DE-RISKING PRODUCTION OF MARS RETURN PROPELLANT AND BOOTSTRAPPING OF MARS AGRICULTURE USING IMPORTED AMMONIA. G. Lordos[1,*], J. Soto[1], O. de Weck[1] and J. Hoffman[1], [1]Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139 (glordos@mit.edu).

Executive Summary: Future large-scale permanent settlements on Mars would require in-situ propellant production, necessitating the development and integration of multiple new capabilities. A stepping-stone approach to gradually develop these capabilities reduces technical and programmatic risk. This work proposes transporting ammonia to Mars as a hydrogen carrier, enabling the production of return propellant from at least 70% (by mass) in-situ atmospheric resources, significantly reducing reliance on Martian ice and cutting initial Earth launch requirements by more than half (e.g., ∼3 Starship tanker deliveries of NH_3 versus ∼8 if all return propellant were brought from Earth). Surplus ammonia can be used directly as fertilizer to bootstrap Mars agriculture, accelerating the soil enrichment cycle, while surplus nitrogen (N_2) may be stored for future use as a buffer gas for large habitats and greenhouses. As the capability to reliably produce water in-situ continues to improve, imported ammonia can be incrementally reduced and eventually phased out. In this way, initial ammonia imports play an important role in reducing cost and risk for early crewed Mars architectures, helping to smooth the transition from brought-along to in-situ resources.

Motivation: Several scaling challenges must be overcome to enable future Mars missions sized for tens of crew. These include large-volume methane (CH_4) and oxygen (O_2) propellant production for return trips, as well as securing sufficient supplies of fertilizer and buffer gases for the expansive habitats and greenhouses needed to support a growing settlement. Importing NH_3 during early missions directly helps address both problems by providing the required hydrogen feedstock for methanation without assuming access to in-situ ice reserves (with CO_2 sourced from the atmosphere) while simultaneously delivering readily usable ("fixed") nitrogen. Rather than relying on tenuous Martian resources for nitrogen (e.g., extracting the ∼2.7% N_2 from the atmosphere or processing nitrates from regolith), early missions can use imported ammonia immediately: the NH_3 can be applied as fertilizer to rapidly enrich Martian "soil", and its cracked N_2 byproduct can augment habitat and greenhouse atmospheres as an inert pressurizing gas. Early ammonia imports thus create a viable pathway to long-term settlement, reducing uncertainties and inefficiencies associated with extracting water and nitrogen from in-situ Martian resources in the initial stages.

Process Concept of Operations: The proposed ISRU plant produces approximately 21.8 kg/hr of CH_4 and 78.2 kg/hr of O_2. The operational process is outlined as follows:

Step 1: Power Infrastructure. Any large Mars settlement with ISRU capabilities will be power-intensive. To support a 100 kg/hr propellant production rate, a ∼1 MW-class fission surface power (FSP) system (e.g., eVinci (TM) Space Microreactor by Westinghouse [1], or similar) is assumed to be available.

Step 2: Propellant Production Systems. This ISRU plant is delivered to Mars fully pre-integrated within a landed Starship and is connected to the FSP power source by a utility rover. The imported ammonia is carried in liquid form at ∼240 K, stored in payload bay tanks designed for up to ∼3 atm pressure. The cryogenic methane and oxygen propellants produced are likewise stored in the Starship's CH_4 and O_2 tanks which are fitted with a broad area cooling system, ready for use in the return vehicle.

Step 3: Ammonia Cracking (H_2 Generation). Imported liquid NH_3 is thermally decomposed at ∼400-600 °C over a nickel catalyst[2]. This strongly endothermic reaction (∼46kJ per mol NH_3) consumes about ∼30–40kW of thermal power to yield hydrogen and nitrogen gases. The nitrogen byproduct is produced at ∼25.5kg/hr and can be collected and stored as habitat buffer gas (for later use in life support atmospheres) or vented if not immediately needed.

Step 4: Martian Air Acquisition and CO_2 Processing. A high-capacity intake system captures $\sim 6 \times 10^6$ L/hr of Martian air at ambient pressure (0.6–0.7 kPa). A heavy-duty blower/compressor then boosts this flow to a processor at 0.5–1 bar, drawing on the order of 200–300 kW of electrical power. The moving air stream also provides forced convection for heat rejection[3]. Dust is continuously removed by a two-stage dust filtration system [4], after which cryogenic or sorption-based separation techniques concentrate CO_2 to over 99.9% purity. The extracted residual gases (mainly N_2 and Ar, totaling 3.5–4.0 kg/hr) are vented back to the atmosphere, greatly simplifying storage requirements and enhancing system reliability.

Step 5: Methanation and Oxygen Generation. The Sabatier reactor operates at 300–400 °C with a ruthenium or nickel catalyst[5]. This exothermic reaction ($\Delta H = -165$ kJ/mol) releases 62.5 kW of thermal energy, which is captured and used to preheat incoming reactants, improving overall system thermal efficiency. Output gases pass through a condenser to remove water, separating methane from unreacted CO_2/H_2. The unreacted gases are recycled via a membrane separator to maximize conversion. Water from the reactor is electrolyzed, regenerating H_2 and producing O_2, thus closing the hydrogen loop and reducing net H_2 consumption to only 5.45 kg/hr. Supplemental solid-oxide electrolysis of CO_2 provides additional oxygen (up to 9 kg/hr excess) to ensure the O_2/CH_4 production ratio meets rocket propellant requirements. To the extent that some water can be sourced in-situ, it may be fed into the system, offsetting an equivalent amount of NH_3 consumption.

Step 6: Cryogenic Liquefaction and Storage. Product CH_4 and O_2 gases are dried, compressed, and then liquefied using cascading refrigeration (e.g., a reverse-Brayton cryocooler). Gas liquefaction demands on the order of 50 kW electrical. Active thermal management is employed, with broad-area cooling loops integrated into foam-insulated cryotanks to ensure continuous zero-boiloff storage (maintaining CH_4 at ∼111 K and O_2 at ∼90 K). Radiative and conductive heat ingress are minimized, preventing evaporation losses and ensuring propellants remain ready for transfer when needed.

System Inputs and Outputs: Table 1 summarizes key mass flow rates and production metrics for the integrated system.

Table 1: Key Inputs and Outputs

Parameter	Value (approx.)
CO_2 intake	85 kg/hr
Mars air intake	6×10^6 L/hr
H_2 input (net)	5.45 kg/hr
NH_3 consumption	30.9 kg/hr
CH_4 produced	21.8 kg/hr
O_2 produced (stored)	78.2 kg/hr
Excess O_2 vented	∼9 kg/hr
CO, N_2, Ar vented	∼12 kg/hr
Electrical power	1 MW (avg.)
Thermal demand	40 kW in, 600 kW out
Total system mass	30–40 tons

Power and Thermal Demands: The ISRU plant's power system continuously draws on the order of ∼1MW of electrical power, with capability to surge to ∼1.5–2MW during peak operations. Major power loads include atmospheric compression (∼250kW), electrolysis systems (∼340kW total), cryogenic refrigeration (∼50kW), and ancillary pumps and controls (∼100kW). The nuclear fission power source also provides ∼40kW of high-temperature heat directly for the endothermic reactors (ammonia cracker and CO_2 electrolyzer), while roughly ∼600kW of waste heat from exothermic processes and liquefaction is rejected via a dedicated radiator system tailored to the Martian environment, thereby maintaining thermal balance.

Mars-Specific Structural and Environmental Design: All system components must be capable of reliable, long-term autonomous operation on Mars with minimal human intervention. Materials and components are chosen to withstand extreme thermal cycling and the low ambient pressure. Pressure vessels, reactors, and electrolyzers are reinforced to safely contain their internal operating pressures (∼1–5bar) against Mars' near-vacuum ambient (∼0.005atm). Dust mitigation strategies (such as sealed enclosures and the vortex air-intake separator) limit dust ingress into sensitive machinery. Insulation and radiator sizing are addressed through advanced materials and structural design strategies to ensure proper thermal control given Mars' thin atmosphere.

Discussion and Conclusion: Early ammonia imports efficiently deliver hydrogen for propellant production, fixed nitrogen as fertilizer, and inert N_2 for habitat pressurization—resources that are all vital to sustainably bootstrap a large human settlement on Mars. For example, producing ∼800tons of CH_4/O_2 propellant on Mars would require delivering ∼250tons of NH_3 from Earth (about three fully-loaded SpaceX Starship tankers), whereas bringing all 800tons of return propellant directly from Earth would require on the order of eight Starship launches. The ammonia-import strategy thus significantly reduces initial launch mass and de-risks the propellant production process by decoupling it from uncertain in-situ water access. Moreover, it offers operational flexibility: mission planners can dynamically allocate ammonia toward fuel synthesis or agricultural needs as situations demand, providing a built-in redundancy against shortfalls in either regime. Using imported ammonia as an efficient hydrogen and nitrogen carrier is a pragmatic stepping-stone approach, enabling a smooth transition toward broader use of Martian resources. As in-situ water and other in-situ resource production become reliable at scale, ammonia deliveries can be tapered off and ultimately discontinued, with in-situ resources taking over the role of sustaining the settlement's propellant and agricultural needs.

References: [1] Westinghousenuclear.com eVinci data sheet; [2] Welch, A. "Ammonia Cracking with Starfire's Catalyst", Amm.En.Conf 11/2019; [3] Colgan et al., Appl. Therm. Eng. 242 (2024) 122463; [4] Chepko et al., ICES-2018-233 (2018); [5] Lunde et al., J. Catal. 30 (1973) 423-429.