Sustainable Waste Management System for Martian Exploration

Team ReClaimX
Jezero Crater Mission Engineering

October 2025

Abstract

This comprehensive technical report details the design, process flow, and predictive mathematical models for four integrated recycling systems essential for managing the **12,600 kg** of inorganic waste during a three-year Mars mission. Our approach focuses on high-efficiency, water-minimizing **In Situ Resource Utilization (ISRU)** to establish a circular economy at the Jezero Crater habitat. The four core processes—**Electrothermal Compression Sintering (ECS)**, **Regolith-Polymer Composite Tile Pressing (RPCTP)**, **Aluminum Scrap to WAAM Feedstock**, and **UV-Protecting Film Production**—are modeled using specialized mathematical frameworks to maximize resource recovery (83-97% yield) and minimize unusable outputs. Each process features distinct mathematical models tailored to its specific physical and chemical mechanisms, with weekly production capacities of 32-1100 kg and specific energy consumption of 1.0-1.4 MJ/kg, demonstrating viability for sustained Martian operations.

Contents

1 Introduction: Mars Recycling System Architecture

The Martian environment presents unique challenges for sustainable habitation, including extreme resource constraints, intense UV radiation, and the absolute necessity of closed-loop systems. Our integrated recycling architecture addresses these challenges through four complementary processes that transform waste streams into valuable products:

- **Electrothermal Compression Sintering (ECS)**: Converts mixed polymer-aluminum waste into radiation-shielding composites using Joule heating
- **Regolith-Polymer Composite Tile Pressing (RPCTP)**: Creates construction materials using Martian regolith and polymer waste through thermal compression
- **Aluminum to WAAM Feedstock**: Recycles structural aluminum into certified wire for additive manufacturing via solid-state processing
- **UV-Protecting Film Production**: Transforms cellulose waste into protective films using ionic liquid solvents and dissolution kinetics

Each process employs a specialized mathematical framework optimized for its specific physical mechanisms, enabling precise prediction of yields, energy consumption, and production capacity under Martian operational constraints.

2 Process 1: Electrothermal Compression Sintering (ECS)

2.1 Electrothermal Compression Sintering (ECS)

2.2 Process Overview and Applications

ECS addresses the critical challenge of multi-material waste processing by employing **Joule heating** through a conductive carbon network [1]. This dry process eliminates water usage while transforming complex food packaging materials into high-density composites suitable for radiation shielding in Martian habitats.

2.2.1 Key Process Innovations

- **Carbon Percolation Network**: Minimum 8% carbon content enables resistive heating
- **Multi-Material Compatibility**: Processes mixed streams without separation
- **Dry Operation**: Zero water requirement, critical for Mars operations
- **Automated Processing**: Minimal crew intervention required

2.3 Mathematical Model 1: Unified PDE Framework

The ECS process follows a partial differential equation that tracks dynamic material conversion through the combined effects of thermal kinetics and mechanical compaction:

$$\frac{\partial Y_i}{\partial t} = k_i \cdot (1 - Y_i) \cdot (1 - e^{-t/\tau_i}) + C_{\text{comp}} \cdot v_s \frac{\partial Y_i}{\partial x} \tag{1}$$

2.3.1 Model Parameters and Initial Conditions

Table 1: ECS Process Parameters and Material Properties

Parameter	Symbol	Value	Unit
Compaction Coefficient	C_{comp}	0.01	min^{-1}
Solid Velocity	v_s	1×10^{-6}	m/s
Process Duration	t_{process}	15	min
Spatial Domain	x	0-0.01	m
Temperature	T	260	°C
Pressure	P	6	MPa

2.3.2 Material-Specific Kinetics

Table 2: ECS Material Conversion Parameters

Material	Weight Fraction	k_i (min^{-1})	τ_i (min)	Final Yield
Polyethylene	40%	1.2	8	0.99
PET	12%	1.1	10	0.96
Aluminum	28%	1.4	5	0.99
Carbon Powder	8.2%	1.6	3	1.00
Other	11.8%	1.0	12	0.95
Overall	**100%**	—	—	**0.97**

2.4 Energy Consumption Model

$$Q_{\text{heating}} = \left[\sum_i (w_i \cdot m_{\text{total}} \cdot C_{p,i} \cdot \Delta T) \right] \cdot \eta_{\text{loss}} \tag{2}$$

Where $\Delta T = 260\text{K}$, $\eta_{\text{loss}} = 1.10$.

2.5 Performance Summary

Table 3: ECS Process Performance Metrics

Parameter	Value	Unit
Output per Batch	0.97	kg
Weekly Capacity	1106	kg/week
Minimum Capacity	885	kg/week
Specific Energy	1.2	MJ/kg
Energy per Unit	0.33	kWh/kg
Process Yield	97.0	%
Carbon Requirement	≥ 8.0	%

3 Process 2: Regolith-Polymer Composite Tile Pressing (RPCTP)

3.1 Regolith-Polymer Composite Tile Pressing (RPCTP)

3.2 Process Overview and ISRU Integration

RPCTP maximizes **In Situ Resource Utilization** by incorporating 80% Martian regolith (MGS-1 simulant) with 20% mixed polymer waste [2]. This process addresses the massive material requirements for habitat construction while valorizing plastic waste streams.

3.2.1 Key Process Features

- **High Regolith Content**: 80% indigenous material reduces Earth-supply dependency
- **Enhanced Compression**: 10MPa pressure ensures high-density tiles
- **Thermal Conduction Heating**: External heating sources required
- **Construction-Grade Output**: Tiles suitable for flooring and structural applications

3.3 Mathematical Model 2: Mineral-Polymer Composite Formulation

The RPCTP process adapts the unified PDE framework with specific modifications for mineral-polymer composites:

$$\frac{\partial Y_i}{\partial t} = k_i \cdot (1 - Y_i) \cdot (1 - e^{-t/\tau_i}) + C_{\text{comp}} \cdot v_s \frac{\partial Y_i}{\partial x} \tag{3}$$

With regolith-specific treatment:

$$k_{\text{regolith}} = 0 \quad \text{(No chemical conversion)} \tag{4}$$

$$Y_{\text{regolith}} = 1.0 \quad \text{(Always fully incorporated)} \tag{5}$$

$$\tau_{\text{regolith}} = \infty \quad \text{(Infinite time constant)} \tag{6}$$

3.3.1 Fixed Composition Constraints

$$w_{\text{regolith}} = 0.8 \quad \text{(80\% regolith)} \tag{7}$$

$$\sum_{\text{polymers}} w_{\text{polymer},i} = 0.2 \quad \text{(20\% polymer mix)} \tag{8}$$

3.3.2 Process Parameters

Table 4: RPCTP Process Parameters

Parameter	Symbol	Value	Unit
Compaction Coefficient	C_{comp}	0.015	min^{-1}
Solid Velocity	v_s	1.5×10^{-6}	m/s
Process Duration	t_{process}	25	min
Temperature Range	T	280-350	°C
Pressure	P	10	MPa
Regolith Fraction	w_{regolith}	0.8	—

3.4 Energy Consumption Model

$$Q_{\text{heating}} = \left[\sum_i (w_i \cdot m_{\text{total}} \cdot C_{p,i} \cdot \Delta T) \right] \cdot \eta_{\text{loss}} \tag{9}$$

Where $\Delta T = 295\text{K}$, $\eta_{\text{loss}} = 1.15$.

3.5 Performance Summary

Table 5: RPCTP Process Performance Metrics

Parameter	Value	Unit
Output per Batch	0.965	kg
Weekly Capacity	725	kg/week
Weekly Tile Area	52	m^2/week
Specific Energy	1.4	MJ/kg
Process Yield	96.5	%
Tile Density	1800-2000	kg/m^3

4 Process 3: Aluminum Scrap to WAAM Feedstock

4.1 Aluminum Scrap to WAAM Feedstock

4.2 Process Philosophy: WAAM-First Approach

This comprehensive 8-stage process transforms structural aluminum waste into certified wire feedstock for **Wire Arc Additive Manufacturing (WAAM)** [3]. The "WAAM-First" philosophy prioritizes wire production in O-temper condition, with final metallurgical properties imparted during the WAAM process itself.

4.3 Mathematical Model 3: Multi-Stage Solid-State Recycling

4.3.1 Stage 4: Enhanced Consolidation PDE

The core bonding stage employs an advanced PDE capturing multiple bonding mechanisms:

$$\frac{\partial Y}{\partial t} = k_{\text{plastic}} \cdot \dot{\epsilon}(x,t) \cdot (1-Y) + k_{\text{diff}} \cdot \exp\left(-\frac{Q}{RT(x,t)}\right) \cdot (1-Y) + D \cdot \frac{\partial^2 Y}{\partial x^2} + v_s \cdot \frac{\partial Y}{\partial x} \quad (10)$$

4.3.2 Initial and Boundary Conditions

$$Y(x,0) = Y_0 \cdot Q_{\text{surface}} \quad \text{(Initial condition)} \quad (11)$$

$$\frac{\partial Y}{\partial x} = 0 \quad \text{at } x = 0, L \quad \text{(Zero gradient boundaries)} \quad (12)$$

4.3.3 Numerical Solution

Finite difference formulation:

$$\begin{aligned} Y_j^{n+1} = Y_j^n + \Delta t \Bigg[& k_{\text{plastic}} \cdot \dot{\epsilon}_j^n \cdot (1-Y_j^n) + k_{\text{diff}} \cdot \exp\left(-\frac{Q}{RT_j^n}\right) \cdot (1-Y_j^n) \\ & + D \cdot \frac{Y_{j+1}^n - 2Y_j^n + Y_{j-1}^n}{\Delta x^2} + v_s \cdot \frac{Y_{j+1}^n - Y_{j-1}^n}{2\Delta x} \Bigg] \end{aligned} \quad (13)$$

4.3.4 Key Parameters

Table 6: Aluminum Bonding PDE Parameters

Parameter	Symbol	Value/Range	Unit
Plastic Deformation Constant	k_{plastic}	2-5	s^{-1}
Strain Rate	$\dot{\epsilon}$	0.1-1.0	s^{-1}
Diffusion Pre-exponential	k_{diff}	10^8-10^{12}	s^{-1}
Activation Energy	Q	150	kJ/mol
Temperature Field	T	450-500	°C
Diffusion Coefficient	D	10^{-13}-10^{-11}	m^2/s
Solid Velocity	v_s	10^{-6}	m/s

4.4 Lithium Management Model

$$m_{\text{vaporized}} = k_{\text{vap}} \cdot [\text{Li}] \cdot m_{\text{in},1} \tag{14}$$

$$f_{\text{weldability}} = 1 - k_{\text{crack}} \cdot \max(0, [\text{Li}] - 1.5\%)^2 - k_{\text{oxide}} \cdot (1 - Q_{\text{surface}}) \tag{15}$$

4.5 Performance Summary

Table 7: Aluminum to WAAM Performance Metrics

Parameter	Value	Unit
Process Yield (Y_{total})	0.83	—
Bond Quality ($\bar{Y}$)	0.94	—
Spatial Homogeneity (H)	0.92	—
Final Output Mass	0.88	kg
Weekly Capacity	1058	kg/week
Specific Energy	1.05	MJ/kg
Energy Efficiency (η_{energy})	1.14	—

5 Process 4: UV-Protecting Film Production from Waste Cellulose

5.1 UV-Protecting Film Production from Waste Cellulose

5.2 Process Overview and Radiation Protection Strategy

This process addresses Mars' intense UV radiation environment (100-1000× Earth levels) by transforming cellulose-rich waste streams into transparent, flexible protective films [4]. The innovative use of **ionic liquid solvents** eliminates water requirements while **lignin integration** provides natural UV-blocking capability.

5.3 Mathematical Model 4: Dissolution Kinetics Framework

5.3.1 First-Order Dissolution Kinetics

The process follows first-order kinetics for cellulose dissolution and lignin integration:

$$\frac{dY_c}{dt} = k_c \cdot (1 - Y_c) \tag{16}$$

$$\frac{dY_l}{dt} = k_l \cdot (1 - Y_l) \tag{17}$$

5.3.2 Analytical Solutions

$$Y_c(t) = 1 - e^{-k_c t} \tag{18}$$

$$Y_l(t) = 1 - e^{-k_l t} \tag{19}$$

5.3.3 Overall Process Yield

$$Y_{\text{total}} = w_c \cdot Y_c(t_{\text{process}}) + w_l \cdot Y_l(t_{\text{process}}) \tag{20}$$

5.3.4 Kinetic Parameters

Table 8: UV Film Production Kinetic Parameters

Parameter	**Symbol**	**Value**	**Unit**
Cellulose Fraction	w_c	0.96	—
Lignin Fraction	w_l	0.04	—
Cellulose Dissolution Rate	k_c	0.015	min^{-1}
Lignin Integration Rate	k_l	0.05	min^{-1}
Process Time	t_{process}	240	min
Auxiliary Time	t_{aux}	60	min
Total Cycle Time	t_{cycle}	300	min

5.4 Energy Consumption Model

$$Q_{\text{heating}} = (m_{\text{total}} \cdot C_{p,\text{mix}} + m_{\text{solvent}} \cdot C_{p,\text{solvent}}) \cdot \Delta T + Q_{\text{loss}} \tag{21}$$

Where:

- $C_{p,\text{mix}} = 1200\text{J/kg} \cdot \text{K}$ (Cellulose-lignin mixture)
- $C_{p,\text{solvent}} = 1500\text{J/kg} \cdot \text{K}$ (Ionic liquid solvent)
- $\Delta T = 70\text{K}$ (20°C to 90°C)
- $Q_{\text{loss}} = 20\%$ of sensible heating

5.5 Performance Summary

Table 9: UV Film Production Performance Metrics

Parameter	**Value**	**Unit**
Cellulose Yield (Y_c)	0.973	—
Lignin Yield (Y_l)	1.000	—
Overall Yield (Y_{total})	0.974	—
Output per Batch	0.974	kg
Weekly Capacity	32.7	kg/week
Minimum Capacity	26.2	kg/week
Specific Energy	1.397	MJ/kg
Film Thickness	0.5-1.0	mm

6 Comparative Analysis and System Integration

6.1 Performance Comparison

Table 10: Comparative Performance of Four Recycling Processes

Parameter	ECS	RPCTP	Al-WAAM	UV Film
Process Yield (%)	97.0	96.5	83.0	97.4
Weekly Capacity (kg/week)	1106	725	1058	32.7
Specific Energy (MJ/kg)	1.2	1.4	1.05	1.4
Energy per Unit (kWh/kg)	0.33	0.39	0.29	0.39
Primary Output	Shielding	Tiles	WAAM Wire	UV Films
Water Usage	None	None	None	Minimal
Crew Time	Low	Low	Medium	Medium

6.2 Mathematical Framework Characteristics

Table 11: Mathematical Model Characteristics by Process

Process	Mathematical Approach	Key Features
ECS	Unified PDE with Joule heating	Multi-material conversion, Carbon network de
RPCTP	Adapted PDE with mineral constraints	Fixed composition, Regolith as inert filler
Al-WAAM	Multi-stage with advanced bonding PDE	Solid-state processing, Lithium management
UV Film	First-order kinetics with mass balance	Dissolution dynamics, Solvent recovery

6.3 Mission Integration Benefits

- **Complementary Outputs**: Radiation shielding, construction materials, manufacturing feedstock, and protective films
- **Water Minimization**: All processes designed for minimal or zero water usage
- **Energy Efficiency**: Range of 1.0-1.4 MJ/kg competitive with terrestrial recycling
- **Waste Stream Coverage**: Comprehensive management of major inorganic waste categories
- **ISRU Maximization**: Significant use of indigenous resources (regolith, atmospheric CO_2)

7 Conclusion

The four specialized recycling processes presented demonstrate technical viability for sustained Martian operations, each with distinct mathematical frameworks optimized for their specific mechanisms. The ECS process achieves 97% yield for radiation shielding composites, RPCTP provides construction materials with 96.5% yield using Martian regolith, the aluminum process delivers WAAM feedstock with 83% yield through solid-state processing, and UV film production achieves 97.4% yield using dissolution kinetics.

Each mathematical model provides precise prediction capabilities under Martian constraints, enabling reliable system design and operational planning. The complementary nature of these processes establishes a comprehensive waste management architecture that supports long-term human presence on Mars through closed-loop resource utilization.

References

References

[1] Team ReClaimX, "Final Report: Electrothermal Compression Sintering (ECS) Process," Mars Recycling System Documentation, 2025.

[2] Mars Recycling Systems Team, "Unified Mathematical Model for Mars Recycling Processes: ECS and RPCTP Performance Prediction," Mars Mission Engineering, 2025.

[3] Mars Mission Engineering Team, "Complete Unified Process Model: Martian Aluminum Scrap to Certified WAAM Feedstock," Additive Manufacturing Division, 2025.

[4] Team ReClaimX, "Mathematical Model for UV-Protecting Film Production from Waste Cellulose on Mars," Sustainable Materials Group, 2025.

[5] X. Yang, Y. Zhang, Y. Zhao, and J. Wang, "Sustainable cellulose-based transparent UV-protecting films with enhanced mechanical properties," *Carbohydrate Polymers*, vol. 285, p. 119235, 2022.

[6] T. Mohan, S. Spirk, R. Kargl et al., "Watching cellulose grow - Kinetic investigations on cellulose thin film formation," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 400, pp. 67-72, 2012.

[7] S. Koehler, T. Liebert, and T. Heinze, "Advanced cellulose derivatives by homogeneous catalysis," *Journal of Polymer Science: Polymer Chemistry*, vol. 46, no. 12, pp. 4070-4080, 2008.

[8] E. Kontturi, T. Tammelin, and M. Osterberg, "Cellulose-based model films," *Chemical Society Reviews*, vol. 35, no. 12, pp. 1287-1304, 2006.

[9] B. Zhang, J. Zhou, and M. Li, "Prediction of Sinter Yield and Strength in Iron Ore Sintering Process by Numerical Simulation," *Materials Processing Journal*, vol. 45, no. 3, pp. 234-245, 2023.