Bioregenerative Closed-Loop Habitat

Detailed Write-Up

Design Philosophy

Closed-loop life support systems fail when designers prioritize theoretical efficiency over operational reliability. This design inverts that priority:

1. **Predictability over optimization**: Rice cultivation provides steady, well-characterized gas exchange
2. **Redundancy over minimalism**: Multiple out-of-phase crop cylinders eliminate single points of failure
3. **Mechanical over chemical**: Biomass cascades through mechanical uses (filters, composites) before chemical breakdown
4. **Human oversight over automation**: Automation assists, humans decide

The result is a system that may be less "efficient" on paper but far more survivable in practice.

System Overview

Scale

- **Crew**: 25 people
- **Total agricultural area**: 1,430 m²
- **Primary crops**: Brown rice (350 m²), soybeans (250 m²), sweet potatoes (300 m²), peas (180 m²), leafy greens (350 m²)
- **Caloric output**: ~2,800 kcal/person/day
- **Oxygen generation**: ~625 kg O_2/day (crew consumption: ~600 kg/day)

Rice Cylinders: The Oxygen Engine

Concept

Rather than relying on algae bioreactors (unpredictable, prone to crashes) or mechanical CO_2 scrubbers (consumables-dependent), this system uses rice as the primary oxygen generation mechanism.

Why Rice?

- **Predictable gas exchange**: Well-characterized photosynthetic rates across growth stages
- **Caloric yield**: ~2,160 kg/year (primary carbohydrate source)
- **Materials cascade**: Rice husks have multiple post-harvest uses
- **Cultural familiarity**: Crew understands rice cultivation (reduces training burden)
- **Flood tolerance**: Hydroponic cultivation minimizes soil pathogens

Operational Strategy

- **Multiple cylinders operated out-of-phase**: Ensures steady O_2 production (no "harvest gap")
- **150-day growth cycle**: Planting to harvest
- **Staggered cohorts**: 17 weekly planting groups (continuous harvest every week)
- **Targeting steady-state**: Always have cylinders in vegetative (high O_2), flowering (moderate), and ripening (low) phases

Monitoring & Adjustment

- **Hourly "lite" gas sampling**: O_2, CO_2, humidity
- **Deep analysis every 8 hours**: N_2, trace gases, particulates
- **Mandatory dark-cycle sampling**: Verify respiration rates match predictions
- **Sigma-based alerting**: Deviations $>2\sigma$ from expected trigger alarms
- **Forced human acknowledgment**: No auto-dismissal of alerts

Crop Diversity & Staggered Planting

Monoculture systems are fragile. Diversity provides resilience.

Crop Breakdown

Crop	Area (m^2)	Cycle (days)	Annual Yield (kg)	Kcal/kg	Total Kcal/year
Brown Rice	350	150	2,160	3,500	7,560,000
Soybeans	250	120	1,875	4,460	8,362,500

Sweet Potatoes	300	120	4,500	860	3,870,000
Peas	180	90	1,080	810	874,800
Leafy Greens	350	40	3,150	230	724,500
Total	**1,430**	—	**12,765**	—	**21,391,800**

Daily average caloric yield: ~58,600 kcal/day ÷ 25 crew = **2,344 kcal/person/day**

Gap: Crew requires ~2,800 kcal/day → **456 kcal/person/day shortfall**

Shortfall Management

- **Stored caloric reserves**: 90-day buffer of dried/preserved foods
- **Supplemental production**: Mushroom cultivation (uses agricultural waste, adds ~200-300 kcal/person/day)
- **Reduced activity periods**: Lower caloric demand during low-workload phases

Nitrogen Fixation

Legumes (soybeans, peas) fix atmospheric N_2 via rhizobial bacteria:

- **Annual N fixation**: ~150-200 kg N/year
- **Crew N loss**: ~60 kg N/year (harvest removal, minor air leaks)
- **Surplus**: ~90-140 kg N/year (supports leafy greens, rice)

Materials Cascade: "Never Chemically Destroy Before Mechanical Use"

Biomass is too valuable to immediately combust or chemically digest. This system mandates mechanical uses first.

Rice Husk Cascade

1. **Coarse filter media**: Pre-filter irrigation water (traps particulates)
2. **Biochar production**: Pyrolysis → porous carbon (soil amendment, filtration)
3. **Composite filler**: Mix with 3D-printed plastics (structural reinforcement)
4. **Fuel**: Only after exhausting 1-3 → burn for heat/power

Green Waste Cascade

1. **Composting**: Convert to soil amendment (closed nutrient loop)
2. **Mushroom substrate**: Oyster/shiitake cultivation (adds protein, calories)
3. **Biogas digestion**: Methane production (supplemental power)
4. **Digestate**: Nutrient-rich liquid fertilizer

Human Waste Management

- **Urine**: Directly usable as nitrogen fertilizer (urea → ammonia)
- **Feces**: Composted separately (long-cycle thermophilic composting for pathogen kill)
- **Greywater**: Filtered through biochar, UV-sterilized, returned to irrigation

Self-Replicating Manufacturing

The habitat must repair itself. 3D printers become life-support infrastructure.

Target: 70-80% Self-Printable

- **Printable**: Structural brackets, pipe fittings, tool handles, plant supports, filter housings
- **Non-printable**: Motors, pumps, valves, seals, electronics, UV lamps

Standardized Non-Printables

- **Catalog system**: M6 bolts, 1/2" NPT fittings, 12V DC motors, etc.
- **Large stockpile**: 5-year supply of consumables and wear parts
- **Cross-compatible**: Minimize unique part types (one motor type for multiple applications)

Filament Production

- **Source material**: Agricultural waste (cellulose), recycled plastics
- **Extrusion system**: Convert waste → filament spools
- **Quality control**: Diameter tolerance ±0.05mm (critical for reliable printing)

Environmental Control

Lighting

- **Technology**: LED grow lights (red/blue spectrum)
- **Power**: ~150 kW continuous during 14-hour photoperiod
- **Daily energy**: 150 kW × 14 hours = **2,100 kWh/day**

- **Spectral tuning**:

- Leafy greens: High blue (compact growth, high antioxidants)
- Fruiting crops (soy, peas): Balanced red/blue
- Tubers: More red (promote root growth)

Temperature

- **Target**: 20-25°C (most crops)
- **Heat load**: 150 kW lighting + 20 kW plant metabolism = **170 kW heat rejection required**
- **Cooling system**: Integrated with habitat HVAC (heat exchangers, radiators)

Humidity

- **Target**: 60-70% RH
- **Condensate collection**: ~2,500-3,000 L/day (plant transpiration)
- **Dehumidifiers**: Recover water, prevent mold/mildew

CO_2 Enrichment

- **Source**: Crew respiration (25 people × 1 kg CO_2/day = 25 kg/day)
- **Target**: 800-1,200 ppm (vs. ambient 400 ppm)
- **Distribution**: Ducting from crew quarters to agricultural zones
- **Circulation**: Fans maintain 0.5-1.0 m/s airflow (strengthens stems, prevents disease)

Labor Requirements

Agriculture is labor-intensive. This system estimates crew time required.

Weekly Agricultural Tasks

- **Planting**: 2-4 hours/week per crop type × 5 crops = **10-20 hours/week**
- **Harvesting**: 3-6 hours/week per crop type × 5 crops = **15-30 hours/week**
- **Maintenance**: Pruning, monitoring, pest control = **5-10 hours/week**
- **Total**: **30-60 hours/week agricultural labor**

Crew Allocation

- **2-3 FTE dedicated agricultural specialists**
- **All crew trained in basic tasks** (emergency backup)

- **Heavy labor**: 5 hours/week (transplanting, major harvests)
- **Light/moderate**: 20 hours/week (monitoring, light pruning, packaging)

Failure Modes & Redundancy

Rice Cylinder Failure

- **Scenario**: One cylinder develops disease, fails to flower
- **Response**: Quarantine cylinder, sterilize, replant
- **Impact**: Temporary O_2 shortfall (~50 kg/day for 150 days)
- **Mitigation**: Spare substrate stockpiles, mechanical O_2 backup (electrolysis)

Crop Disease Outbreak

- **Scenario**: Fungal pathogen spreads through leafy greens
- **Response**: Cull infected cohorts, increase air circulation, UV sterilization
- **Impact**: Loss of 1-2 weeks' harvest (~150 kg greens)
- **Mitigation**: Diversity (other crops unaffected), stored reserves

Power Outage

- **Scenario**: Primary power fails, LED lights go dark
- **Response**: Emergency battery backup (4-hour minimum)
- **Impact**: Photosynthesis halts, respiration continues (O_2 drawdown)
- **Mitigation**: Backup generators, crew activity reduction, mechanical O_2

Water System Contamination

- **Scenario**: Pathogen enters irrigation loop
- **Response**: Drain system, UV sterilize, refill from reserve tanks
- **Impact**: 2-3 days irrigation downtime
- **Mitigation**: Compartmentalized loops (disease in one zone doesn't spread)

Monitoring & Automation Philosophy

Automation assists; humans decide.

Automated Systems

- **Gas monitoring**: Continuous O_2, CO_2, humidity tracking
- **Irrigation**: Scheduled watering based on soil moisture sensors
- **Lighting**: Photoperiod timers, spectral intensity adjustment
- **Temperature/humidity**: HVAC regulation

Human-in-the-Loop Requirements

- **Alert acknowledgment**: Sigma deviations must be manually reviewed (no auto-dismiss)
- **Harvest decisions**: Automation suggests timing, humans verify readiness
- **Replanting schedules**: Automation tracks cohorts, humans approve new plantings
- **Emergency overrides**: Manual cutoffs for all automated systems

Open Questions & Areas for Development

Water Budget Refinement

- **Transpiration losses**: Requires precise measurement across growth stages
- **Condensate recovery efficiency**: Real-world vs. theoretical
- **Storage reserves**: How much buffer is "safe"?

Trace Elements & Micronutrients

- **Soil mineral depletion**: How fast do P, K, Ca, Mg deplete?
- **Resupply schedule**: Every 6 months? Annual?
- **Crew supplementation**: Vitamin B12, D, others?

Food Preservation & Storage

- **Drying**: Energy cost vs. shelf-life extension
- **Fermentation**: Sauerkraut, kimchi, miso (adds flavor, probiotics)
- **Canning**: Pressure canners for long-term storage

Psychological Factors

- **Menu fatigue**: Same 5 crops every day
- **Cooking facilities**: Limited spices, oils, variety
- **Social rituals**: Shared meals, celebrations

System Specifications Summary

Parameter	Value
Crew Size	25 people
Total Agricultural Area	1,430 m²
Caloric Output	2,344 kcal/person/day (base crops)
Oxygen Generation	625 kg O_2/day
Water Recycling	>95% (via transpiration recovery)
Power Demand	2,100 kWh/day (lighting), ~500 kWh/day (HVAC, pumps, controls)
Crew Labor	30-60 hours/week (agricultural tasks)
Resupply Frequency	6-12 months (trace minerals, non-printable parts)
Self-Sufficiency Target	70-80% (mass basis)