Mars Habitat Resource Recycling & Manufacturing System

Team Name: Project Aura'x

Members:

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1 Problem Definition

1.1 Need Statement

During a three-year mission, an eight-person crew would accumulate over 12,000 kg of inorganic waste, or trash, which is a huge problem. If the issue is not addressed as soon as possible, we humans might cause some permanent damage to the environment on Mars.

1.2 Goal

Find an efficient and reliable way to recycle and reuse the waste on Mars.

1.3 Objectives

Objective	Basis for Measurement	Units
Must be reliable	The endurance of the solution (how many years it can last)	Years
Must not be too expensive	The cost to implement the solution	CAD
Must minimize the emission	The amount of chemical the solution might emit	–
Must be buildable by no more than eight people	Number of people required for the workload	People

Table 1: Objectives and Measurement Basis

1.4 Constraints

- Solutions must be completed within one week.
- Solutions must not burn anything without proper collection on Mars.
- Solutions must not cost too much money.
- Solutions must not be too complicated to implement.

2 Our Solution: Mars Habitat Recycling-to-Manufacturing System (MHRMS)

2.1 System Overview

Purpose: Convert waste materials from Mars habitat operations into usable 3D printing filament and manufacturing feedstock, with emphasis on CO2 extraction byproducts.

Design Philosophy: Modular, relocatable, powered by habitat grid, zero-waste discharge

Total System Mass: ∼720 kg (disassembled into <100 kg components)

2.2 Mars Environment Context

1. Mars has a thin atmosphere made up mostly of carbon dioxide, nitrogen, and argon gases, with temperatures ranging from 70°F (20°C) to -225°F (-153°C)
2. Mars' sparse atmosphere doesn't offer much protection from impacts by meteorites and the thin atmosphere causes heat from the Sun to easily escape
3. Dust storms can cover much of the planet, sometimes taking months for all dust to settle
4. Mars completes one rotation every 24.6 hours (a "sol"), with a year lasting 687 Earth days
5. These conditions directly impact recycling system design: thermal management is critical, dust mitigation essential

2.3 Critical Mars-Specific Design Considerations

2.3.1 Waste Behavior in Mars Environment

- **Vacuum Exposure Challenges:** Based on NASA Glenn Research Center analysis of waste behavior when exposed to vacuum
- **Water Sublimation:** When waste is exposed to Mars' near-vacuum conditions (0.6% Earth pressure), approximately 20% of water content will sublimate before the waste completely freezes. This process takes:
  - Small items (3mm droplets): ∼7 seconds to freeze
  - Standard waste "football" (20cm compressed bundle): ∼3.4 hours to freeze

- **Implications for Recycling System:**
  1. Pre-processing must handle both frozen and partially sublimated materials
  2. Vapor capture systems required to prevent water loss during initial processing
  3. Grinding chambers must be sealed to capture sublimating volatiles
  4. Temperature control critical: waste arriving at facility may be frozen solid (-153°C from overnight exposure)

2.3.2 Thermal Management on Mars

- **Challenge:** Mars temperature swings from 70°F (20°C) to -225°F (-153°C)
- **Solutions:**
  - Insulated processing chambers: Maintain optimal processing temperatures (150-1400°C depending on module)
  - Pre-heating systems: Thaw frozen waste before processing
  - Waste heat recovery: Capture heat from processing for habitat use
  - Phase-change thermal buffers: Smooth out temperature fluctuations

2.3.3 Mars Sol Adaptation

- **Mars Day:** 24.6 hours (24h 39m) vs Earth's 24 hours
- **Operational Impact:**
  - Processing schedules calibrated to Mars sols
  - Automation advantage: rovers and processing continue during crew sleep cycles
  - Benefit: Extra 39 minutes per sol allows for extended processing cycles

Source: NASA Mars Facts.

3 Input Categories

1. **Category A – Carbon Materials:**
   - Surplus carbon from CO2 extraction (primary feedstock)
   - Activated carbon filters (spent)
   - Carbon-containing composites
2. **Category B – Polymers/Plastics:**
   - Nitrile gloves
   - Resealable bags (PE/PP)
   - EVA waste from spacesuits and cargo transfer bags (Nomex, nylon, polyester)
   - Packaging materials (air cushions, bubble wrap, anti-static bags)

- Tape, labels, plastic clips
- Foam packaging (Zotek F30, Plastazote foam)

3. **Category C – Fabrics:**
   - Clothing (cotton, polyester, nylon)
   - Washcloths and wipes (cellulose, cotton)
   - Disinfectant wipes
4. **Category D – Food Packaging:**
   - Overwrap materials
   - Rehydratable pouches (polyester, polyethylene, aluminum, nylon)
   - Drink pouches
   - Thermal pouches
5. **Category E – Metals:**
   - Filter mesh (stainless steel, aluminum)
   - Broken tools and fasteners
   - Structural components from temporary structures
   - Electronics casings
   - Wire scraps
   - Aluminum structures
6. **Category F – Composites:**
   - Polymer matrix composites with carbon fiber
   - Multi-layer materials
   - Fabric-backed materials
   - Adhesive-bonded assemblies

3.1 NASA Data Reference

Based on ISS and shuttle waste studies, daily waste generation averages 1.45 kg per crew member, including 0.160 kg clothing, 0.352 kg food/packaging, 0.449 kg human waste, and other consumables. For a 4-person crew on a 180-day mission, this totals approximately 1,046 kg of recyclable waste.

3.2 Sorting Protocol

- Manual inspection - crew separates by visual category
- Magnetic separation - ferrous vs non-ferrous metals
- Density sorting - polymer type identification
- Quality control - contamination check, damage assessment
- Storage: Separate sealed containers for each category in airlock staging area

4 Alternative Waste Processing Options

1. **Option A – Direct Venting to Space (NOT RECOMMENDED)**

   NASA Glenn Research Center evaluated simply disposing waste via airlock to space. Key findings:

   Technical Challenges:

   (a) Time-intensive: Using existing airlock technology (3-hour depressurization cycle), disposing of waste from a 180-day, 4-person mission would require 1,250-2,500 hours of crew time

   (b) Hazard: 20% of water content sublimates and can re-condense on spacecraft surfaces or contaminate equipment

   (c) Trajectory risk: Low-velocity disposal at L2 libration points risks waste re-impacting spacecraft

   Conclusion: Direct disposal to space is impractical and hazardous for Mars missions

2. **Option B: Partial Processing to Mixed Gases**

   NASA's "Trash-to-Gas" (TtG) Approach: Process waste in primary reactor only, producing mixed gases:

   - 10% H_2, 22% CO, 68% CO_2
   - Can be used in resistojet thrusters (134.3 sec Isp)
   - Requires 0.28 kg/crew-day makeup water

   Benefits:

   - Simpler system (fewer processing steps)
   - Can provide station-keeping propulsion
   - Lower energy requirements

   Limitations:

   - Lower-quality propellant (vs. pure O_2/CH_4)
   - Still requires makeup water
   - Limited manufacturing applications

3. **Option C: Full Processing to High-Quality Propellants (RECOMMENDED)**

   NASA's "Trash-to-Supply Gas" (TtSG) - Our Baseline: Complete processing through secondary reactors:

   - 59% O_2, 41% CH_4 (optimal rocket propellant)
   - Can achieve 250+ sec Isp in rocket engines
   - Enables both propulsion AND manufacturing uses
   - Requires 0.15 kg/crew-day makeup water (less than TtG)

4.1 Our Enhanced System vs NASA's Approach

NASA TtSG (gases only):

- Produces O_2 and CH_4 for propulsion
- Vents excess gases or stores in tanks
- Limited to propellant applications

Our Integrated System (gases + solids + ISRU):

- Processes waste into filament AND propellant gases
- Combines with regolith to create metals, glass, ceramics
- 3D prints replacement parts, tools, habitat components
- Enables true self-sufficiency vs. just propellant production
- Creates complete manufacturing economy

Result: Our system achieves everything NASA's TtSG does PLUS enables permanent settlement through manufacturing capability.

5 System Modules

5.1 Module 1: Carbon Processing Station

Equipment Components:

- Enclosed ball mill grinder (50 kg)
- Compression mold press (75 kg)
- Electric heating elements (25 kg)
- Polymer binder mixing chamber (25 kg)
- Extrusion die set (15 kg)
- Control electronics (10 kg)
- **Total Module Mass: 200 kg**

Process Flow:
Path 1A: Carbon-Composite Filament (Primary Output)

1. **Grinding:** Load carbon material into sealed ball mill, grind to 10-50 micron powder (2-4 hours)
2. **Binder Preparation:** Shred compatible plastic waste, heat to 180-220°C
3. **Mixing:** Ratio: 20-40% carbon powder, 60-80% polymer binder, blend at 200-250°C (30-60 minutes)

4. **Extrusion:** Feed through heated barrel, extrude through 1.75mm or 2.85mm die
5. **Spooling:** Wind onto reusable spools, label and store

Path 1B: Pure Carbon Products

- Activated Carbon Filters: Compress powder, heat to 800-1000°C
- Graphite Components: High-pressure compression, high-temperature treatment (2000-3000°C)
- Radiation Shielding Blocks: Mix carbon with regolith simulant

Energy Profile:

- Power source: Habitat electrical grid
- Power consumption: 2-3 kW continuous
- Processing time: 4-8 hours per batch (5-10 kg output)

5.2 Module 2: Polymer Recycling Station

Equipment Components:

- Enclosed shredder/grinder with HEPA filtration (80 kg)
- Multi-zone heating chamber (60 kg)
- Filament extruder with puller (45 kg)
- Diameter sensor and feedback control (8 kg)
- Vapor capture and carbon scrubber (35 kg)
- Spooling mechanism (12 kg)
- **Total Module Mass: 240 kg**

Process Flow:

1. Material Preparation: Remove contaminants, cut to ¡10cm pieces
2. Size Reduction: Grind to 3-8mm pellets/flakes
3. Drying: Desiccant chamber at 60-80°C (if needed)
4. Melting: Temperatures by polymer type (160-260°C)
5. Filtration: Pass through 100-mesh stainless filter
6. Extrusion: Precision gear pump, temperature-controlled barrel
7. Cooling & Diameter Control: Air cooling, servo-controlled puller
8. Quality Control: Visual inspection, diameter verification

9. Spooling: Wind onto 1 kg spools, store in sealed containers

Safety Systems:

- Vapor Management: Enclosed heating, carbon scrubber filtration
- Microplastic Control: Sealed negative-pressure chamber, HEPA filtration

Energy Profile:

- Power consumption: 1.5-2.5 kW continuous
- Processing time: 6-10 hours per 5 kg batch

5.3 Module 3: Metal Processing Station

Equipment Components:

- Heavy-duty metal shredder (100 kg)
- Induction furnace with crucible (150 kg)
- Wire drawing die set (40 kg)
- Casting molds (30 kg)
- Cooling system (25 kg)
- Metal powder atomizer (optional, 35 kg)
- **Total Module Mass: 380 kg (345 kg without atomizer)**

Process Flow:
Path 3A: Metal Filament (Wire Drawing Method)

1. Shredding: Cut/shred metal components, separate by type
2. Melting: Induction crucible (Al: 660°C, Cu: 1085°C, Steel: 1400-1450°C)
3. Casting: Pour into rod molds (3-5mm diameter)
4. Wire Drawing: Pull through progressively smaller carbide dies
5. Quality Control: Diameter measurement, tensile testing
6. Spooling: Wind onto spools, label

Alternative Paths:

- Path 3B: Metal Powder (atomization for advanced printing)
- Path 3C: Direct Casting (tools, fasteners, brackets)

Energy Profile:

- Power consumption: 3-5 kW continuous, 5-7 kW peak
- Processing time: 8-12 hours per 3-5 kg batch

5.4 Module 4: Integrated Manufacturing Hub

Equipment Components:

- FDM 3D printer (plastic/composite) (35 kg)
- Metal FDM printer with sintering (55 kg)
- Direct pellet extruder (40 kg)
- CNC finishing station (60 kg)
- Quality testing equipment (20 kg)
- Parts cleaning/post-processing (15 kg)
- **Total Module Mass: 225 kg**

Manufacturing Capabilities:

- Plastic/Composite Printing: Uses filament from Modules 1 & 2
- Metal Printing: Uses metal filament from Module 3
- Direct Pellet Printing: Uses pellets directly from Module 2
- Post-Processing: CNC milling, drilling, surface finishing

Output Examples:

- Tools & Equipment: Wrenches, screwdrivers, pliers, utensils
- Habitat Components: Storage containers, furniture, ductwork
- Life Support Parts: Filter housings, valves, pipe fittings
- Scientific Instruments: Sensor housings, sample containers
- EVA/Spacesuit Parts: Tool attachments, replacement clips
- Structural Elements: Habitat expansion, radiation shielding

6 Supporting Systems

6.1 Power Distribution

- Power Source: Habitat electrical grid (nuclear/RTG or other primary power)
- Power Requirements:
  - Module 1: 2-3 kW continuous
  - Module 2: 1.5-2.5 kW continuous
  - Module 3: 3-7 kW (varies with operation)
  - Module 4: 0.5-2 kW continuous
  - **Total system: 7.5-14.5 kW peak demand**

6.2 Environmental Control

- Atmosphere Management: Sealed/vented chambers, vapor capture, HEPA filtration
- Temperature Control: Insulation, waste heat recovery, radiator cooling

6.3 Waste Management

- Non-Recyclable Residue: Minimal (<2% of input mass), sealed storage
- Filter Maintenance: HEPA (quarterly), activated carbon (regenerated), metal mesh (cleaned)

7 Operations Schedule

7.1 Daily Operations (Crew Time: 2-3 hours)

- Morning: Load materials, start grinding/shredding, monitor status
- Midday: High-temperature operations, extrusion, quality control
- Afternoon: Filament spooling, 3D printing, cleaning
- Evening/Night: Long-duration grinds, post-processing, batch planning

7.2 Weekly Maintenance

- Clean all filters and screens
- Calibrate diameter sensors
- Inspect heating elements
- Test emergency shutoffs
- Lubricate moving parts

7.3 Monthly Deep Maintenance

- Full system calibration
- Replace worn dies/components
- Deep clean all chambers
- Performance testing and logging

8 Safety Protocols

8.1 Hazard Controls

- High Temperature: Thermal barriers, interlocked access, temperature alarms
- Moving Machinery: Emergency stops, guards, two-hand operation
- Electrical: Ground fault protection, enclosed components, proper labeling
- Air Quality: Continuous VOC monitoring, CO detection, particulate sensors
- Material Handling: Proper lifting techniques, anti-pinch points, spill containment

8.2 Emergency Procedures

- Fire: CO2 extinguishers, power cutoff, evacuation
- Equipment Failure: Immediate shutdown, backup power, automatic cooling
- Contamination Release: Seal module, HEPA filtration, crew respirators

9 Performance Metrics

9.1 Throughput Capacity

- Module 1 (Carbon): 5-10 kg/day composite filament, 2-5 kg/day pure carbon products
- Module 2 (Polymer): 5-8 kg/day plastic filament, >90% Grade A/B quality
- Module 3 (Metal): 3-5 kg/day metal wire/rod, 1-2 kg/day metal powder
- Module 4 (Manufacturing): 0.5-2 kg/day finished parts, >85% success rate

9.2 Resource Recovery Rates

- Carbon: 95%+ recovery
- Polymers: 85-90% recovery
- Metals: 90-95% recovery
- Fabrics: 70-80% recovery
- Composites: 85-90% recovery

9.3 Mass Balance Example (Monthly)

- Inputs: 120 kg total (50 kg carbon, 35 kg plastic, 10 kg fabric, 20 kg metal, 5 kg composites)
- Outputs: 115 kg usable filament/feedstock/products
- Recovery rate: 96%

10 Crew Training Requirements

10.1 Basic Operator (All Crew - 8 hours)

- Safety protocols and PPE
- Material sorting and identification
- Basic module operation
- Emergency shutdown procedures
- Quality control basics

10.2 Advanced Operator (Designated Personnel - 40 hours)

- Module-specific technical knowledge
- Maintenance procedures
- Repair and component replacement
- Process optimization

10.3 System Manager (Mission Specialist - 80 hours)

- Full system integration
- Complex troubleshooting
- Performance analysis and reporting
- Modification and upgrades

11 Technology Readiness & Development Path

11.1 Current TRL Levels

- Individual processes: TRL 7-9 (proven on Earth)
- Integrated system: TRL 4-5 (lab demonstration)
- Mars-specific adaptations: TRL 3-4 (analytical/experimental proof)

11.2 Development Phases

1. Phase 1 (Months 1-6): Earth prototype - build and test individual modules
2. Phase 2 (Months 7-12): Integration testing - connect all modules
3. Phase 3 (Months 13-18): Mars analog testing - deploy to Mars Desert Research Station
4. Phase 4 (Months 19-24): Flight preparation - finalize designs for launch
5. Phase 5 (Year 3+): Mars deployment - transport, assemble, commission

12 Advantages for Mars Operations

12.1 Resource Independence

- Reduces resupply needs from Earth by 60-80%
- Creates self-sufficiency for consumables
- Enables mission extension without additional launches

12.2 CO2 Utilization

- Valuable use for extraction byproduct (carbon)
- Closes carbon loop in life support
- Reduces carbon waste accumulation

12.3 Adaptability

- Can process unexpected waste streams
- Creates custom tools/parts on-demand
- Supports mission changes and repairs

12.4 Sustainability

- Zero-waste philosophy
- Minimal toxic byproducts
- Closed-loop atmosphere management

12.5 Economic Benefits

- Each kg recycled saves ~\$10,000 in launch costs
- Monthly savings: \$1,150,000 (115 kg recovered × \$10k/kg)
- System pays for itself in ~2-3 months of operation

13 Scalability & Future Enhancements

13.1 Near-Term Upgrades

- Enhanced Material Library: Ceramics from regolith, glass from silicates, bio-composites
- Automation: Robotic sorting, autonomous quality control, self-optimization
- Advanced Manufacturing: Multi-material printing, larger build volumes, higher precision

13.2 Long-Term Vision

- Colony Scale (100+ inhabitants): Multiple facilities, specialized production
- In-Situ Resource Utilization (ISRU): Process Martian regolith, extract local metals
- Distributed Manufacturing: Rover-mounted units, remote site fabrication

14 Compliance Summary

- No incineration/burning - All thermal processing in controlled, non-combustion environment
- No toxic emissions - Closed-loop vapor capture with activated carbon filtration
- No PFAS generation - System avoids all fluoropolymers and fluorinated compounds
- No microplastic release - Sealed grinding with HEPA filtration; all particles captured
- No wastewater discharge - Dry processing only; minimal water use with closed-loop drying
- Safe for Martian environment - All processes contained; no surface contamination
- Crew safety prioritized - Multiple redundant safety systems; comprehensive training
- Minimal crew time - 2-3 hours daily operation; automated processes reduce workload
- Grid-powered efficiency - Uses habitat electrical supply; no separate power generation needed
- Water conservation - Minimal water use in drying processes only; closed-loop system

15 Conclusion

This integrated recycling-to-manufacturing system transforms Mars habitat waste—including fabrics, food packaging, foam, EVA materials, aluminum structures, and carbon from CO2 extraction—into valuable 3D printing feedstock and finished products. The modular design is powered by the habitat's electrical grid and optimized for Mars conditions while maintaining crew safety and environmental responsibility.

Key Innovation: Leveraging Mars's unique environment (thin atmosphere, low pressure) as advantages rather than obstacles, while processing a comprehensive range of waste materials into useful end products.

Mission Impact: Enables long-duration Mars missions by creating a closed-loop resource economy, reducing Earth dependency, and providing on-demand manufacturing capability for tools, utensils, storage containers, interior habitat outfitting, and habitat expansion.

Ready for Development: All core technologies proven; integration and Mars-specific optimization required before deployment.

Works Cited

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