At-Scale Process Engineering for Starship Martian ISRU

Sam Ross

1 Overview

- The overwhelming majority of total system mass of an ISRU plant is the power generation and heat rejection subsystems. Using heavy process equipment that reduces power and heat rejection demands is probably always optimal.
- Turbomachinery-based carbon dioxide acquisition is feasible, and around five times as energy-efficient as existing state of the art.
- Liquefying carbon dioxide overnight with passive radiators may be overall advantageous, as propellant liquefaction power and heat rejection demands can be reduced.
- Propellant liquefaction power and heat rejection demands can be reduced by a factor of three or more using a Claude or Kapitza cycle, rather than cryocooler approaches.
- Many of the technologies required for Martian ISRU have direct short-term implications for Starship operations including depot propellant management.

Subsystem	Thermodynamic minimum (kW)	Current technology	Current efficiency	Proposed alternative	Proposed efficiency
Water extraction	4.4	21 [1]	21%	21	21%
Carbon dioxide acquisition	**0.85**	**50** [2]	**1.7%**	**10**	**8.3%**
Electrochemical processing	215	972 [2]	22%	972	22%
Propellant liquefaction	**7.51**	**150** [2]	**5%**	**46**	**16.4%**
Total		1193		1049	

Table 1.1: Overview of power consumption of proposed Martian ISRU stack

Material	Mass flow (kg/d)	Boundary condition
Water	820	Input: 190 K ice
Carbon dioxide	1000	Input: 800 Pa, 190 K
Methane	360	Product: 100-200 kPa, saturation temperature
Oxygen	1460	Product: 100-200 kPa, saturation temperature
Total	1820	

Table 1.2: Mass flows and boundary conditions (inlet for ISRU inputs, outlet for ISRU products) for the ISRU stack.

A rough overview of energy consumption for a Starship-scale ISRU stack is shown in Table 1.1, with values obtained from linear scaling of current technology. The values for this scaling are given in Table 1.2. This uses Rodriguez wells or similar direct-melt ice extraction, cryofreezers for carbon dioxide acquisition, a scaled microchannel Sabatier reactor and PEM electrolysis stack for electrochemical processing, and cryocoolers for propellant liquefaction.

The proposed alternative uses turbomachinery for carbon dioxide acquisition and a Kapitza cycle for propellant liquefaction with a carbon dioxide reboiler to reduce the required cooling. Through these alternative technologies applied in isolation, energy demands for the ISRU stack are reduced by around 12%.

2 Carbon dioxide acquisition (CDA)

Acquisition of the carbon dioxide feedstock requires around 2% of the total energy requirements of legacy systems, using the extremely inefficient cryofreezer architecture. Through the use of intercooled turbocompressors, the energy demands of the CDA system can be reduced five-fold. This heavily leverages existing technology, both in industrial compressors and aerospace heat exchangers. The mass of turbomachinery is also substantially lower than equivalent cryofreezers.

Turbomachinery has been identified in the past as a potentially viable approach for CDA, but generally rejected due to perceived inefficiencies at small scales. Over the course of a Masters thesis project the viability at the low end of Starship scale has been established with the preliminary end-to-end design of a CDA system. This system uses a series of compressor stages with intercooling heat exchangers to achieve a low specific work of compression and low mass compared to the state of the art. Despite overall pessimistic modelling assumptions for efficiency and mass, this system substantially outperforms both few-stage reciprocating compressor systems (including scrolls) and cryofreezers. An optimiser code for generating and evaluating arbitrary systems has been created and is freely available for use.

In order to carry out this analysis, a series of low-order component models for axial, centrifugal and scroll compressors and heat exchangers were developed with flexibility to allow component evaluation across the working envelope of a CDA system. These models were validated against appropriate data available in the literature, and were found to be either accurate or reliably conservative enough to be useful for this analysis. These component models each used a minimal number of parameters to allow for rapid optimisation to maximise efficiency and minimise mass.

These component models were then wrapped into an architecture-level design loop which varied mass flow, the number of intercoolers, heat exchanger outlet temperature and heat exchanger temperature difference. These parameters were swept through to determine the combination that minimise either total system mass (including the masses of power and heat rejection systems) or specific energy of compression. This optimal choice is dependent on both the mass cost of power/heat rejection and the level of coupled optimisation with the rest of the ISRU stack.

If the goal of the ISRU system optimisation is to minimise Equivalent System Mass, or a similar metric that accounts for the total mass of the ISRU system along with auxiliary power and heat rejection systems, the optimal CDA system has the lowest possible mass flow. If the goal is instead to minimise either specific energy of compression, or another metric per unit output, then the mass flow should instead be maximised as much as reasonably possible. This is due to the overall favourable scaling of the efficiency and mass of turbomachinery compression systems, which makes the CDA system more efficient at larger scales. Increasing mass flow from the minimum to supply Starship ISRU (1000 kg/d) to five times this value results in a 9% reduction in specific compression work.

This design work placed limits on the speeds, sizes and architectures of all components to ensure they are feasible with modern technology and can leverage existing industrial experience. For instance, the speeds and blade heights of turbomachinery components were limited based on literature values, and the heat exchanger design was based on proven architectures from Reaction Engines' air-breathing intercooler. Despite this, a number of models were deliberately conservative to prevent overestimation of efficiencies and underestimation of weights, and so substantial room exists to improve the performance of the CDA system described. In particular the efficiency of the centrifugal compressor stator/diffuser (a variable which the performance model was sensitive to) was conservative compared to the performance of optimised systems in literature and industry. Achieving higher performance from this subcomponent type could lead to a further 5-10% reduction in specific energy and Equivalent System Mass.

One common concern raised for CDA systems, and turbomachinery in particular, is dust damage. Due to the relatively high flow speeds involved with turbomachinery, conventional dust filtration systems (cyclone separators and electrostatic filters) would likely suffice for the vast majority of airborne dust removal. The expected dust loading is also less than is experienced by aviation compressors and does not suffer from high-temperature erosion and blockage which is the largest source of dust-related damage to compressors on Earth.

3 Carbon dioxide liquefaction

One key decision in the CDA architecture that affects the ISRU system at large is whether to run the CDA system intermittently with liquefaction and storage of carbon dioxide at low pressures, or continuously with no storage.

Liquefying carbon dioxide overnight carries a number of advantages. Firstly, it allows the CDA system to be run intermittently to increase mass flow (and thus volumetric flow and efficiency while reducing specific weight). It also allows for continuous electrochemical process operation to limit thermal stress issues and reduce the demand for energy storage. However, the biggest benefit is in reducing propellant liquefaction demands. The evaporation of liquid carbon dioxide can be used to cool the gaseous propellants, by as much as 50 K. This could reduce liquefaction loads by around 8%. A preliminary analysis suggests that carbon dioxide liquefaction would be possible with entirely passive (radiator-driven) cooling rather than cryocooling, although a more advanced study would be required for complete evaluation.

However, liquefaction approximately doubles the heat rejection demands and adds substantial mass in the storage tank and liquefying heat exchanger. The need for heat pumping to a higher rejection temperature, if required, would add a substantial power demand as well. The savings in the propellant liquefaction must therefore be compared to the costs in heat rejection and mass in the CDA system before a decision is made.

4 Kapitza cycle propellant liquefaction

Current proposals for Design Reference Mission-scale ISRU plants use helium cryocoolers to liquefy propellant at the outlet of the electrochemical reactor. This is highly scalable (as crycoolers can operate down to 10 W cooling power) but extremely heavy and inefficient. Current systems with spaceflight heritage have coefficients of performance of 5-10% compared to Carnot efficiency, and a specific weight of around 50 kg/kW. This results in propellant liquefaction requiring about 13% of total system power and a large proportion of system mass.

Replacing this with an alternative liquefaction cycle has the potential for huge gains in both efficiency and weight, as well as allowing existing industrial systems to be used. This could be achieved with a secondary refrigerant circuit, or perhaps more advantageously a flow-through process such as the Claude or Kapitza cycle. These both use a medium pressure ratio compressor (around 5-10, rather than the >40 pressure ratio of the Linde cycle), a Joule-Thomson throttle valve and turbine with intercooling to greatly improve on the efficiencies of both the cryocooler and Linde cycle approaches. A gain of performance of perhaps three times is possible, with a higher overall temperature of heat rejection and the use of extensive industrial heritage components. Compressor-turbine cycles at relatively mass low flow rates are relatively common in large refrigeration systems and often use scroll compressors and expanders.

5 Short-term implications

The clearest short-term crossover from Martian ISRU to the current Starship program is the use of flow-through system for propellant liquefaction. This exactly mirrors the need for boiloff recondensing on a zero-boiloff fuel depot in LEO for lunar and Mars missions. The required cooling power for a depot recondenser is probably larger than for a Martian ISRU application, although even a single large system would build valuable experience with this regime. The same design should also be viable for methane recondensing in Starship/Super Heavy ground support, although this is almost certainly less economical than using COTS natural gas condensers or liquid nitrogen reboilers.

The other consideration that should ideally be addressed in the short term is laying out a series of baseline assumptions/expectations on Starship ISRU concept of operations and high-level system parameters like mass flows and system pressures. Establishing a baseline conops in the style of the Design Reference Architectures would allow future subsystem studies to be much more relevant and allow for potential synergies between subsystems to be taken advantage of. Specifying some variables like pressure and mass flow, even if in a relatively wide range, would similarly allow future studies to be more relevant and effective.

The outcome of future work making use of a Starship Reference Architecture may make some recommendations for the operations of Starship on Mars, and possibly on the Moon. One parameter that appears significant from preliminary work on propellant liquefaction is the value of tank pressure during the surface phase of the mission. Certain ranges may make Kapitza/Claude cycle more effective by varying the liquid propellant outlet pressure, although this range is not currently know.

Overall, the preliminary design work thus far suggests that ISRU operations on the Starship scale have the potential to improve efficiency and reduce specific weight compared to existing designs. Future work should focus on design integrations between subsystems of the ISRU stack, and optimisation of the electrochemical process which remains the largest contributor to energy consumption.

References

[1] Stephen J. Hoffman, Alida D. Andrews, and Kevin D. Watts. "Simulated water well performance on Mars". In: *2018 AIAA SPACE and Astronautics Forum and Exposition* (2018). DOI: 10.2514/6.2018-5293.

[2] Julie E. Kleinhenz and Aaron Paz. "An ISRU propellant production system for a fully fueled Mars Ascent Vehicle". In: *10th Symposium on Space Resource Utilization* (2017). DOI: 10.2514/6.2017-0423.