Technical Document Plan: The Martian Multi-Recycler (MMR) at Jezero Crater

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Section I: Operational Summary and Context (Introduction)

This section provides a concise overview of the challenge, the proposed solution (MMR), and the strategic alignment of the project with the sustainability objectives of the Martian mission.

1. Executive Summary (Abstract)

The survival and autonomy of a human base on Mars rely on integrated resource management, including waste. This technical document introduces the **Martian Multi-Recycler (MMR)**, a modular In Situ Resource Utilization (ISRU) unit designed to process 12,600 kg of inorganic waste (metals, polymers, composites) generated by the crew over a 3-year mission.

The MMR operates in closed loops (water ≥95% recovery) and energy symbiosis. It prioritizes dry processing and the integration of regolith (MGS-1) to achieve a recycling rate of ≥98% of inorganic materials.

The three key high-value extrants are:

- **Composite Filaments** (MGS-1/Polymer) for 3D printing.
- **Purified Aluminum Alloys** for spare parts refounding.
- **Martian Geopolymer** (Jezero Shield) for the construction of structural radiation shielding.

The system is designed to meet logistical and safety challenges by minimizing crew workload (automation via PLC/SCADA) and ensuring the controlled elimination of HSE risks (notably PFAS and microplastics).

2. Mission Context and Challenge

- **Scenario: "Habitat Renovations"** The MMR solution is developed for the "Habitat Renovations" scenario, which highlights the imperative need to immediately use the recycled extrants for the **securing and expansion** of the Martian habitat at Jezero Crater. The necessity of manufacturing spare parts and tools on demand (reducing terrestrial logistical dependency) is central to this scenario.

- **Justification for the Circular Approach** Sending payload (mass-to-orbit) to Mars represents a prohibitive cost and logistical challenge. A linear system (waste → landfill/storage) is non-viable for sustained human presence. The MMR aligns with sustainability and autonomy objectives by transforming what would be a burden of 12,600 kg into a **local source of renewable raw materials** for the mission, thereby ensuring operational resilience.

3. Synthesis of the MMR Architecture and Competitive Advantages

The architecture is modular and structured around **three primary transformation modules** and critical support systems.

Synthesis of Modules and Symbioses

Transformation Module	Primary Function	Key Loops (Symbiosis)
Module 1: Polymers (E'3, E'7)	Production of 3D Filaments and conversion into Pure Carbon and Syngas.	**Energy Extrant:** Syngas→M2 (Induction Furnace).
Module 2: Metals (E'4)	Remelting of Aluminum Alloys for spare parts.	**Energy Intrant:** Syngas from M1. **Additive Extrant:** Slag →M3 (Shielding).
Module 3: Aggregates (E'5)	Manufacturing of Geopolymer using MGS-1 and recycled Carbon.	**Heat Extrant:** Exothermic Heat →M1 (Drying/Preheating).

Design Originality and Competitive Advantages

The MMR is distinguished by the following advantages, which guarantee its performance in the Martian environment:

Domain	Design Originality (MMR)	Competitive Advantage
ISRU / Waste Integration	Low Water MGS-1 Geopolymerization: Use of recycled Pure Carbon (M1) as the main alkaline binder to activate local MGS-1.	Production of the **Jezero Shield** (shielding) without requiring heavy terrestrial binders (cement) and minimizing the consumption of Martian water.
Energy Efficiency	**Inter-Module Thermal Symbiosis**: Syngas from polymers (M1) is used to create the reducing atmosphere for the Alu furnace (M2). Exothermic heat from the geopolymer (M3) preheats the Polymer Module (M1).	Reduction of 20−30% in net electrical demand for thermal processing. Transferring heat is more efficient than producing energy.
HSE Safety	**Double Defense against Microplastics and PFAS**: AI sorting for PFAS quarantine before thermal treatment. 0.2 µm filtration and encapsulation of microplastics in the geopolymer.	Guarantee of **Zero Discharge** of toxic contaminants and microparticles into the Martian environment or habitat.

Operations	**Priority on Dry/Mechanical Processing**: Dry Extrusion/Granulation before pyrolysis. PLC/SCADA for Nightly Batch Scheduling.	Minimization of Crew Workload and maximum water conservation.

The MMR directly addresses the technology gaps (Gap IDs) identified by NASA regarding on-demand manufacturing and material recycling in space environments (Ref. Gap ID 642,952,1341−1343).

Section II: Input Analysis and Technological Choices

The feasibility of the **Martian Multi-Recycler (MMR)** is conditioned by our capacity to transform the 12,600 kg inorganic waste stream into construction and maintenance materials, while maximizing the use of **In Situ Resources Utilization (ISRU)** available at Jezero Crater. This section justifies the technical choices based on the inputs and the Martian context.

4. Detailed Characterization of Waste Streams

The eight-person crew will generate a substantial amount of inorganic waste (metals, polymers, composites) over a three-year mission. The analysis of non-metabolic waste classification tables reveals target material streams that, if not processed, represent a logistical burden and a risk to the habitat.

Our MMR system is optimized to recover materials with high structural or energetic value:

Waste Category	Key Materials (Examples)	MMR Target Process	Recycled Product End-Use
Voluminous / Foam	Zotek F30 (Foam Packaging)	Pyrolysis Controlled (E'7)	Pure Carbon (Geopolymer Binder) & Syngas (Fuel)
Flexible Plastics	Polyethylene, Nylon (Packaging, Bags)	Dry Extrusion (E'3)	Composite Filaments for 3D Printing
Textiles / Composites	Nomex, Carbon Fiber	Controlled Grinding → Pyrolysis (E'1, E'7)	Carbon Fibers (Structural Reinforcement)
Metals	Aluminum (Containers, Structures)	Induction Melting (E'4)	Aluminum Alloys for Spare Parts and Tools

Operational Priority: The MMR prioritizes the processing of polymers for filament production and carbon for binder production, which are the primary inputs for the construction of the **Jezero Shield** ("Renovations" scenario).

5. Analysis of In Situ Resources Utilization (ISRU) at Jezero Crater

The MMR solution is intrinsically an ISRU solution, transforming waste into resources via local materials.

The Central Role of MGS-1 (Mars Global Simulant)

The simulated Martian regolith is the most abundant and critical element for manufacturing aggregates and voluminous structures.

- **Construction Material (Module 3):** MGS-1 forms the main aggregate (≥80% of volume) of the Martian Geopolymer. Its composition, rich in silicates and oxides, is ideal for the geopolymerization reaction (ref. MGS-1 Mars Global Simulant).
- **Filler Agent (Module 1):** The addition of 5−15% of powdered MGS-1 into polymers during extrusion (E'3) is used to stiffen the printable filament and reinforce the mechanical properties of the recycled plastic.
- **Molding Matrix (Module 2):** Compacted MGS-1 serves as the mold matrix for aluminum foundry (E'4), reducing the need for complex terrestrial molds (requires a refractory barrier to prevent contamination).

Management of ISRU Risks (Perchlorates)

Martian regolith may contain high levels of **Perchlorates**, which are toxic and can interfere with certain chemical processes.

- **Mitigation:** The MMR integrates an optional localized **deperchlorate step** (E'5) through targeted micro-washing, if initial tests confirm a high concentration in the local Jezero regolith. The washing water is then reinjected into the closed loop (E'6).

6. Selection of Transformation Processes

The selection of processes was made to ensure maximum efficiency in energy and water, while respecting the principle of **Mechanical > Thermal**.

Target Process	MMR Module	Operational Justification	ISRU / Energy Advantage
Dry Extrusion (E'3)	Polymers (Module 1)	Absolute priority on dry processing. Avoids high-energy washing and microplastic generation.	Low energy consumption compared to pyrolysis.
Controlled Pyrolysis (E'7)	Polymers (Module 1)	Reduction of complex polymers into Pure Carbon and Syngas. Operates in an airtight enclosure for HSE safety.	Produces Syngas (H_2, CO, CH_4) which serves as secondary fuel for Module 2 (**Energy Loop**).
Induction Melting (E'4)	Metals (Module 2)	More efficient, stable, and faster than a traditional resistance furnace.	Allows a reducing atmosphere (using Syngas from M1) to improve alloy purity.
Geopolymerization (E'5)	Aggregates (Module 3)	Uses MGS-1 and recycled carbon as a binder. Low-water process.	Exothermic reaction that provides low-temperature heat reusable by

			Module 1 (**Heat**

Section III: Detailed Technical Description of the MMR

The **Martian Multi-Recycler (MMR)** is a modular solution composed of three main units (Polymers, Metals, Aggregates) and support systems for effluents and gases. Its efficiency relies on the serialization of flows and the priority given to dry processing to minimize water and energy consumption.

7. Physical Architecture and Footprint of the MMR

The MMR is designed as a modular unit of **Euro-pallet size** to facilitate its transport and assembly within the Martian habitat or in a separate work module.

7.1 Modular Design and Dimensions

The architecture is optimized for easy maintenance and redundancy.

Physical Characteristic	Target Specification	Logistical Justification
Total Footprint (Volume)	4.5 m3 (2.0 m L x 1.5 m W x 1.5 m H)	Allows for compact transport and deployment in a standard-sized Martian laboratory.
Configuration	3 Independent Primary Modules	Each module can be repaired or replaced without stopping the others.
Interconnection	Transfer Ports (Gas, Fluid, and Heat Lines)	Use of qualified space fittings (quick and sealed) for energy symbiosis.
Isolation	Sealed Enclosure (N2 or Argon atmosphere)	**HSE Security:** Absolute containment of toxic gases (E'7) and dust (MGS-1).
Estimated Mass (Empty)	600−800 kg (depending on space qualification)	This mass is justified by the logistical savings realized by not having to transport spare parts/construction materials.

7.2 <u>Flows and Operator Interface</u>

- **Human-Machine Interface:** A single control panel (PLC/SCADA) is located at the front of the unit. It displays the operating status of the loops (temperature, pressure) and allows the launching of **Batch Scheduling**.

- **Transfer Zones (Ports):** Human contact points are minimized.
  - **Input Port:** Access to empty the sorted waste bins (E'0).
  - **Quarantine Port:** Sealed container for removing suspect PFAS (E'2).
  - **Output Port:** Secured access to retrieve Filaments (M1), cast Alloys (M2), and fresh Geopolymer (M3).

8. E'0−E'2: Reception, Sorting, and Pretreatment (Unified Platform)

These steps are essential to guarantee the purity of the flows before thermal processing, thereby protecting the equipment and the crew.

Operational Step	Description and Equipment	Quality and Safety Control
E'0: Reception & Sorting	Waste is deposited in coded bins (ex: Alu, foams, composites). → Rapid manual sorting followed by an automated conveyor.	**Crew Gain:** 5−10 min/day of guided sorting. **Objective:** Immediately separate suspect PFAS or contaminated metals for quarantine.
E'1: Mechanical Pretreatment	Priority on dry processing. Low-speed grinder and sieve to prevent overheating and microplastics. → Density separation (air classifier) to isolate fines before extrusion.	**Composites/Foams:** Controlled grinding: <2−5 mm (composite) or <50 µm (filament).
E'2: Risk Elimination	Identification of critical materials via an onboard database. → Quarantine of suspect items (PFAS, unknowns) in a dedicated storage area.	**Required Action:** Mandatory initial inventory of all mission materials to anticipate PFAS before the start of operations.

9. Module 1: Polymers and Composites (Filaments and Carbon)

This module manages the production of 3D printing filament and Carbon binder.

Operating Sequence	Technical Description	Closed Loop & Optimization
E’3: Filament Manufacturing	Dry granules (polymers, ground MGS-1) are introduced into the extruder. The extruder uses carbide screws/inserts to resist MGS-1 abrasion. → Controlled flow rate, cooling in a closed chamber.	**ISRU Input:** Addition of 5−15% powdered MGS-1 (filler) to stiffen the filament. **Heat Input:** Pre-heating by residual heat from the Induction Furnace (M2) or exothermic heat from the Geopolymer (M3).
E’7: Controlled Pyrolysis	Used only if necessary (no mechanical alternative or for pure Carbon extraction). Cycles in an airtight enclosure under an inert atmosphere (N2 or recycled Argon).	**Energy Extrant →M2:** Production of Syngas (H2/CO/CH4) for preheating and the reducing atmosphere. **Binder Extrant →M3:** Production of **Pure Carbon** (fine ash) for the geopolymer binder.

10. Module 2: Metals and Alloys

This module manages the recycling of metals, primarily aluminum.

Operating Sequence	Technical Description	Closed Loop & Optimization
E'4: Melting / Remelting Aluminum	Disassembly/cutting into ingots ≤5 kg. → Induction furnace (energy efficiency and stability). → Casting and minimal machining.	**Energy Input ←M1:** Use of Syngas for pre-heating or to create a reducing atmosphere (reduction of alloy oxidation).
ISRU Molding	Molds are made of compacted MGS-1 regolith, ensuring a voluminous ISRU matrix.	**Safety:** MGS-1 is lined with a refractory barrier (silicate coating) to prevent contamination and facilitate demolding.
Extrant Management	Metallic oxides and slag that are not remelted are collected.	**Extrant →M3:** Metallic oxides/slag serve as **additives** to the geopolymer to increase the density and strength of the shielding (Jezero Shield).

11. Module 3: Aggregates and Structural Construction

This module uses ISRU and carbon by-products for essential structural construction.

Operating Sequence	Technical Description	Closed Loop & Optimization
E’5: Geopolymerization	MGS-1 Preparation: Sieving, fine grinding (<100 µm). → Option: Targeted micro-washing for deperchloration if necessary.	**Low-Water Formulation:** Target ≤10% by mass. Uses **Pure Carbon (M1)** as the main binder and a low onboard alkaline input.
3D Printing & Cure	Mixing → Semi-dry, pumpable paste. → Construction 3D printing (thick layers). → Hollow layers filled with compacted regolith.	**Energy Extrant →M1:** The exothermic heat from the chemical reaction is recovered and directed towards the pre-heating of the polymers in M1 (**Heat Loop**).
E’8: Manufacturing & Installation	Printing of slabs, anchor cores, junction pieces. In situ assembly of the **Jezero Shield** (anti-radiation shielding) around the base.	**Predictive Maintenance:** Sensors on machines to report anomalies (15–60 min maintenance).

Section IV: Performance and Closed Loops (Integration of Support Systems)

This section is dedicated to demonstrating the efficiency and sustainability of the MMR by quantifying the key loops that ensure water self-sufficiency and "zero atmospheric discharge."

12. Energy Efficiency and Thermal Loops

The scarcity of energy on Mars necessitates a design based on a **symbiotic economy**, where the heat and by-products from one module become the inputs for another. The MMR transforms waste into energy sources and thermal inputs.

12.1 Syngas Recovery (M1→M2)

The controlled pyrolysis of Module 1 (E'7) converts polymers and foams (Zotek F30) into Syngas (H_2, CO, CH_4).

- **Mechanism:** This Syngas is channeled to Module 2 (Metals).
- **Performance:** It is used for pre-heating the induction furnace or to create a non-oxidizing reducing atmosphere around the molten aluminum.
- **Impact:** This loop reduces the demand for stable electrical energy during the initial melting phase and increases the purity of the alloys produced, a critical advantage for on-demand spare parts.

12.2 Residual Heat Recovery (M2/M3→M1)

The waste heat from thermal processes is reintegrated to decrease the load on Module 1.

Heat Source	Producer Module	Consumer Module	Purpose in the MMR
High Temperature (HT) Heat	Module 2 (Alu Induction Furnace)	Module 1 (Polymers)	Pre-heating and drying of polymer granules before extrusion/pyrolysis (reduces specific electrical energy).
Low Temperature (LT) Heat	Module 3 (Geopolymerization, E'5)	Module 1 (Polymers)	Recovery of exothermic heat from the cure for drying or for maintaining the extruder temperature.
Condensation Heat	E'6 (Water Loop)	Module 1 (Polymers)	Used to pre-heat the drying/extrusion chamber.

The estimated energy gain over the total cycle is significant, allowing a **20% to 30% reduction** in electrical energy dedicated to thermal processing through the optimization of heat loops.

13. Integrated Water Management (E'6 : Closed System)

The MMR is designed for **zero water discharge**, as water is a vital and scarce resource. Wet processes (targeted washing, deperchloration, geopolymer curing) are minimized and managed by the E'6 Support System (effluent treatment).

13.1 Filtration and Purification Chain

Wastewater, originating from the washing of organic contaminants or deperchloration cycles, goes through a rigorous purification chain before being reinjected.

1. **Coarse Filtration:** Elimination of large debris.
2. **Fiber Filter:** Captures microfibrils and large polymers.
3. **Membrane Filtration:** Use of **0.2 µm filters** to capture almost all microplastics and fine suspended particles.
4. **Final Purification:** Vacuum distillation or membrane distillation (for low energy) is employed to purify the water from chemical contaminants (detergent, residual alkalis) and return it to the circuit.

13.2 Water Efficiency and Valorization

- **Performance:** The expected efficiency is ≥95% water recovery for immediate reuse.
- **Captured Solids:** Sludge and concentrated solids recovered by the filters (including microplastics) are dried (via condensation heat) and integrated as **filler** or filling material into Module 3 (Geopolymer) for **permanent immobilization**.

14. Gas Management and Controlled Pyrolysis (E'7 : HSE Safety System)

Step E'7 is the guarantor of crew safety and the principle of "**zero emission**" into the Martian environment.

14.1 Safe Pyrolysis Procedure

The basic rule is to avoid pyrolysis if a mechanical or composite process is possible.

- **Airtight Enclosure:** If pyrolysis is activated, it takes place in a **sealed enclosure**, under an inert atmosphere ($N2$ or recycled Argon), preventing any reaction with oxygen.
- **Condensation:** Condensers recover oils and other volatile compounds for secure storage or potential use as lubricants.

14.2 Zero Atmospheric Discharge

Non-condensable gases resulting from pyrolysis are treated before any use or storage.

- **Catalytic Scrubbers:** These are used to neutralize potential toxic compounds (such as HCl or HCN) that might result from the decomposition of certain polymers or composites.
- **Monitoring:** Continuous sensors are used for gas analysis, ensuring that no toxic discharge or particles are released into the Martian environment or the habitat.

This integration of support systems ensures that the MMR does not create secondary pollution (water or atmosphere) while maximizing the recovery of all materials and energy.

Section V: HSE, Operations, and Conclusions

This section consolidates the MMR strategies designed to ensure the safety of the crew and the Martian environment (HSE), while minimizing human workload through automation and modular design.

15. Health, Safety, and Environmental (HSE) Controls

The MMR is designed with a **Zero Contamination** approach to manage chemical risks (toxins, PFAS) and physical risks (microplastics, abrasive particles).

15.1 Management of PFAS and Toxic Emissions (E'2, E'7)

- **PFAS Protocol:** This is the most critical risk. The mandatory initial inventory of mission materials (before MMR activation) is the first barrier. AI sensors during sorting (E'0) flag any suspect materials (PFAS found in insulations, coatings) which are immediately quarantined (E'2) and excluded from thermal treatment (Pyrolysis/Melting).
- **Thermal Safety:** All high-temperature processes (E'4, E'7) are conducted in a **sealed enclosure** and under an inert atmosphere. Emitted gases are directed to **catalytic scrubbers** to neutralize hazardous compounds (HCl, HCN) before condensation. This ensures zero toxic discharge to the Martian atmosphere or habitat.

15.2 Control and Immobilization of Microplastics (E'1, E'6)

- **Mitigation at the Source:** Priority is given to **low-speed grinding** (E'1) and **dry processing** to minimize polymer fragmentation and water usage.
- **Effective Capture:** The effluent treatment system (E'6) is equipped with 0.2 µm membrane filters on all washing circuits.
- **Immobilization:** Captured microplastics and sludge are dried (via condensation heat) and permanently **encapsulated** in the Martian Geopolymer (M3) as filler or aggregate material. This approach guarantees zero microparticle emission.

16. Operations and Minimization of Crew Workload

The MMR is designed to be a production tool, not an operational burden.

16.1 Automation and Supervision (PLC/SCADA)

- **Control Architecture:** A local PLC/SCADA (Programmable Logic Controller/Supervisory Control and Data Acquisition) system manages the orchestration of modules and exchange loops (Syngas, Heat, H2O).
- **Workload Reduction:** The crew uses a simple interface for supervision and **Batch Scheduling**, which programs long cycles (pyrolysis, melting, 3D printing) during off-peak or Martian night hours. Total human intervention time is reduced to 5−10 minutes/day for sorting and 30−60 minutes/week for maintenance.

16.2 Design for Minimal Maintenance

- **Modularity:** The use of **plug-and-play modules** allows for rapid replacement of critical units by the crew, reducing downtime.
- **Abrasion Resistance:** Given the use of abrasive MGS-1, the MMR integrates **carbide screws/inserts** for the wear parts of grinders and extruders, requiring minimal stock of spare parts.
- **Simplified Procedures:** Quick 3−5 minute checklists are provided for batch start-up and shutdown, based on predictive maintenance sensor analysis.

17. Conclusion and Recommendations

17.1 Operational Impact of the MMR

The **Martian Multi-Recycler** directly addresses several NASA Technology Gaps (Gap ID 642,952,1341−1343) by offering a solution for on-demand manufacturing (spare parts, tools) and ISRU construction.

The success of the "Habitat Renovations" scenario relies on the three key extrants:

1. **Composite Filaments:** For the manufacturing of functional parts.
2. **Alu Alloys:** For the maintenance of critical metallic systems.

3. **Martian Geopolymer:** Construction material for the **Jezero Shield** (radiation shielding and external structures).

17.2 Technical Barriers and Mitigation Solutions

While the design incorporates robust solutions, the following challenges are identified as barriers requiring validation in terrestrial (or analogue) laboratories before deployment.

Technical Challenge	Problematic	Integrated Mitigation Solution
MGS-1 Abrasivity	Rapid wear of mechanical parts (screws, sieves) due to the fineness and hardness of the regolith.	**Hard Materials:** Systematic use of Tungsten Carbide screws and inserts (or ceramic). **Maintenance:** Plug-and-play design (rapid replacement).
Alloy Contamination	Risk of reaction between molten aluminum (M2) and the MGS-1 mold, creating impurities.	**Refractory Barrier:** Silicate or alumina-based coating on the compacted MGS-1 mold to insulate the metal.
Perchlorate Content	Perchlorates in MGS-1 are toxic and can potentially alter the geopolymer reaction.	**Targeted Deperchloration:** If local regolith requires it, activation of a localized **micro-washing step** managed by the E'6 System (Closed Water Loop).
PFAS Toxicity	Thermal treatment of certain polymers (PFAS) releases extremely toxic gases.	**Quarantine and Exclusion:** AI sorting and secure storage (E'2). Prohibition of feeding these materials into the furnaces.

17.3 Immediate Recommendations (Pre-Mission Tests)

To validate the robustness of these mitigation solutions, the following terrestrial tests are recommended as a priority:

1. **MGS-1 Abrasivity Tests:** Evaluate the actual wear of carbide screws/inserts during Polymer/MGS-1 filament extrusion to size the spare parts inventory.
2. **Low-Water Geopolymer Formulation:** Test different Carbon+Alkaline binder formulations with the MGS-1 simulant to ensure the minimal fluidity for 3D printing while maintaining water content at $\leq 10\%$.
3. **PFAS Validation:** Conduct a **complete inventory** of all onboard materials to determine the exact quantity of PFAS to be isolated and stored.

Appendix A: Detailed Technical Data Sheet for the Martian Multi-Recycler (MMR)

This document lists the design parameters and critical technical specifications governing the operation of the three transformation modules and the support systems of the MMR.

1. E'0−E'2: Reception and Pretreatment Specifications

Parameter	Detailed Specification	Operational Role
Automated Sorting (E’0)	Sensors: RGB Camera / simple IR Spectrometry. Objective: Recognition of basic shapes and polymers.	Identification of contaminants (metals) and suspect PFAS (quarantine).
Grinding/Granulation (E’1)	Speed: Low speed (controlled), max 100 rpm. Target Sieve: Polymers: <50 µm (for extrusion). Composites: 2−5 mm (for reinforcement).	Minimize friction, avoid local melting, and prevent the creation of microplastics.
Abrasive Material	Extrusion Screws/Inserts: **Tungsten Carbide** (or other ceramic/hard metal).	Resist MGS-1 abrasion and ensure equipment longevity.
Quarantine (E’2)	Location: Exclusion zone (inert, sealed atmosphere).	Storage of PFAS and unknown chemical materials to prevent pyrolysis/melting.

2. Module 1: Polymers and Composites

Parameter	Detailed Specification	Impact on Performance
ISRU Load (Filler)	5% to 15% powdered MGS-1 (≤50 µm).	Stiffening of the extruded filament (increased compressive strength).
Extrusion Temperature	Depends on the recycled polymer (ex: HDPE/PE: 180−220 ∘C).	Maintain viscosity for 3D printing and uniformly integrate the MGS-1.
Extrusion Filtration	Internal Sieve: Mesh ≤50 µm.	Eliminate potential inclusions/contaminants to ensure filament quality.
Controlled Pyrolysis (E'7)	Temperature: 450−600 ∘C (depending on the polymer). Atmosphere: Recycled N2 or Argon (inert).	Maximize production of Pure Carbon (binder M3) and Syngas (fuel M2).

3. Module 2: Metals and Alloys

Parameter	Detailed Specification	Impact on Performance
Melting Technology	Induction Furnace (electric).	Energy efficiency and fast/precise temperature control.
Input Size	Alu Ingots/Cut-offs ≤5 kg.	Optimize melting speed and furnace stability.
Furnace Atmosphere	**Reducing**, fed by Syngas (M1).	Minimize oxidation of molten metals (slag) to increase alloy purity.
ISRU Molds	Compacted MGS-1. Coating: Refractory barrier (silicate/alumina).	Use local MGS-1 as a matrix with protection against liquid metal contamination.

4. Module 3: Geopolymerization and Structural Construction

Parameter	Detailed Specification	Impact on Performance
MGS-1 Granulometry	Fine Grinding: <100 µm.	Increase the regolith contact surface to ensure the geopolymerization reaction.
Target Water Content	≤10% by mass.	Minimize water usage. The formulation must remain pumpable for 3D extrusion.
Primary Binder	**Pure Carbon (M1)** and low initial Alkaline input (NaOH/KOH).	Substitute terrestrial binders (cement) and utilize an MMR by-product.
Curing Process	Controlled Temperature. Residual heat (M2/M1) directed to the curing unit.	Accelerate the exothermic setting of the geopolymer while looping LT heat.
Structural Additives	Metallic Oxides/Slag (M2).	Increase the density and **radiological shielding** of the Jezero Shield.

5. Support Systems (Closed Loops)

Parameter	Detailed Specification	Role in Mission Autonomy
Effluent Filtration (E'6)	Final Filter: **0.2 µm Membrane**. Technology: Vacuum Distillation / Membrane Distillation.	Capture microplastics and ≥95% water recovery.
Gas Management (E'7)	Catalytic Scrubbers.	Neutralization of toxic gases (HCl, HCN) before use/storage.
Thermal Looping	Heat Exchangers (High and Low Temperature).	Reduction of total electrical load by **20−30%** by reusing residual heat.
Maintenance	Automation: PLC/SCADA for **Batch Scheduling**. Checklist: 3−5 min/task.	Minimization of crew time and increased reliability.

Appendix B: MMR Operator Checklist (Startup, Shutdown, and Inter-Module Exchanges)

This checklist is designed to minimize the crew workload, with interventions being short and scheduled (estimated time: 3−5 min/task). It is divided into daily, weekly, and monthly protocols.

1. Daily Procedures (Daily: 5−10 min total)

Task	Module / Step	Operator Procedure	Control and Safety Point
Sorting and Reception	MMR (Intake, E’0)	1. Check that the coded bins (Alu, Polymers, Foams) are correctly filled and not overloaded. 2. Start the **AI conveyor** for final inspection.	**Input:** Raw waste. **Control:** Validation of AI sorting (green/red signal).
Quarantine Management	Quarantine (E’2)	1. Check the PLC/SCADA alert if a suspect item (PFAS) has been detected. 2. If alert: Manually transfer the item to the **secure storage** (without processing).	**Safety:** Confirm that the PFAS item is out of the MMR circuit.
Standby Systems	MMR (Global)	Launch **Batch Scheduling** (starting long batches during off-peak/night hours).	**Control:** Confirm activation of H2 O (E’6) and energy loops.

2. Weekly Procedures (Batch Planning)

Task	Module	Operator Procedure	Inter-Module Exchange (Material Transfer)
Polymer Batches	Module 1 (E’3, E’7)	1. Launch the **Extrusion** batch (Filaments). 2. Launch the **Pyrolysis** batch (if Carbon stock is low). 3. Check the quality of the produced filament (diameter, porosity).	**Outgoing →M3:** Transfer of **Pure Carbon (Binder)** to Module 3 silo.
Metals Batches	Module 2 (E’4)	1. Launch the Alu **Melting** batch (Check incoming Syngas). 2. Retrieve molded/cast parts and perform minimal machining.	**Incoming ←M1:** Verification of the Syngas piping and the HT heat exchanger. **Outgoing →M3:** Transfer of **Slag/Oxides (Additives)** for the geopolymer.
Aggregate Batches	Module 3 (E’5, E’8)	1. Prepare the MGS-1/Carbon mixture (low-water formulation). 2.	**Consumption:** Carbon (M1), Slag (M2). **Output:**

		Launch **3D Printing** (Slabs, Jezero Shield). 3. Check the correct direction of the **LT exothermic heat** towards M1.	Shielding structures.
Water Loop	E'6 (Effluents)	1. Check 0.2 µm filter pressure. 2. Launch the **Vacuum Distillation/Membrane** cycle. 3. Transfer dried and concentrated sludge to M3 for encapsulation.	**Loop:** Re-injection of ≥95% purified water into washing/curing circuits.

3. Monthly and Predictive Maintenance Procedures

Task	Module / Step	Operator Procedure	Task Goal (Maintenance)
Preventive Maintenance	MMR (Global)	Scheduled intervention (30−60 min). 1. Replace carbide screws/inserts (M1/M3 wear parts). 2. Clean extrusion sieves and coarse filters.	Avoid failures due to MGS-1 abrasion and guarantee the quality of inputs.
Spare Parts Stock	MMR (Global)	Check the minimum stock level (Alkaline, carbide inserts, spare membranes, N2 /Argon).	Ensure continuous operation for 3 years (reduced reliance on Earth).
HSE Control	E’7 (Gas)	Analyze residual gas levels in the scrubber and check the integrity of the pyrolysis enclosure.	Guarantee **Zero Discharge** and crew safety.

Appendix C: Acronyms List and Glossary

This document lists the design parameters and critical technical specifications governing the operation of the three transformation modules and the support systems of the MMR. The updated list includes operational identifiers that are crucial for understanding the serialization of flows in the MMR.

List of Acronyms and Operational Identifiers

Acronym / Identifier	Full Definition	Domain
MMR	**M**artian **M**ulti-**R**ecycler	Core System
ISRU	**I**n **S**itu **R**esource **U**tilization	Mission Concept
MGS-1	**M**ars **G**lobal **S**imulant	Material (Local Resource)
HSE	**H**ealth, **S**afety, **E**nvironment	Protocol / Safety
PFAS	**P**er- and **P**oly**f**luoro**a**lkyl **S**ubstances	Critical Contaminant
PLC/SCADA	**P**rogrammable **L**ogic **C**ontroller / **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition	Automation
HT/LT	**H**igh **T**emperature / **L**ow **T**emperature	Thermal Exchange
E'0	**Step 0:** Reception & Sorting	Operational Flow
E'1	**Step 1:** Mechanical Pretreatment	Operational Flow
E'2	**Step 2:** Risk Elimination (PFAS Quarantine)	Operational Flow

E'3	**Step 3:** Filament Manufacturing (Module 1)	Operational Flow
E'4	**Step 4:** Aluminum Melting / Remelting (Module 2)	Operational Flow
E'5	**Step 5:** Geopolymerization (Module 3)	Operational Flow
E'6	**Step 6:** Effluent Treatment and Water Loop	Support System
E'7	**Step 7:** Gas Management and Controlled Pyrolysis	Support System
E'8	**Step 8:** Fabrication & Installation (Post-Processing)	Operational Flow

Argument for the MVP (Minimum Viable Product)

The Martian Multi-Recycler (MMR) is presented as an MVP focused on **immediate mission resilience**, concentrating on the two most vital outputs: **Pure Carbon** and the **Martian Geopolymer**.

MVP Characteristic	Description	Value Proposition
Priority to Carbon & Geopolymer	The MVP prioritizes Module 1 (Pyrolysis) to produce **Pure Carbon** from foams (Zotek F30) and Module 3 to produce the **Martian Geopolymer**.	**Immediate HSE Security:** The **Jezero Shield** (anti-radiation shielding) is the first manufactured product, ensuring crew survival.
Basic Thermal Loop	Implementation of the simplified **Exothermic Heat** Loop (M3) →M1 (Drying).	**Symbiosis Demonstration:** Proves the energy efficiency of the concept without immediate reliance on the complexity of Syngas.
Demonstrative Zero Discharge	Validation of 0.2 µm filtration and the encapsulation of solids and microplastics in the Geopolymer.	**Environmental Compliance:** Confirms the system's ability to operate in a closed loop, protecting the Martian environment and the habitat.
ISRU Focus	Exclusive use of regolith and waste; the input of terrestrial alkaline activators is minimized to the strict necessary.	**Logistical Autonomy:** Proves the feasibility of local manufacturing at 90%.

Feasibility and Material Cost (Terrestrial MVP Estimation)

For a hackathon, feasibility rests on the simplicity of engineering and the reuse of existing technologies. The argument is that the chosen processes are **mature technological blocks** (pyrolysis, extrusion) adapted for space.

1. Cost Minimization Strategy

The cost of the MMR system will primarily be governed by the necessity to use space-qualified materials (radiation resistance, vacuum, low mass). However, the design minimizes the need for complex components.

Critical Component	Standard Terrestrial Cost	Feasibility Justification
Extruder / Pyrolyzer (M1)	Industrial lab equipment ($15,000 - 50,000$ $)	**Controlled Pyrolysis** is preferred over incineration because it is more energy-efficient, easier to confine (gas safety), and produces high-value by-products (Carbon, Syngas). It is a well-mastered technology.
Induction Furnace (M2)	Small foundry furnaces ($5,000 - 15,000$ $)	More efficient and more compact than a traditional resistance furnace. The **reduction of equipment mass** sent is a major advantage, justifying a higher unit cost.
Abrasive Materials	**Tungsten Carbide** Inserts	Carbide is a high-performance material common in wear industries. Its cost is justified by the imperative of **longevity** on a 3-year mission without resupply.
Membrane Filters (E'6)	0.2 µm Membranes	High cost, but **essential** to guarantee ≥95%

		water recycling and the immobilization of microplastics. This is a non-negotiable cost compensated by the reduction of water mass to be transported from Earth.

2. MVP Realizability (Proof of Concept)

The MVP can be validated by the three recommended tests (Section V, 16.3):

1. **Formulation Test (Geopolymer):** Mix MGS-1 (simulant), Carbon (obtained by pyrolysis of standard foams), and an activator to validate mechanical strength.
2. **Abrasion Test:** Use a Carbide grinder to process a mixture of polymer and MGS-1 to confirm minimal wear.
3. **Filtration Test:** Run water charged with microplastics through the 0.2 µm filter to validate the closed loop.

These tests focus on the critical barriers and prove that the **symbiosis between waste and regolith is functional**.