	Leakage Rate (%/year)	Leakage at 1,000 kg Inventory (kg/year)	Leakage at 10,000 kg Inventory (kg/year)
Tight-Containment Target	0.100	1.00	10.0
He–Xe Measured Analog	0.318	3.18	31.8
Tenfold Analog Upper Bound	3.18	31.8	318

NASA CR-1401 reported a makeup-gas allowance of 0.008 lb/h for a He–Xe closed-Brayton rotating-unit design, equal to ten times the measured seal leakage [5]. The allowance corresponds to 31.8 kg/year, whereas the measured leakage corresponds to 3.18 kg/year. When normalized to the baseline inventory of 1,000 kg, these values yield 3.18%/year and 0.318%/year, respectively. A tight-containment target of 0.100%/year was retained as a design goal. These values are used only as engineering analog scenarios and not as direct fluid-similarity conversions to sCO₂.

$$M_{\text{makeup}} = S_F M_{\text{loss}} ; \dot{m}_{\text{req}} = \frac{M_{\text{makeup}}}{8,760A} \quad (2)$$

The annual processing capacity in Eq. (2) includes a design margin factor of $S_F = 2.0$; the annual leakage replacement duty does not. At 3.18%/year leakage, the design capacity and nominal annual throughput are 63.6 and 31.8 kg/year, respectively. A subsystem operating availability of $A = 0.80$ was assumed. Using the MOXIE atmospheric intake rate as a feed-rate reference, the effective CO₂ processing rate was estimated as $55 \times 0.954 \times 0.90 = 47.2$ g/h, where 0.954 is the atmospheric CO₂ mole fraction and 0.90 is an assumed capture efficiency for conceptual-design screening. This rate corresponds to an annual throughput of approximately 331 kg at the specified operating availability. The calculation is based solely on the atmospheric feed capacity and does not imply that MOXIE collected or supplied stored CO₂ to the sCO₂ power system [4]. For preliminary power screening, the reported MIP power of 16 W and nominal CO₂ collection of 4 g over 1–3 sols were considered [2,3]. The available data, however, does not establish that the 16 W power demand persists continuously throughout the entire collection interval. Therefore, the corresponding values of 98.64–295.92 kWh/kg should not be interpreted as experimentally demonstrated capture-and-desorption specific energies. If continuous 16 W operation over the full 1–3-sol interval is assumed as a conservative screening case, these values represent an apparent upper-bound energy intensity under that assumption. The process considered in this study consists of atmospheric CO₂ adsorption, thermal desorption, gas conditioning, multistage compression, and cooling, condensation, pumping, and

heating as required to reach the target sCO₂-loop inlet state.

3. Design of the CO₂ Makeup System

The CO₂ makeup system employs the Mars Atmospheric Acquisition and Compression (MAAC) process incorporated into NASA's Mars In-Situ Propellant Production Precursor (MIP) experiment. After the inlet valve is opened, the Martian atmosphere at approximately 6–7 Torr (0.80–0.93 kPa) is introduced into an adsorption bed, where CO₂ is captured using an adsorbent such as zeolite 13X. The valve is subsequently closed, and the bed is heated to desorb the captured CO₂ at approximately 815 Torr (109 kPa). With parallel adsorption beds, one bed can perform CO₂ adsorption while the other undergoes heating and regeneration. The captured CO₂ is thermally desorbed during the Martian daytime. In the power screening, all MIP-proxy electricity is charged to the reference power system without credit for external solar energy. The MAAC heater raises the bed temperature to approximately 450 K [2,3]. The resulting CO₂ gas, desorbed at 0.109 MPa, is subsequently compressed in multiple stages. For the preliminary comparison, a heat-sink temperature of 230 K was assumed for the condensation route. Under this design assumption, a process combining multistage compression, condensation, and liquid pumping offers an energy-efficient pathway.

Table 2. Comparison Of Processes

Process	Compression Configuration	Pressure Ratio per Stage	Specific Shaft Work (kJ/kg)
Direct Gas Compression	Four-stage compressor	3.014	344.4
Condensation at 230 K	Two-stage compressor + pump	3.002	151.6
Condensation at 230 K	Three-stage compressor + pump	2.081	144.6

To minimize the number of components, a two-stage compression system is employed coupled with a pump. Alternatively, a three-stage compression system coupled with a pump is used to reduce the pressure ratio per compressor stage. In both configurations, the pump pressurizes the CO₂ from 0.982 MPa to 9 MPa. CO₂ phase boundaries and thermophysical properties were evaluated using the Span–Wagner equation of state [6].

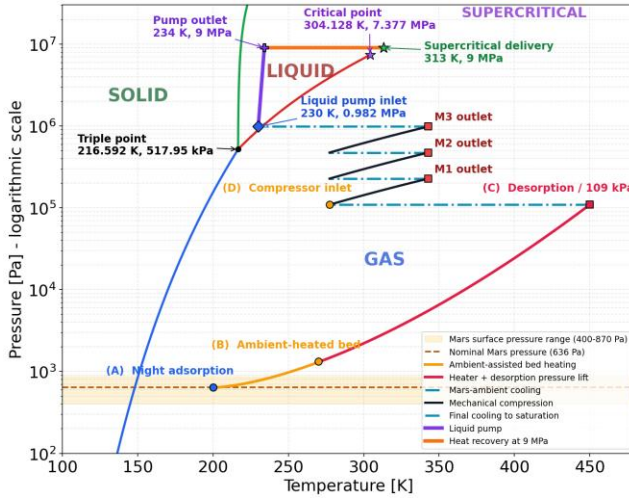


Figure 1. CO₂ triple point and thermodynamic state pathway based on the Span–Wagner equation of state [6]

To limit equipment size and cost in this conceptual comparison, the pressure ratio per compression stage was constrained to approximately 3.0 or less. Accordingly, the pressure ratios adopted in the present process range from approximately 2.0 to 3.0. Because phase change is inherent in the proposed process, the thermodynamic path is selected to avoid the CO₂ triple point and the solid-phase region, as illustrated in Fig. 1, thereby enabling a continuous transition to the supercritical state [6].

4. Results and Discussion

Table 3 summarizes the annual CO₂ loss and required makeup capacity for an initial inventory of $M_0 = 1,000$ kg. A tight-containment target of 0.100%/year, a measured He–Xe analog leakage rate of 0.318%/year, and a tenfold conservative upper bound of 3.18%/year were considered [5]. The design makeup capacity was calculated using $SF = 2.0$, while the required hourly processing rate was determined using the subsystem operating availability of $A = 0.80$.

Table 3. Leakage and Capacity for $M_0=1,000$ kg

Leakage Scenario	λ (%/Year)	Annual Loss (kg/Year)	Design Makeup Capacity (kg/Year)	Required Processing Rate (g/h)
Tight-Containment Target	0.100	1.00	2.00	0.29
He–Xe Measured Analog	0.318	3.18	6.36	0.91
Tenfold Analog Upper Bound	3.18	31.8	63.6	9.07

Even under the conservative upper-bound scenario, the required processing rate is only 9.07 g/h, which is lower than the MOXIE-scale effective atmospheric CO₂ processing rate of 47.2 g/h [4]. The corresponding

throughput margin is approximately 5.2. Therefore, the required makeup capacity is achievable at the atmospheric-intake scale considered in this study, provided that the adsorption beds are modularized and operated cyclically. This comparison represents an intake-capacity screening assessment and does not imply that MOXIE itself recovered or supplied CO₂ to an sCO₂ power system.

Table 4. MIP-proxy power penalties at two throughput bases for the 3.18%/year leakage scenario

Reference output (kWe)	Throughput basis*	Penalty, 1 sol (%)	Penalty, 3 sols (%)
10	Nominal	4.48	13.43
10	Full capacity	8.95	26.86
40	Nominal	1.12	3.36
40	Full capacity	2.24	6.71
100	Nominal	0.45	1.34
100	Full capacity	0.90	2.69

*Nominal: 31.8 kg/year; full capacity: 63.6 kg/year. Penalties use 98.64/295.92 kWh/kg for 1/3 sols and $CF = 0.80$. Downstream shaft work is reported separately.

Table 4 applies the continuous-16-W MIP energy proxy to nominal and hypothetical full design-capacity throughputs. Their annual proxy energies are 3.14/9.41 and 6.27/18.82 MWh/year for the 1/3-sol cases, respectively. The reference output is the electrical output before deducting the proxy load. At a power-system capacity factor of $CF = 0.80$, the 40-kWe system generates 280.3 MWh/year. On the nominal basis, the penalties are 1.12% and 3.36%, corresponding to equivalent net outputs of 39.55 and 38.66 kWe. These outputs are calculated by dividing the annual proxy energy by 8,760 CF hours and subtracting the resulting load from the reference output; they are not instantaneous batch-operation outputs. At 0.318%/year leakage, the nominal-basis 1-sol penalty is 0.112% for the 40-kWe system.

Section 3 evaluates the downstream compression-and-pumping route, whose shaft work of 144.6 kJ/kg equals 0.04017 kWh/kg. This gives 0.00128 MWh/year at 31.8 kg/year and 0.00255 MWh/year at 63.6 kg/year, about 0.041% of the corresponding 1-sol MIP-proxy energy. This shaft work is reported separately and is not included in Table 4. Table 4 therefore represents proxy-based screening, not a complete electrical-energy balance of the proposed process. Such a balance requires explicit component and drive efficiencies, regeneration duty cycles, thermal-conditioning loads, and auxiliary electricity use.

The relative power penalty decreases as the rated output of the power system increases because the assumed makeup demand is determined by the fixed 1,000-kg CO₂ inventory rather than by the rated electrical output. The penalty is therefore limited for the 40- and 100-kWe systems but becomes significant for the 10-kWe system, particularly under the 3-sol capture condition. The assumed MIP proxy dominates this

screening calculation; identifying the dominant loads in an actual makeup system requires a component-resolved duty-cycle and energy balance.

The He–Xe leakage data represent an engineering analog rather than a direct prediction of leakage from an sCO₂ system. Differences in working-fluid properties, seal geometry, pressure, temperature, and leakage-flow regime must therefore be considered in component-level qualification tests. In addition, the MIP-based energy consumption represents a small-scale experimental-system proxy. Detailed system design should include scale-dependent adsorption performance, compressor and pump efficiencies, heat recovery, Martian seasonal temperature variations, and dust effects.

5. Conclusions

A Martian atmospheric CO₂ makeup process was developed to compensate for working-fluid losses from a nuclear sCO₂ Brayton power system. Leakage scenarios were established using operational data from a closed He–Xe Brayton system. For an initial CO₂ inventory of 1,000 kg, the measured analog leakage rate and the tenfold conservative screening upper bound were 0.318%/year and 3.18%/year, respectively.

With SF = 2.0 and a subsystem operating availability of A = 0.80, the upper-bound scenario requires a design makeup capacity of 63.6 kg/year, equivalent to a processing rate of 9.07 g/h. This rate is lower than the MOXIE-scale atmospheric-intake proxy of 47.2 g/h, indicating that the required mass-processing capacity is feasible at the conceptual-design level but not limited by the nominal atmospheric intake rate alone.

The proposed thermodynamic pathway consists of atmospheric CO₂ adsorption, thermal desorption at approximately 0.109 MPa, multistage gas compression, condensation using the Martian nighttime environment as a heat sink, liquid pumping from 0.982 MPa to 9 MPa, and controlled heating to the supercritical state. The phase path avoids both the CO₂ triple point and the solid-phase region. Among the evaluated configurations, the three-stage compressor and liquid-pump arrangement reduces the pressure ratio per compressor stage to approximately 2.08 and requires a specific shaft work of 144.6 kJ/kg.

At 3.18%/year leakage, the nominal annual throughput of 31.8 kg/year yields MIP-proxy penalties of 1.12% and 3.36% for the 40-kWe reference system in the 1- and 3-sol cases, respectively. The equivalent net outputs are 39.55 and 38.66 kWe. The 63.6 kg/year full-capacity case is retained as a conservative sensitivity case. These results depend on the continuous-power proxy assumption and do not establish the total electrical demand or actual feasibility of the proposed process. The downstream shaft work is quantified separately. Further validation should address sCO₂ leakage, adsorption-bed scale-up and duty cycles, regeneration and heat recovery, and long-duration Martian operation. The He–Xe analog cannot directly predict sCO₂ leakage.

Acknowledgement

This research was supported by Korea Hydro & Nuclear Power Co., Ltd. (Grant No. 2024-Tech-16)

REFERENCES

- [1] B. Sondelski and G. Nellis, Mass Optimization of a Supercritical CO₂ Brayton Cycle with a Direct-Cooled Nuclear Reactor for Space Surface Power, *Applied Thermal Engineering*, Vol. 163, 114299, 2019.
- [2] G. A. Landis, MIP: The First ISRU Flight Experiment, AIAA ASCEND 2020, AIAA Paper 2020-4234, NASA NTRS 20205008149, 2020.
- [3] D. I. Kaplan et al., The Mars In-Situ-Propellant-Production Precursor (MIP) Flight Demonstration, *Workshop on Mars 2001: Integrated Science in Preparation for Sample Return and Human Exploration*, pp. 54–56, 1999.
- [4] J. A. Hoffman et al., Mars Oxygen ISRU Experiment (MOXIE)-Preparing for Human Mars Exploration, *Science Advances*, Vol. 8, No. 35, eabp8636, 2022.
- [5] R. Cohen and J. Clausi, Design of Brayton Rotating Unit on Rolling-Element Bearings, NASA CR-1401, 1969.
- [6] R. Span and W. Wagner, A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa, *Journal of Physical and Chemical Reference Data*, Vol. 25, No. 6, pp. 1509–1596, 1996.