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NASA Ames Research Center
Astrobiology Technology Branch

Astrobiology Technology Branch
Advanced Life Support
Research and Technology Development

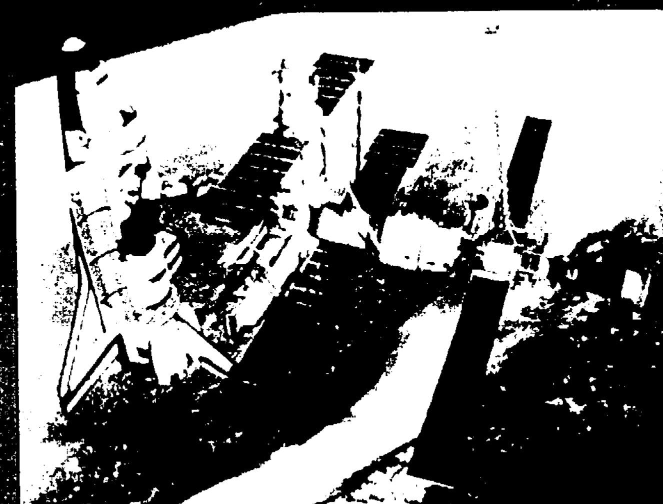
Dr. Mark Kliss, Chief
Astrobiology Technology Branch (Code SSR)

Presented at the
International Advanced Life Support Working Group Meeting
Guelph, Ontario
May 12–16, 2001

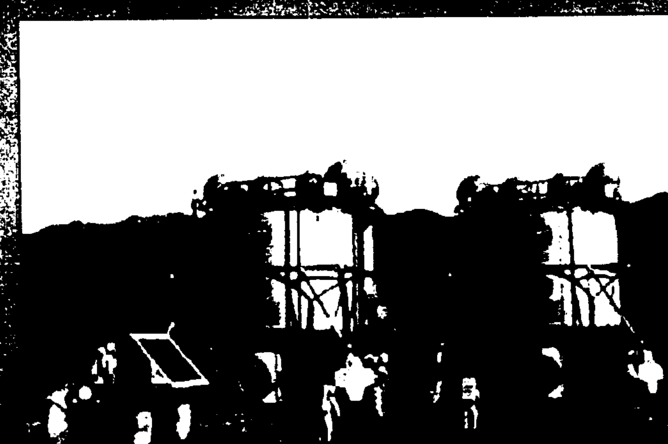
Enterprise

Human Exploration and Development of Space (HEDS)

"We will conduct R&TD for advanced life support systems which will be validated on the ISS."



"We will develop revolutionary advanced technologies that will support future national decisions regarding human missions beyond Earth orbit."

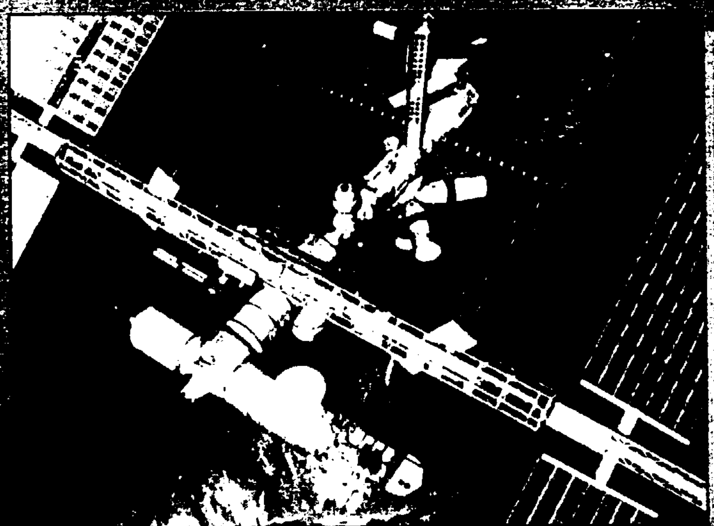


The HEDS Enterprise relies on the Space Science Enterprise missions to demonstrate the feasibility of utilizing local resources to "live off the land."

http://www.hq.nasa.gov/office/nsp/NST PTOC.html

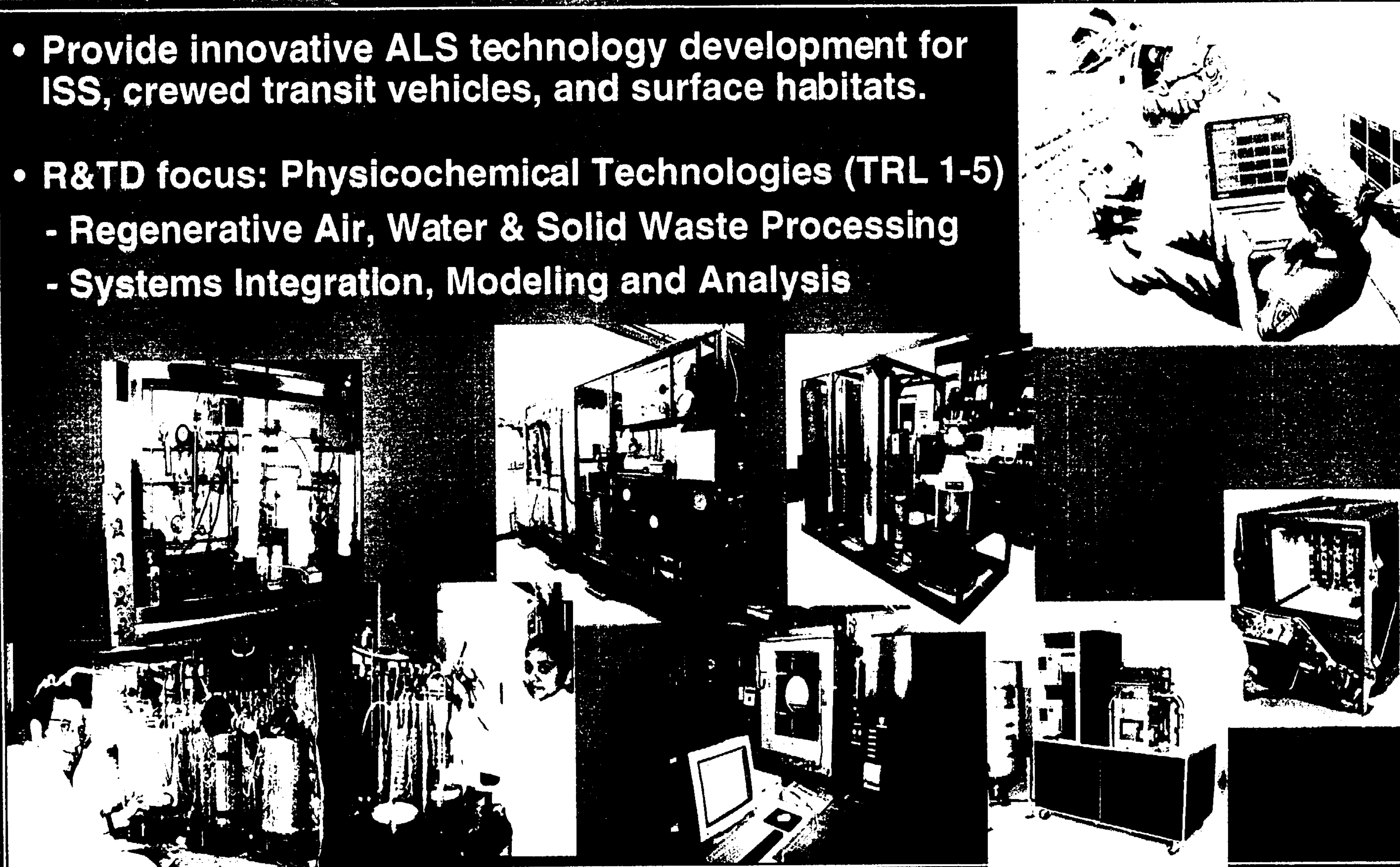
NASA Advanced Life Support

GOAL: Provide life support self-sufficiency for human beings to carry out research and exploration productively in space, to open the door for planetary exploration, and for benefits on Earth.



Role of NASA Ames in Advanced Life Support

- Provide innovative ALS technology development for ISS, crewed transit vehicles, and surface habitats.
- R&TD focus: Physicochemical Technologies (TRL 1-5)
  - Regenerative Air, Water & Solid Waste Processing
  - Systems Integration, Modeling and Analysis



1 Technology Readiness Level (TR L) → 5

Astrobiology Technology Branch

Personnel

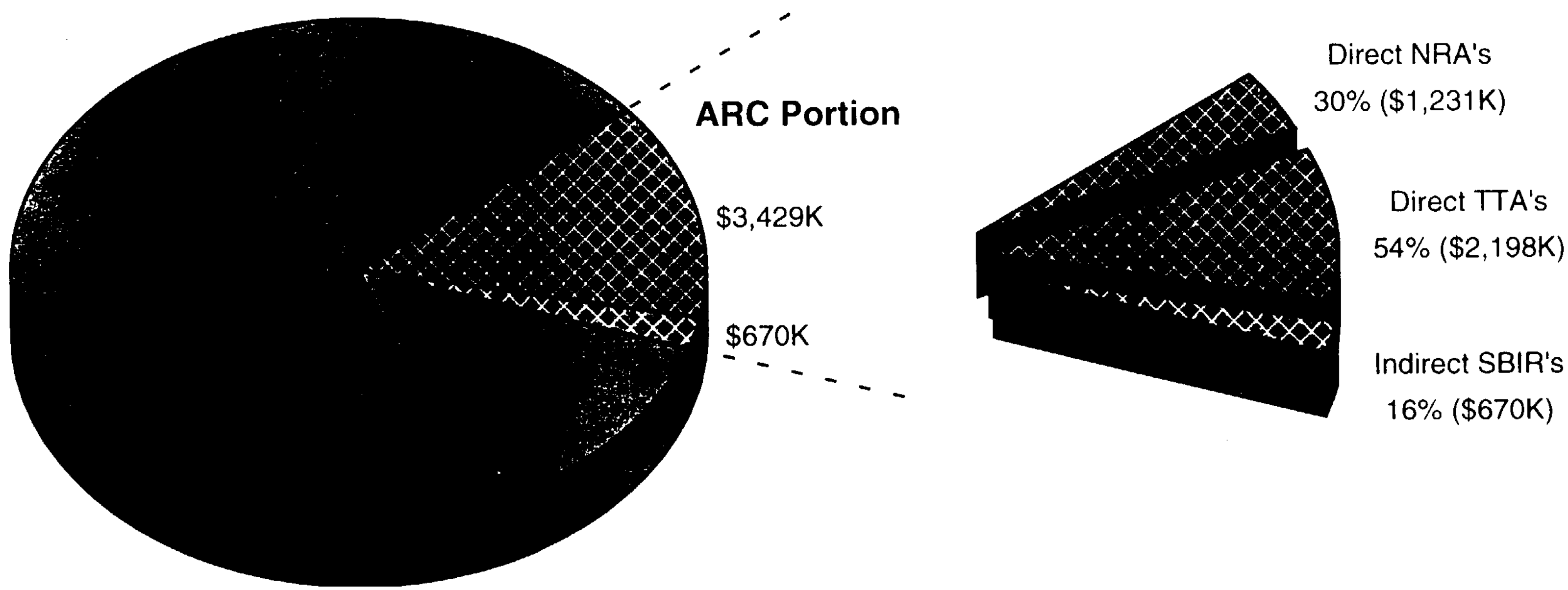
	Contractors / University COOPs 19		
Dr. Mark Kliss, Chief	Dave Affleck	Eric Litwiller	Dr. K. R. Sridhar
Karen Bunn	Warren Belisle	Mark Moran	**Students 7**
Dr. Cory Finn	Dr. Ann Bell	Dr. Les Montgomery	Suzanne Chan
Dr. John Finn	Dr. Charles Blackwell	Lila Mulloth	Joshua Coe
John Fisher	Bruce Borchers	Greg Pace	Janice Cregan
Michael Flynn	Richard Boulanger	Dr. Chris Pawlowski	Kindall Forrest
Dr. Harry Jones	Sheila Cho	Suresh Pisharody	Chris Knoell
Richard Lamparter	Sekou Crawford	Maher Tleimat	Amber Sanford
Julie Levri	Dr. Gerard Heyenga	Sunita Verma	Kerry Wooding
Dr. Andrew McMillan	Jeanie Howard	Barbara Walton	
Dr. Jonathan Trent	Jeff Johnson	Dr. Wiggy Wignarajah	
Richard Wisniewski	Dr. Hiromi Kagawa		

Astrobiology Technology Branch

Advanced Life Support Funding

Total FY01 ALS Funding
(Direct & Indirect)

Total FY01 ALS Funding at ARC
(Direct & Indirect)



Astrobiology Technology Branch

Technical Monitoring for Phase I and Phase II SBIR's

NASA ARC Advanced Life Support SBIR Contracts

COMPANY	TITLE	FY99	FY00	FY01	CONTRACT STATUS	INNOVATION
Phytron Instruments, Inc.	Clean Water: Electrn Beam Water Treatment		70,000		99-1 started FY00	X-ray optic spectrometer
EnerTech Environmenta, Inc.	Wet Carbonization of Space Mission Generated Wastes		70,000		99-2 Started FY00	Make pumpable slurries out of inedible biomass
Reaction Engineering Intl	Integration of a Metal Fluoride Type Catalyst in a Low Temperature Fluidized Bed Incinerator into a Biomass Waste Management System	100,000		300,000	95-2 Phase II Completed 6/99	Unique catalyst for resource recovry system
Umpqua Research Co.	Electrochemically Generated, Hydrogen Peroxide Boosted Aqueous Phase Catalytic Oxidation	100,000			95-2 Del 4-99 Phase II Completed 9/99	Direct generation of H_2O_2 and catalyist selection for reaction promotion
Materials and Electro-chemical Res Corp	Novel Fullerene bed for Low Pressure Oxygen Storage	100,000			95-2 Del 10-99 Phase II Completed 10/99	High density oxygen storage
Umpqua Research Co.	Microwave Regenerable Air Purification Device	100,000			95-2 Del 10-99 Phase II Completed 10/99	Regenaration properties of sorbents for carbon dioxide removal from air
Umpqua Research Company	Biomass Slurry Production	70,000			98-1 contract initiated Dec 98 No Phase II Completed FY99	Efficient continuos feed system for making high solids pumpable biomass slurry
Advanced Fuel Research, Inc.	Pyrolysis Processing for Solid Waste Resource Recovery in Space	70,000	300,000		98-2 contract Phase II Awarded 10/99	Pyrolyze waste without producing undesireable byproducts.
TDA Research, Inc.	System for Removal of the Oxides of Nitrogen and Sulfur from Incinerator Effluents	200,000	300,000	300,000	97-2 initiated 1/99	Remove Nox and SO_2 contaminants from flue gas
Nanotechnology, Inc.	Sublimation-based Water Reclamation and Purification from Solids			70,000	00-1 Started FY01	Efficient stabilization of waste and recovery of water

Focused Research Areas

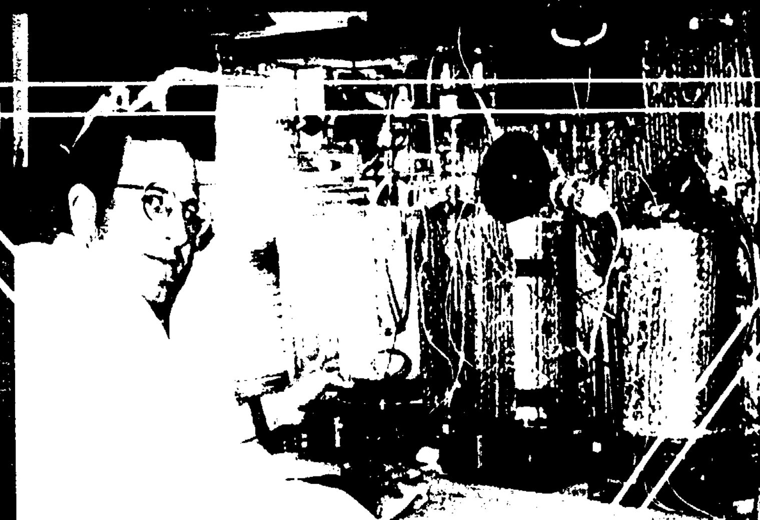
Air Regeneration Research at NASA Ames

Characterization of adsorption in the 4BMS (CO_2 removal for ISS)

Low-power hybrid membrane/ adsorption unit for CO_2 removal

Support of NASA Missions (such as ISS)

New Concepts and Technology for Advanced Life Support



Prediction of effects of water co-adsorption with trace contaminants

Temperature swing adsorption for utilization of Mars atmosphere gases

Solid State CO_2 Compressor for ISS (closes air loop)

Regenerable Trace Gas-Phase Contaminant Control

Basic Physical and Chemical Research

Study of physical chemistry of adsorbed CO_2/H_2O solutions

Adsorption-based gas separation and purification

Why Develop Advanced CO_2 Removal Technologies?

- **The International Space Station (ISS) CO_2 removal subsystem has the highest power penalty of any ISS life support subsystem (~ 3200 W-hr/kg CO_2). Current technology has a thermodynamic efficiency of about 3%.**
- **Current CO_2 removal & reduction technology in closed-loop mode (with Sabatier/oxygen recovery) will require ~ 5400W-hr/kg CO_2.**
- **Life scientists are calling for lower CO_2 levels on International Space Station.**
  - ISS requirement is 7000 ppm, compared to ~400 ppm Earth-normal
  - Confounding influence on gravity-response experiments; blood chemistry effects
  - Achieving lower concentrations translates directly into more energy consumption.
- **Power will be an extremely critical resource for a Mars transit vehicle.**
  - The Mars Reference Mission would use a solar-powered transit vehicle with total estimated available power of 30 kW; 12 kW for ECLS

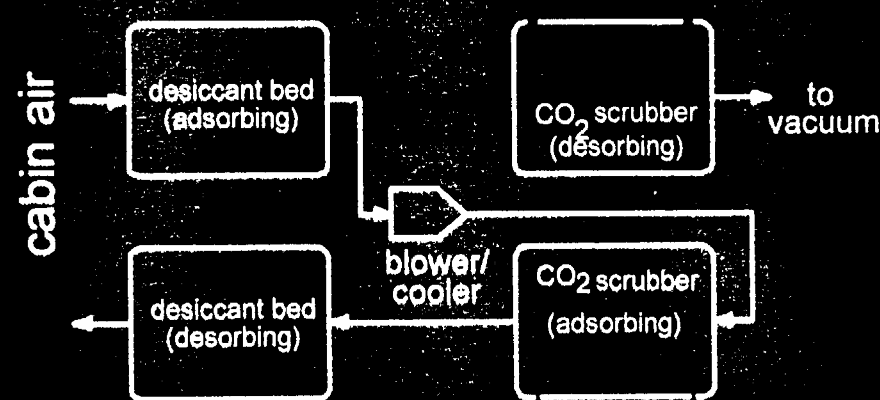
★ Develop CO_2 removal technology that consumes 10x less power than current Space Station technology for same performance.
(or maintains substantially lower concentrations of CO_2 for no increase in power)

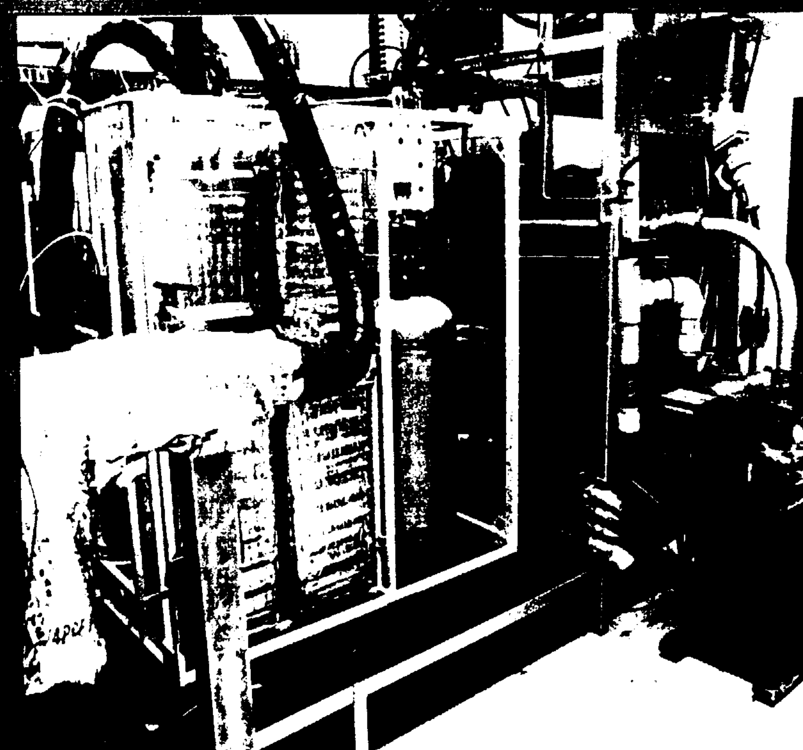
1. Hybrid Membrane/Adsorption CO_2 Removal

State of the Art (ISS): Four-Bed Molecular Sieve
(4BMS, AlliedSignal/Honeywell)

PROS

- **Mature technology (*Skylab*)**
- **Fully regenerable**
- **High removal efficiency (100%)**
- **High-purity CO_2 for reduction**





CONS

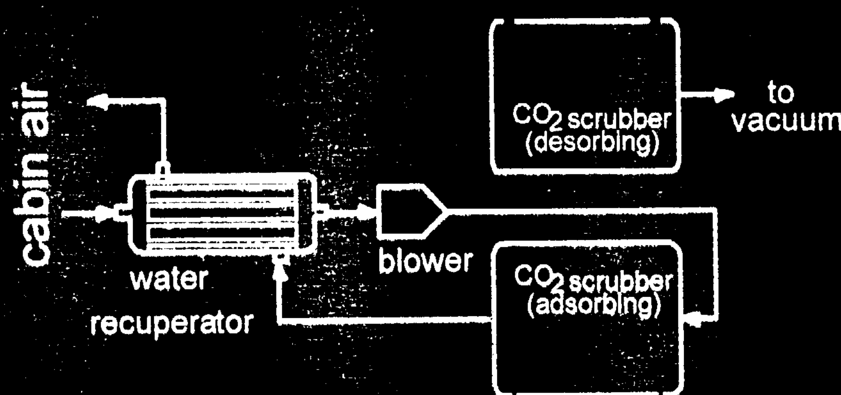
- **High power consumption (860 W avg in open-loop mode), mostly needed for water desorption**

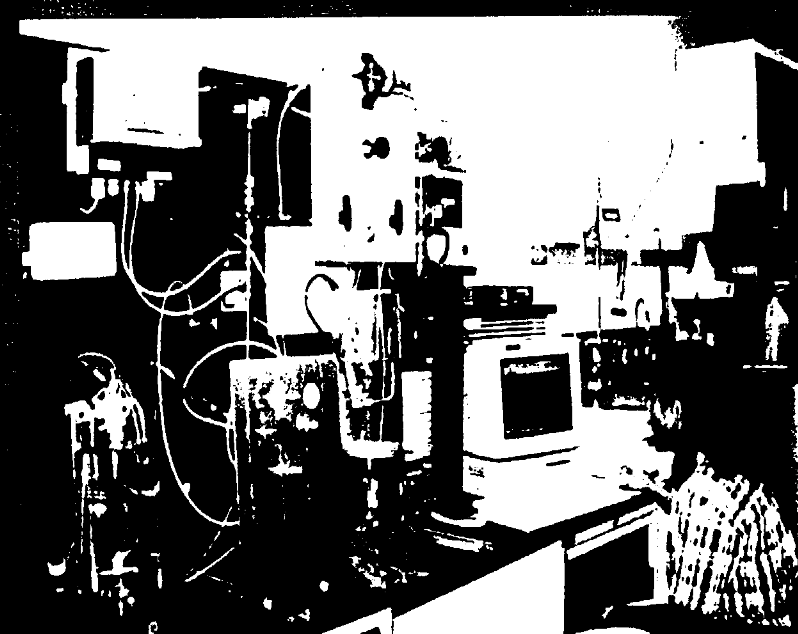
Hybrid Membrane/Adsorption CO_2 Removal

Proposed Technology: WAter Recuperated CO_2 Sorbed
(WARCS, NASA Ames Research Center)

PROS

- **Lower power than 4BMS due to reduced/eliminated need for water desorption**
- **Uses similar materials to existing life support equip.**





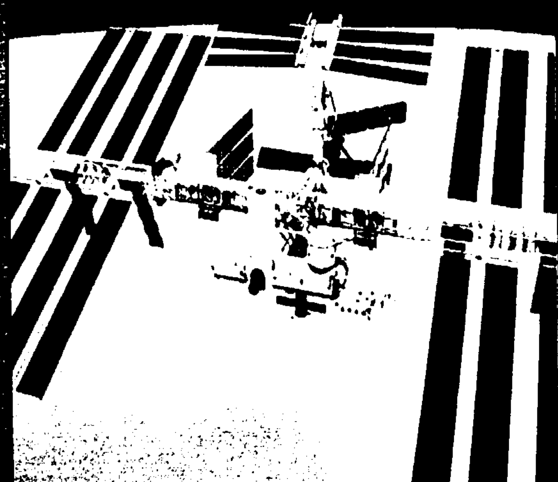
CONS

- **Low technical maturity**

Conclusions — Low Power CO_2 Removal

- ARC research focuses on developing CO_2 removal technology that has significantly lower power requirements for the same performance of current processors.
- Vanderbilt University will perform modeling and optimization work, supported by experimental testing at NASA Ames.
- If the concept has sufficient merit in terms of its power and mass trade (ESM) with existing technology, we will propose further development. Alan Drysdale (SIMA group) is collaborating on system metrics.
- In addition, characterization and development of sorbent materials continue to play an essential and fundamental role in the research.

2. ISRU Technologies for Mars Life Support



Self-Sufficiency Options for Life Support

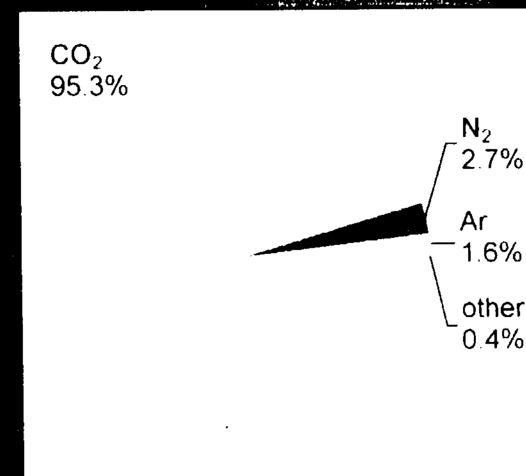
Complete regeneration
No leaks
Total closure (100%)

Relatively relaxed closure and leakage requirements, reliance on local resources (ISRU)

Design Drivers are
- Reduced mass and power
- Increased safety and reliability

Atmospheric Resources of Mars

Mars Pathfinder, 1997



Mars atmosphere composition

- Pressure: ~1% of Earth's
- Temperature: 180 – 290 K (equatorial)
- Dusty, windy

N_2 Consumables / Make-up for Mars Life Support

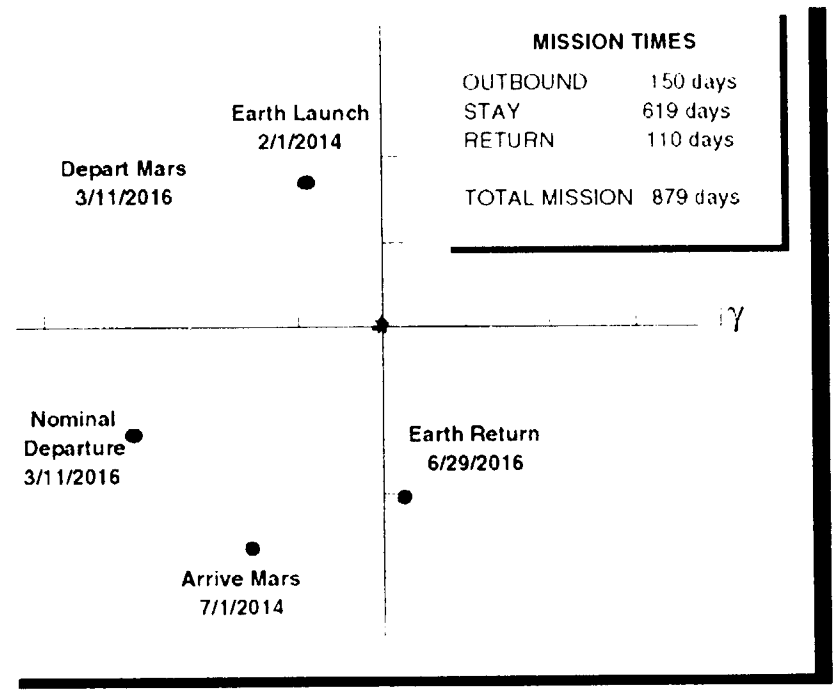


Figure 3-4 Fast-transit mission profile

NASA SP 6107, Mars Reference Mission, 1997.

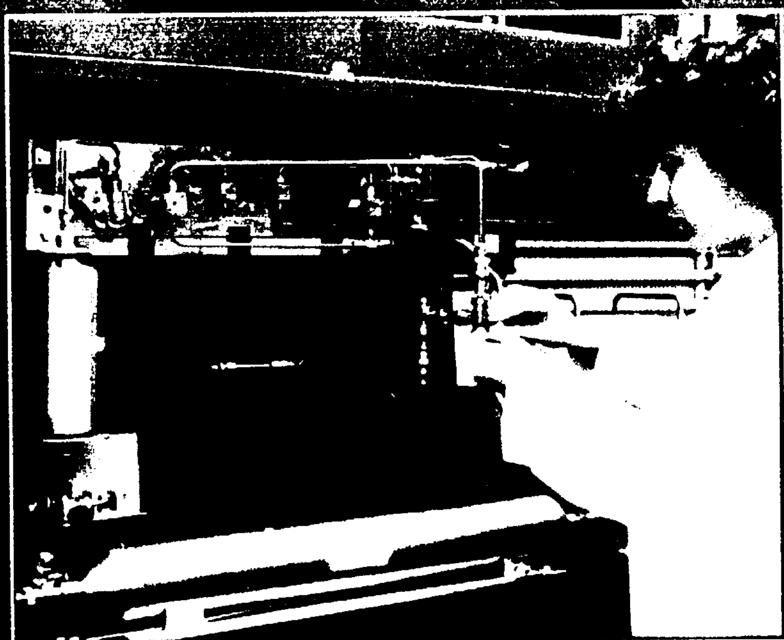
Transit Leakage Losses:
0.1 kg/day leakage,
260 days = 26 kg N_2

Surface Leakage Losses:
0.1 kg/day leakage,
619 days = 62 kg N_2

Surface/Airlock Losses:
1 kg/cycle, 2 cycles/day,
619 days = 1200 kg N_2

Total Mission N_2 Losses:
~1.3 tonnes N_2 lost
(2x safety factor = 2.6 tonnes)

Mars Atmosphere Separation and Compression
NASA Ames Research Center



Basic research on adsorption separations of Mars atmospheric gases at Mars local conditions.

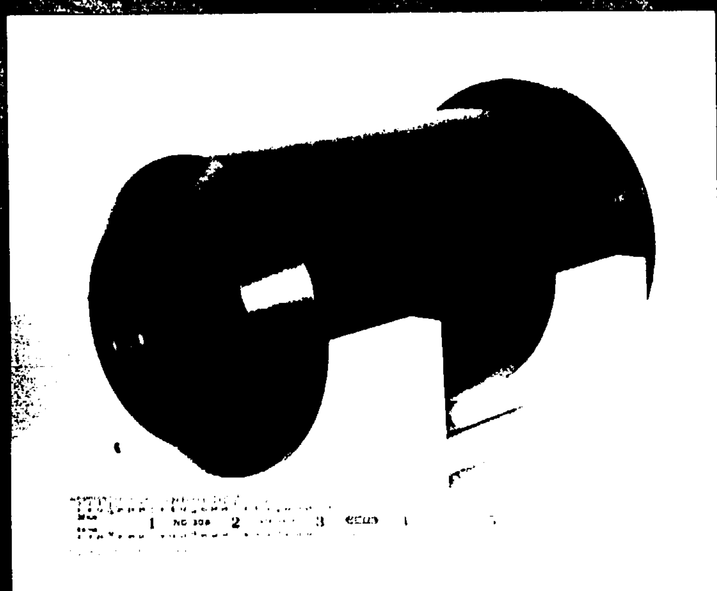
NASA Ames Research Center

Mars In-situ Carrier Gas Generator (MICAGG) will produce compressed N_2-Ar for science payloads at no electrical cost.

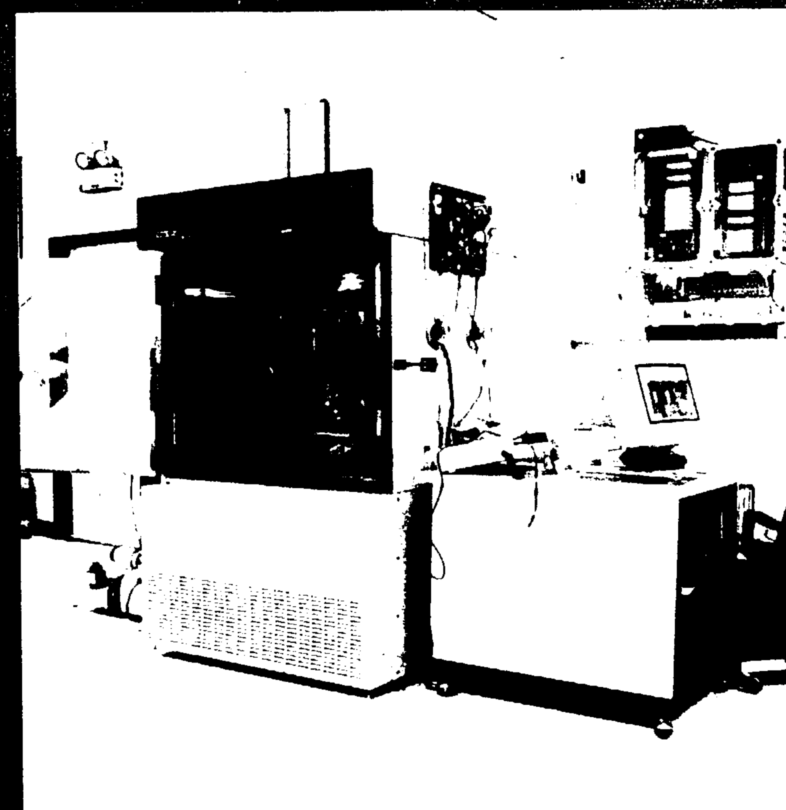
NASA Ames Research Center/University of Arizona

Mars Atmosphere CO_2 Separation and Compression

Propulsion Research



Solid-state CO_2 compressor produces 13 g CO_2 per cycle at 1 bar for 35 W-h electrical energy.

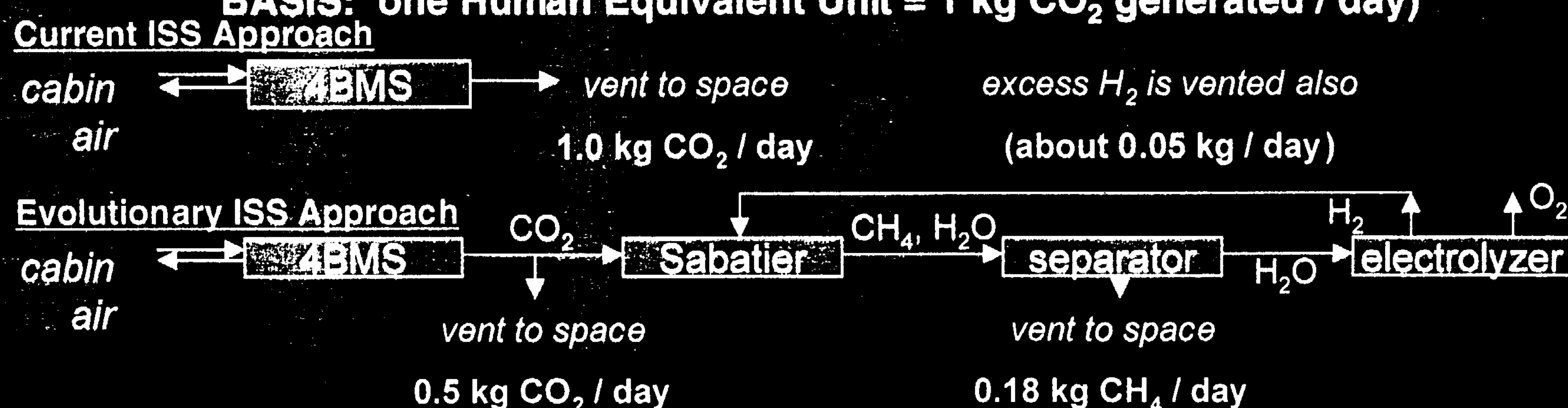


All hardware is tested under simulated Mars conditions of pressure, gas composition, and diurnal temperature cycle.

3. Absorption-Based Compressor for International Space Station Oxygen Recovery

- ISRU research demonstrated low power technology which effectively separated and compressed N_2 and CO_2. Perhaps other applications?
- Until oxygen recovery on the *International Space Station* is implemented, all CO_2 removed from the cabin air and H_2 generated through water electrolysis will be vented.
- Venting of H_2 and oxygen (in the form of CO_2) represents a water resupply penalty. Water loss is minimized when no H_2 is vented. Total venting difference is about 0.37 kg H_2O per HEU per day, (2000 lb or $20M per year

BASIS: one Human Equivalent Unit = 1 kg CO_2 generated / day)



CDRA and CRA Characteristics

Carbon Dioxide Removal Assembly (CDRA)	CO_2 Reduction Assembly (CRA)
• 4BMS adsorption separation (AlliedSignal/Honeywell)	• Sabatier methanation (Hamilton Sundstrand)
• Removes CO_2 from cabin air	• Uses CO_2 (and H_2) to make CH_4 and H_2O
• Operates on a 155-minute "half-" cycle	• Operates on a 90-minute cycle
• Produces CO_2 at vacuum (< 4 psia)	• Needs CO_2 at pressure (~ 14 psia)

<u>Interface equipment</u> is required that

- Can remove CO_2 (4 kg/day) from the CDRA at vacuum
  (To react all available H_2, 4 kg CO_2 needs to be extracted & compressed from the CDRA)
- Compresses the gas
- Stores it at pressure until it can be used by the CRA
- Fits within the OGS rack
- Requires no modifications to existing hardware/software

Characteristics of "2 kg" Compressor

Resource	Mechanical compressor	Temperature Swing Absorption (TSA) compressor
power	500 W nominal, 900 W peak	150 W nominal, 300 W peak
volume	31 liters (1.1 cubic feet)	25 liters (0.9 cubic feet)
buffer tank volume	38 liters (10 gallons)	n/a
mass	27 kg (60 lbs)	22.5 kg (50 lbs)
heat rejection to cold water	up to 500 W	150 W
heat rejection to avionics air	up to 200 W	20 W
operating life	3.1 yr	comparable to 4BMS

Brassboard Development Status/Conclusions

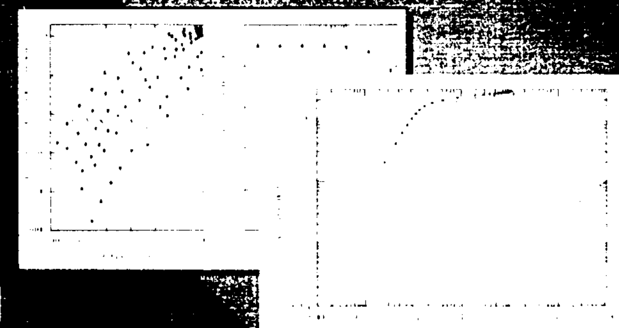
- A single-bed partial unit was developed and tested with the MSFC 4BMS hardware in FY00.

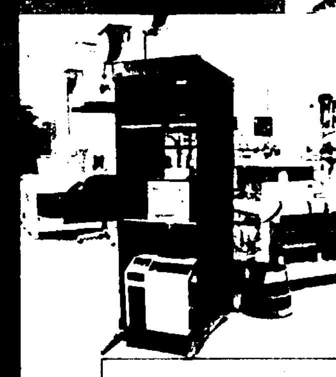
- Development and testing of a complete four-bed brassboard unit is ongoing in FY01.

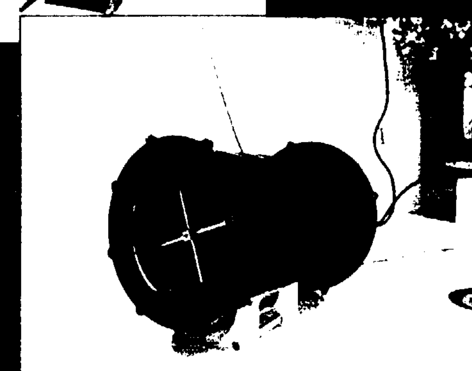
- The TSA compressor is expected to be capable of providing 4 kg CO_2 per day from the CDRA with
  - lower power
  - quieter and vibration-free operation
  - expected better reliability and lifetime

  than the mechanical compressor alternative

- If successful, this technology would solve one of the key technical challenges to closing the air loop for the first time on International Space Station.

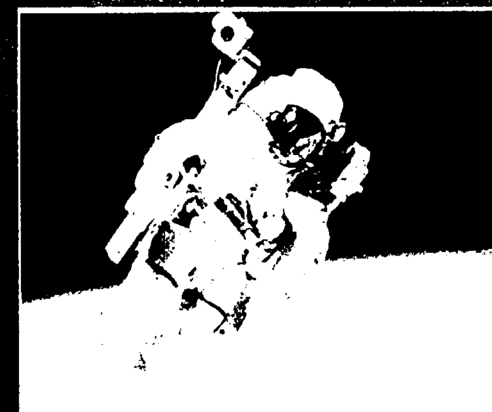






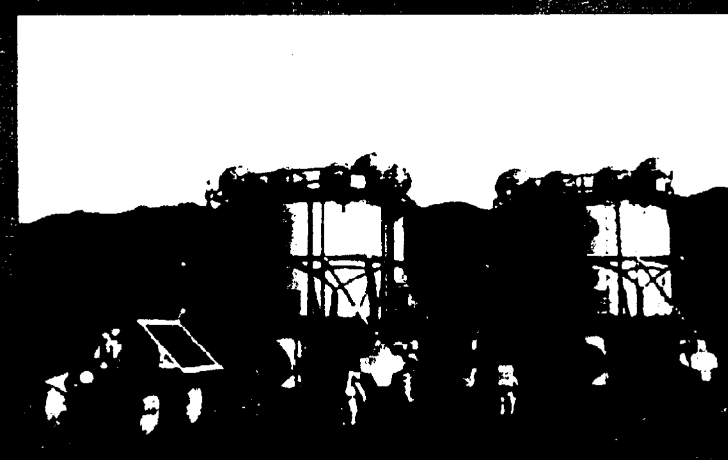
ALS Water Recovery R&TD

Justification



- Water accounts for 87% of the total metabolic resupply requirements to keep an astronaut alive in space.

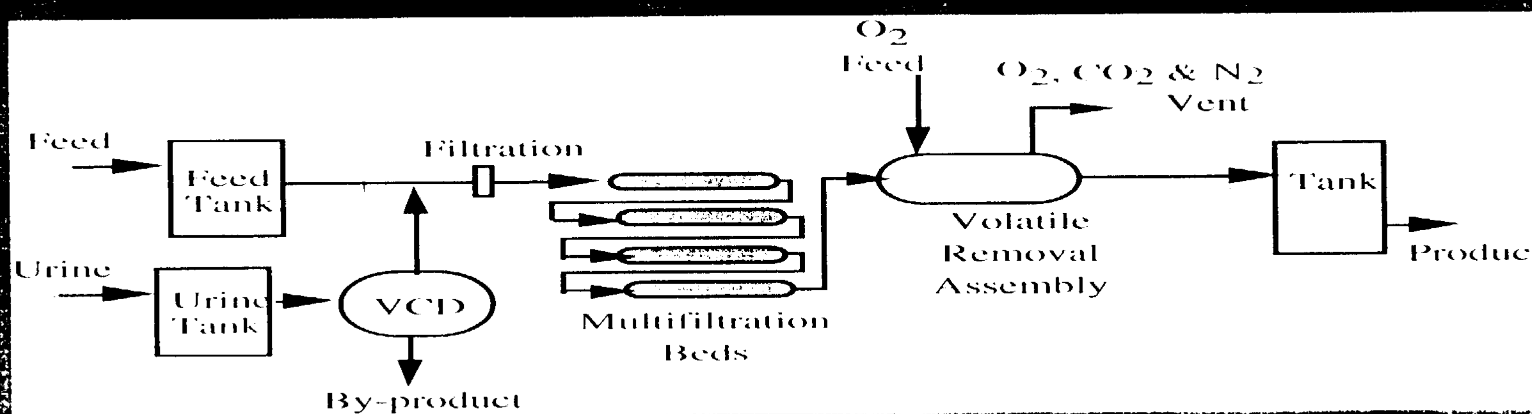
- Using the Mars Reference Mission as a baseline and Mars Pathfinder launch cost data, the cost of supplying water for this mission in the open loop case is over $11 Billion.



Assumptions: 6 astronauts,
duration = 960 days,
launch cost = $150,000/kg,

State-of-the-Art Water Recovery

- The International Space Station (ISS) uses a water recycling system (WRS) which all but eliminates this open loop penalty.



- However, the ISS WRS system has a significant processor- related resupply requirements (primarily adsorption beds, filters, and makeup water).

- Using the Mars Reference Mission as a baseline and the Mars Pathfinder cost data, the cost for resupplying an ISS type WRS for such a mission would be in excess of $1 Billion.

Assumptions: 6 astronauts, duration = 960 days, launch cost = $150,000/kg,
WRS resupply = 1.19kg/person-day, flow rate = 3.18kg/hr

ARC Focus - Water Recovery

The Advanced Life Support (ALS) water treatment technology development program is focused on developing fully regenerative water recycling solutions for <u>nearer term missions</u>.

<u>Candidate Technologies:</u>

* Vapor Phase Catalytic Ammonia Reduction (VPCAR)
* Wiped-Film Rotating-Disk Evaporator
* Lyophilization
* Direct Osmotic Concentration

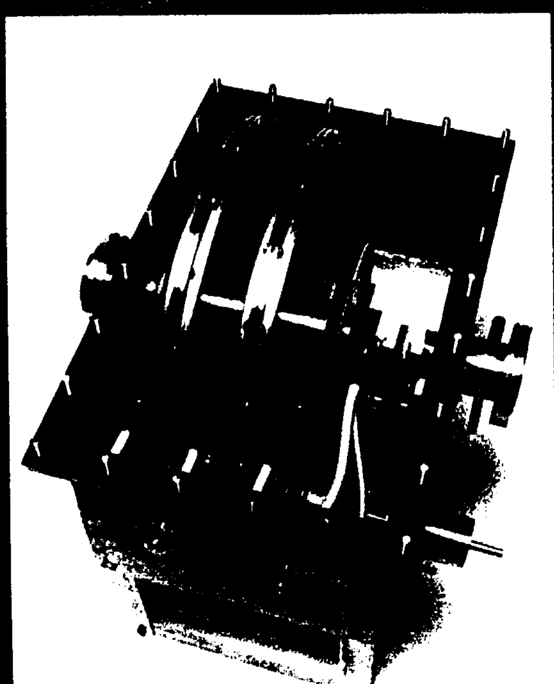
Aqueous Phase Catalytic Oxidation

In situ hydrogen peroxide generation

Electrochemical Oxidation

Vapor Phase Catalytic Ammonia Removal (VPCAR)

- The VPCAR is a distillation-based/catalytic oxidation water processor:
  - Designed to accept a combined waste stream (condensate, hygiene and urine) and produce potable water in a single step.
  - Designed to require no re-supply or maintenance for 3 yrs.
- The technology is modular and can be packaged to fit into a volume comparable to a single Space Station rack.



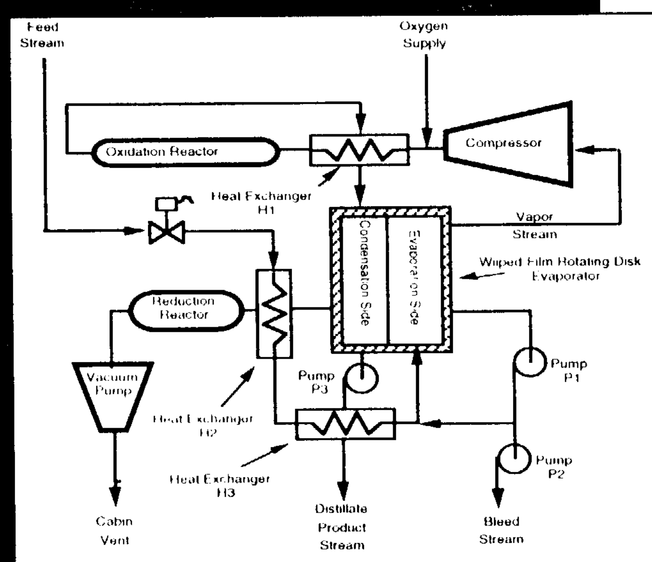
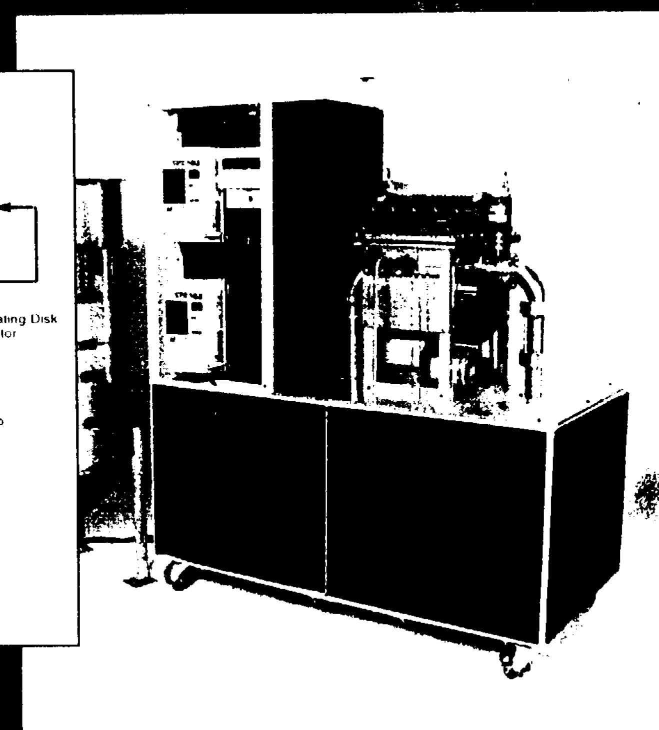


Figure 1 - VPCAR Process Flow Diagram



Comparison Between ISS Baseline and VPCAR

	ISS Water Recycling System	**VPCAR System**
Re-supply (equipment)	413 Kg/year	0 Kg/year
Number of Independent Processors	4	2
Feed Streams	2	1
Weight	193 Kg	68 Kg
Volume	1.1 m^3	0.39 m^3
Power – Water Processor Only	55 W-hr/kg	300 Whr/kg
Oxidant Feed	2 g/hr	>30 g/hr
Oxidant Consumption	0. 67 g/hr	>30 g/hr
Oxidant Energy Penalty	0.7 Whr/ kg feed	0.7 Whr/ kg feed
CO_2 Generation Rate	0.47 g/hr	0.47 g/hr
CO_2 Energy Penalty	0.6 Whr/kg feed	0.6 Whr/ kg feed
Lyophilization Power **	5.2 Whr/kg feed	10.4 Whr/kg feed
Total Subsystem Power	61.5 Whr/kg feed	311.7 Whr/kg feed
Recovery Rate	99%	97%
Scheduled Maintenance	every 50 days	0
TRL	6	4
Mass Metric	2463	434 (332)

The Development of a Lyophilization-based Solid Waste Treatment Technology

A Stanford Univ. - Ames Research Center Collaboration

- The objective of this NRA research is to evaluate the use of a modified lyophilization technique to recover water from/stabilize spacecraft solid wastes.
  (food wastes, feces, general trash, and water treatment system byproduct streams)

- The lyophilization process is a process by which water contained within a solid sample is frozen and then sublimed thus leaving a dry solid material (usually 1-3% water content) and liquid water.

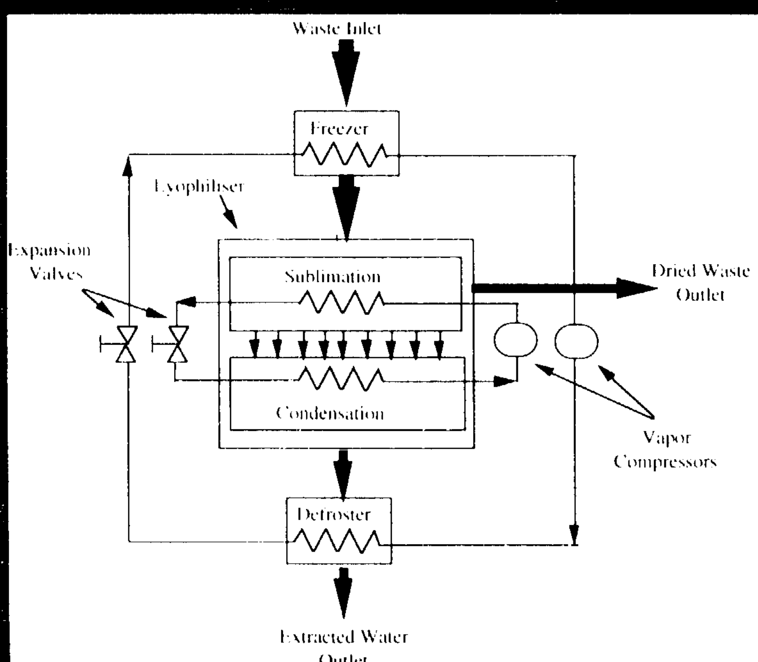
- This technology is ideally suited for an application such as a Mars Transit Vehicle (MTV) where water recovery rates approaching 100% are desirable, but the production of CO_2 (from conversion of solid wastes) is not.

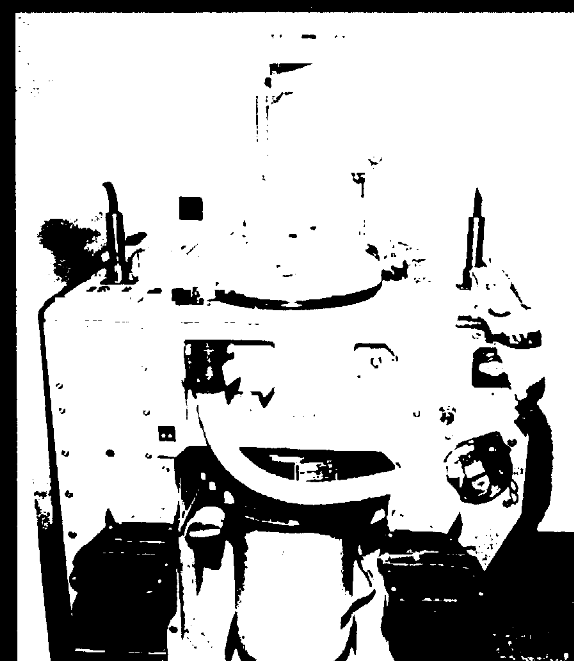
	Mass (wet)	Water Content	Mass Water
	Kg/person day	%	Kg/person day
Feces	0.132	84	0.11
Water Treatment System By-products*	0.27	71	0.19
Leftover food	0.10	70	0.07
paper	0.13	10.2	0.013
Other Trash	0.78	0.2	0.0016
Total	1.41		0.38

* Based on International Space Station water recovery rate of 99%

Lyophilization vs. Other Drying Technologies

- Low pressure, low temperature process (potential for low power operation).
- Complex solids pumping or handling techniques are not required.
- The technique should not produce CO_2, NO_x, SO_x, or any other undesirable oxidation byproducts (gases generated are primarily water).
- The final product is a stable dried material with from 1 to 3% H_2O.
- The approach is fully regenerable, meaning that the process requires no consumables, only energy.

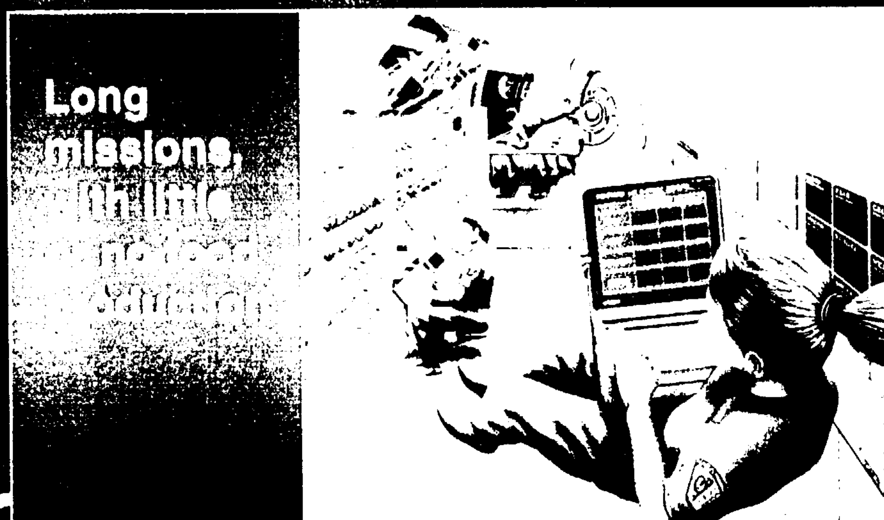




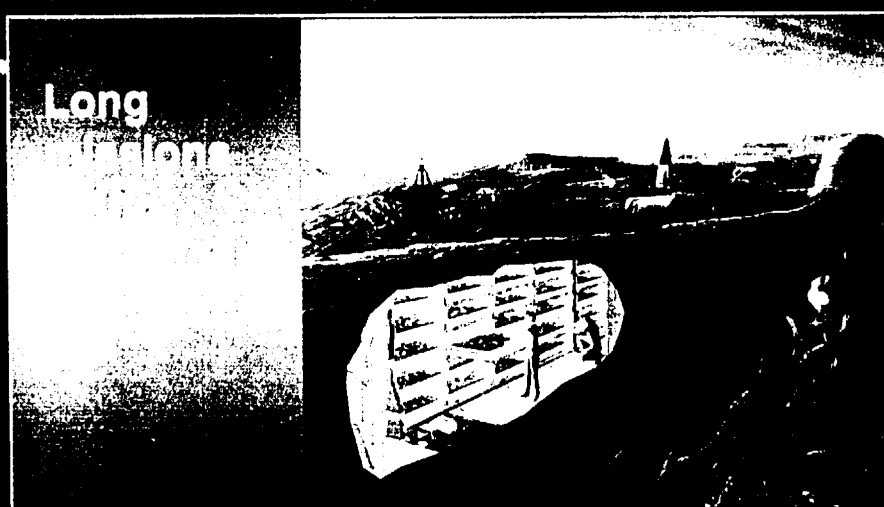
Focused Research Areas

Solid Waste Processing / Resource Recovery

Goal



Stabilize/ Destroy hazardous or noxious wastes



Reclaim CO_2 and nutrients from waste for biological processors

How Do We Get There?

Waste Processing Critical Questions

1. What are the mission scenarios and how do these scenarios affect the requirements on waste processing?
2. What are the desired products of waste processing?
3. What quality/quantity of reclaimed products are necessary?
4. What is the weight, power, volume, and reliability of the candidate processing technology?
5. What is the cost, time, and probability of success for the development effort?

What are the Options? Promising Technologies

Technology	Advantages	Development Issues	Compl. React.	Wt.	Pwr	Vol.	Dev Cost	Reliability Simplicity	Safety	Robust	Novel	Use for No Food Growth Sys?	New Commercial
Incineration	• Low pressure • Commercial applications	• NOx • Sulfur	+ But byprod	+		+	+	–	–	?	+		Existing
Steam Reforming	• Low pressure • Clean syngas for oxidation	• Power and energy rec.	–	?	?	?	?	–	+	+	?	?	+
SCWO	• One step processing	• Corrosion • Slry pump • Reactor Plug	+	?	=/-150% ?	?	?	–	–	+	?	?	+
Wet Ox	• Lower pres. than SCWO	• Post treatment for acetic acid	=	?	+	?		?	?	+	?	–	?
Biological	• Low power • Nutrient recovery	• Incomplete reaction • Sludge control • Large size	=	–	?	–	?	?	+	?	–	=	Existing
Electro-Chemical	• Accelerates reaction at lower T & P	• Incomplete reaction • Energy	=	?	?	?	?	=	?	?	?	?	?

\+ Likely Advantage ☐ Neither Advantage, nor Disadvantage – Maybe Disadvantage = Likely Disadvantage ? Unknown

Incineration - mature technology, complete oxidation, low pressure, but high temp and requires catalysts/resupply for flue gas clean up

SuperCritical Water Oxidation (SCWO) - 'ultimate' processor, complete oxidation, no catalysts/resupply, but high pressure/temp, pretreatment

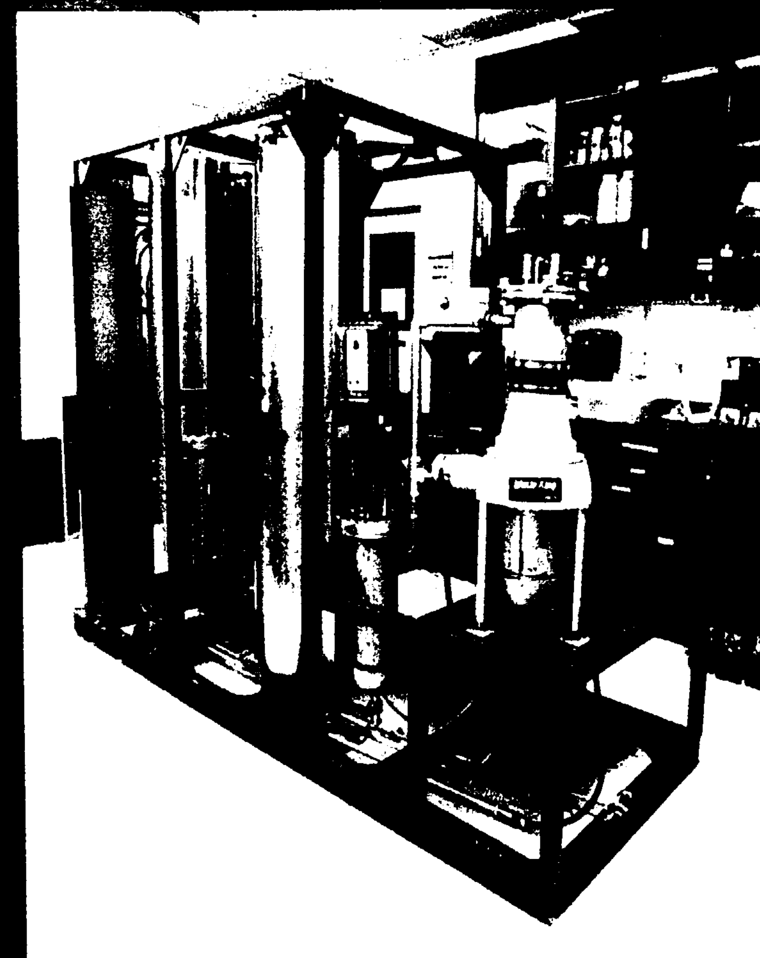
Biological Waste Treatment - limited wastes, but potential 'front end' system to remove K^+/organics for plant growth

Focused Research Areas

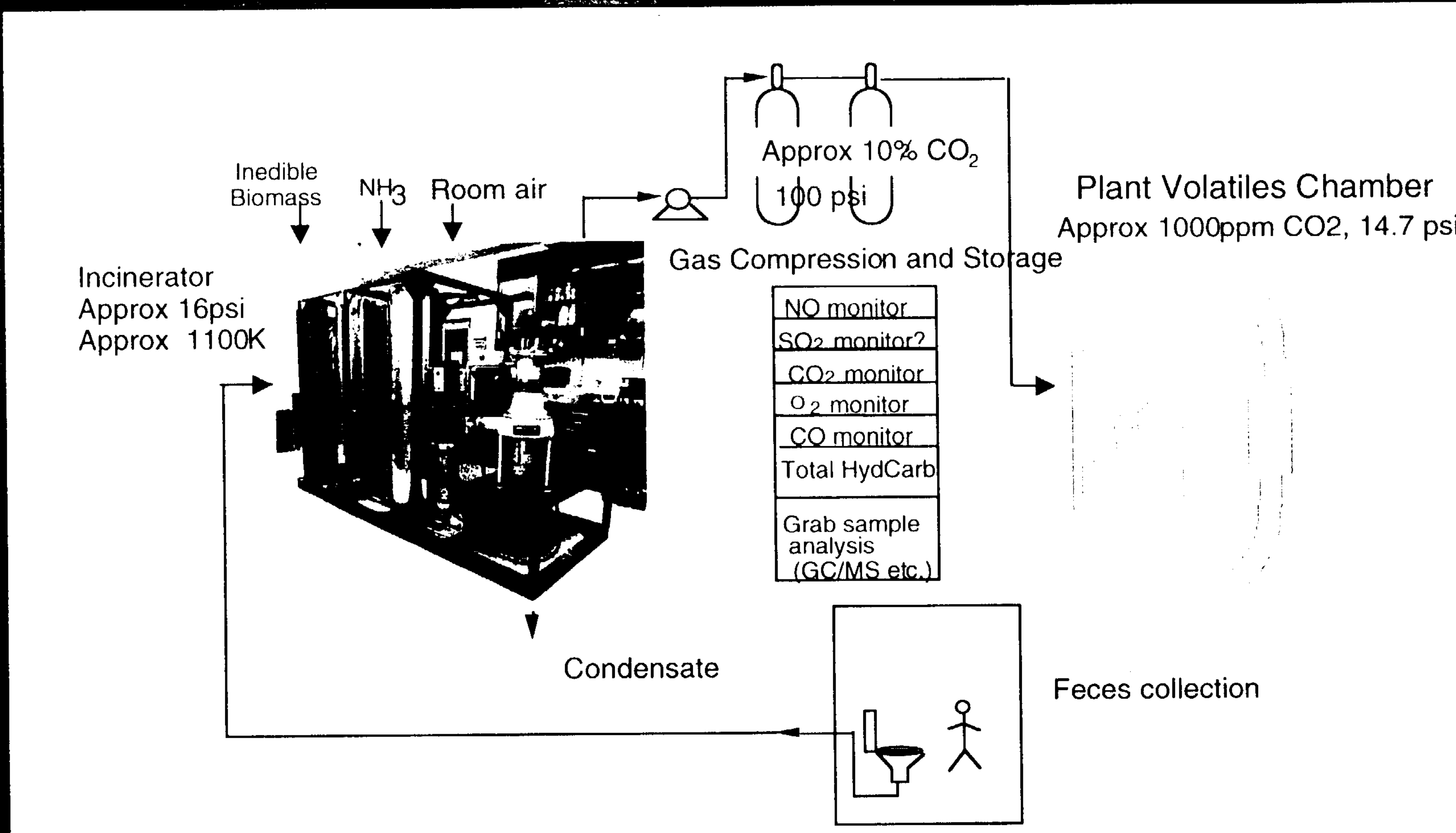
Solid Waste Processing / Resource Recovery

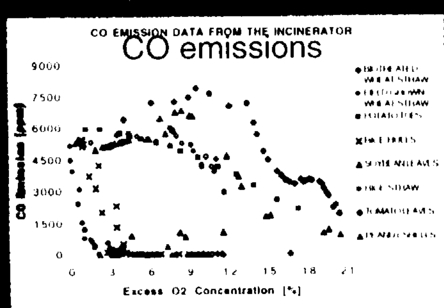
INCINERATION R&TD EFFORTS

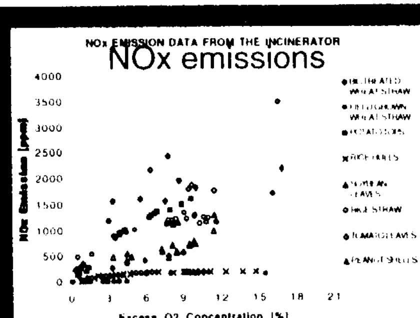
- Feed system development
- Improved energy efficiency
- Improved catalyst lifetime/robustness
- Waste Reutilization
  - Trace gas analysis of flue gas
  - CO,NO, SO_2, trace hydrocarbon dose response studies (plant sensitivity)
  - Ash analysis for plant nutrient solution make up

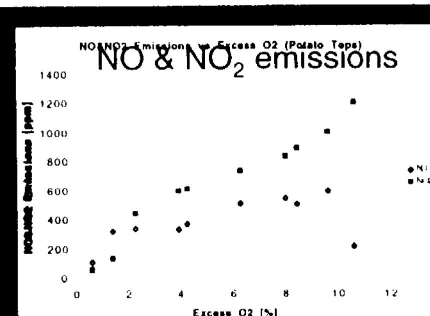


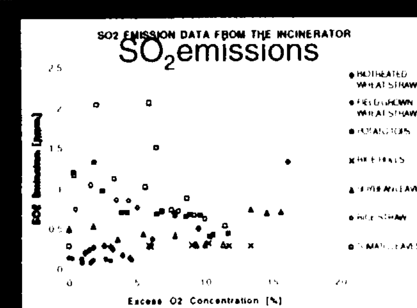
Incineration Resource Recovery Schematic











Reutilization of Incinerator Flue Gas and Ash

Lettuce Grown on Cleaned Flue Gas

General Recovery Factors for Inorganics in the Incinerator Ash

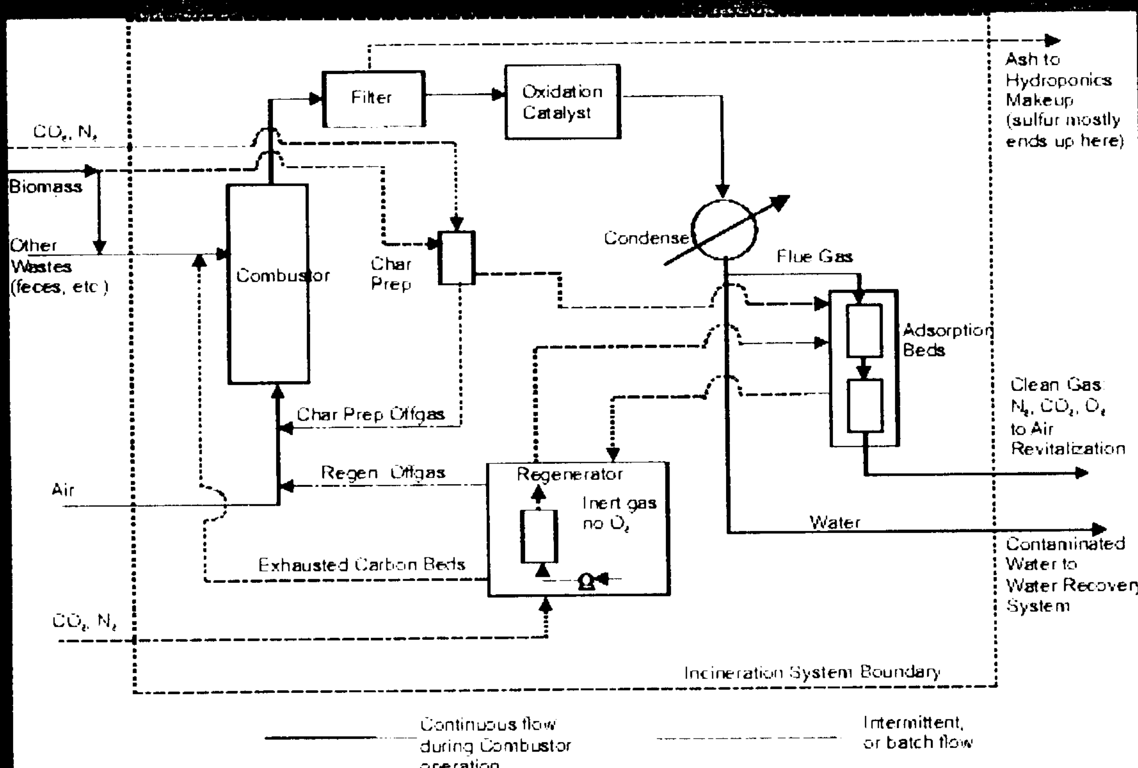
- The inorganics represent about 7.5% of the original plant dry weight
- About 90% of inorganics are retained in the incinerator ash.
- About 72% of the inorganics in the ash are water soluble.
- All of the ash is soluble in acid.

Nutrients Available from Ash

Nutrient	Lettuce hydroponic solution (LHS)(mM)	Elementall composition of Ash (mg/g)	% Supplied by ash alone
K	5	792	101
Mg	1.5	17.3	24
Ca	2.5	133.3	67
B	0.0466	0.8942	44
Cu	0.00015	0.0006	3
Fe	0.096	0.4667	7
Mn	0.0045	0.5333	108
Mo	0.0005	0.1333	416
Zn	0.0038	0.004	8
P	1	28	60

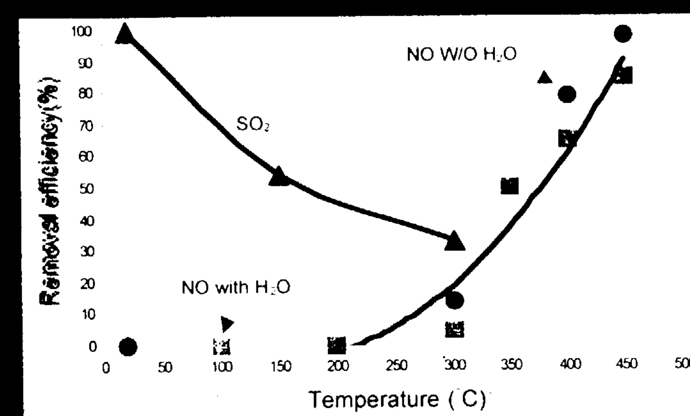
Reactive Carbon for Flue Gas Cleanup

- **Background:** Catalysts and adsorbents (activated carbon) are typically used for clean up of combustion process gases
- **NRA Goal:** convert inedible biomass to activated carbon to eliminate adsorbent resupply (adsorb NO_x, SO_2; reduce NO_x to N_2; SO_2, to S)



Example of flow diagram of reactive carbon for flue gas cleanup

Effect of High Temperature on NO and SO_2 Adsorption/Removal

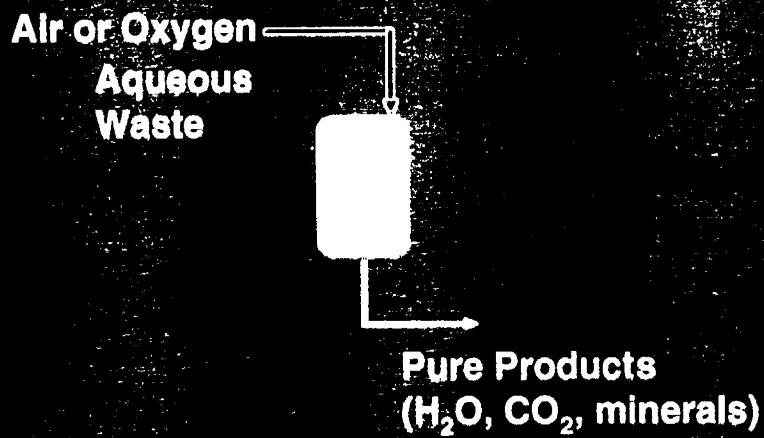


Removal efficiency for NO and SO_2 using char from rice hulls at 3% oxygen

Focused Research Areas

SUPERCRITICAL WATER OXIDATION (SCWO)

Essence of the Process



SCWO R&TD EFFORTS

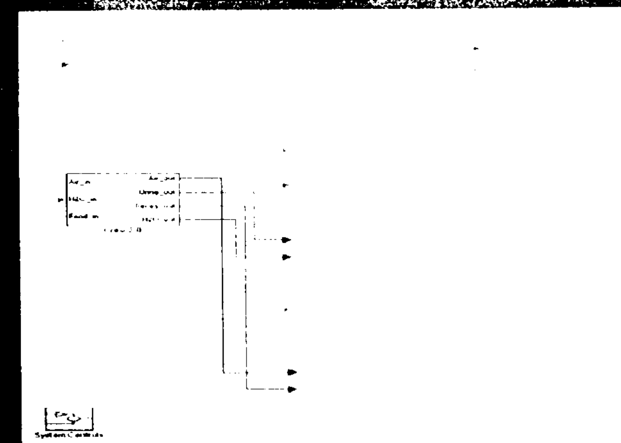
- Demonstrated effectiveness on liquid waste streams
  (complete oxidation w/o catalysts)
- Determine kinetics of biomass particle oxidation
- Development of solid feed system
  - Feed pretreatment (slurry)
  - Feed delivery/pumping
- Investigate batch operation methods
- Evaluate carbonization process to fluidize waste

Systems Integration, Modeling and Analysis (SIMA)

- Mission objectives drive the functional requirements of Advanced Life Support technology development.

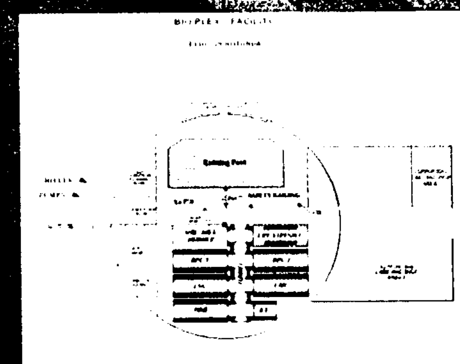
- Systems Engineering (SIMA) enables R&TD efforts to meet the functional requirements the best way possible.
  - Identification and evaluation of feasible designs
  - Performance of technology/configuration trade studies
  - Optimization of operational strategies
  - Provide guidance for future R&TD efforts

Dynamic System Modeling

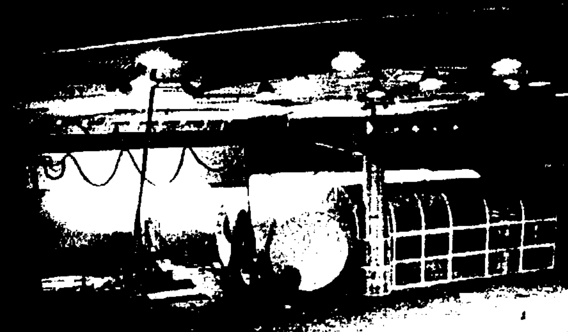


Dynamic mass flow modeling of Bio-PLEX

- Model flow of material through BLSS over time
  - Crew
  - Air Revitalization
  - Water Recovery
  - Solid Waste Processing/Resource recovery
  - Biomass Production Chamber
  - Food Processing System
- Conduct candidate technology trades
  - Bioreactor or incinerator?
  - Grow all food or partial resupply?



- Compare candidate configurations
  - Separate or combined air loops for the crew and crops?
  - Recycle crop transpiration water to WRS or to nutrient solution?
- Optimize operational strategies
  - What is the best crop planting/harvesting schedule?
  - Adjust solid waste processing rate to maintain CO_2 level?



Dynamic System Modeling

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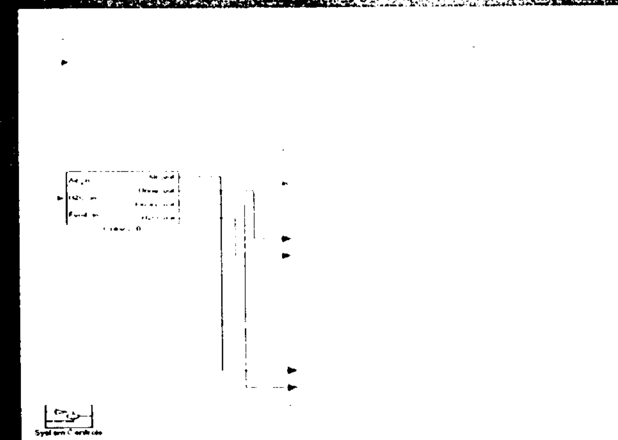
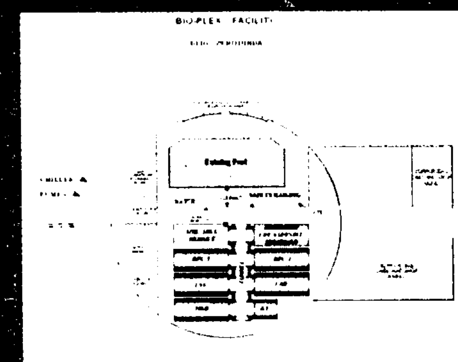
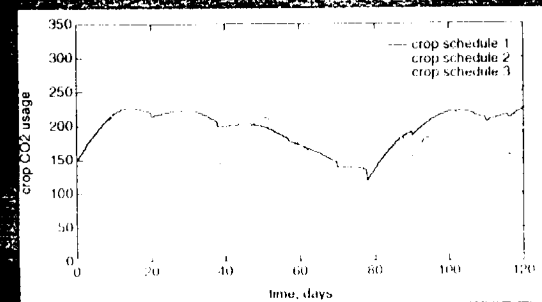


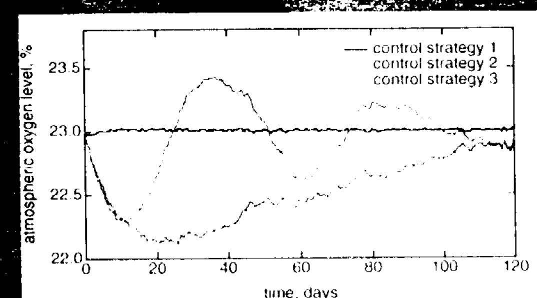


Dynamic Systems Modeling (cont'd)

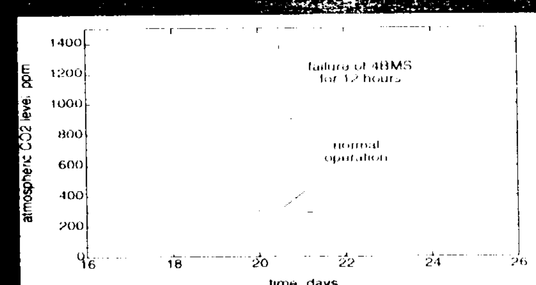
- Develop schedules for crop production
  - Smooth crop gas exchange profiles (CO_2 usage) by altering planting/harvesting schedules



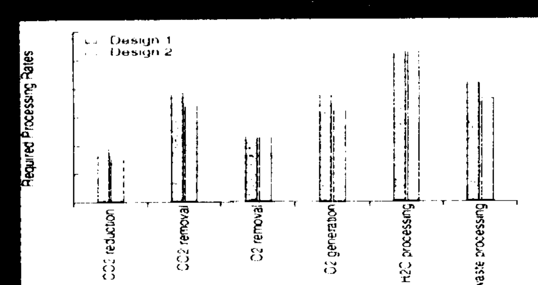
- Develop control system strategies
  - Design controllers that meet performance specifications (atmospheric oxygen level)



- Apply model-based Fault Detection, Isolation and Recovery (FDIR) system
  - Compare model predictions to real-time data for failure diagnosis (simulated 4BMS failure)

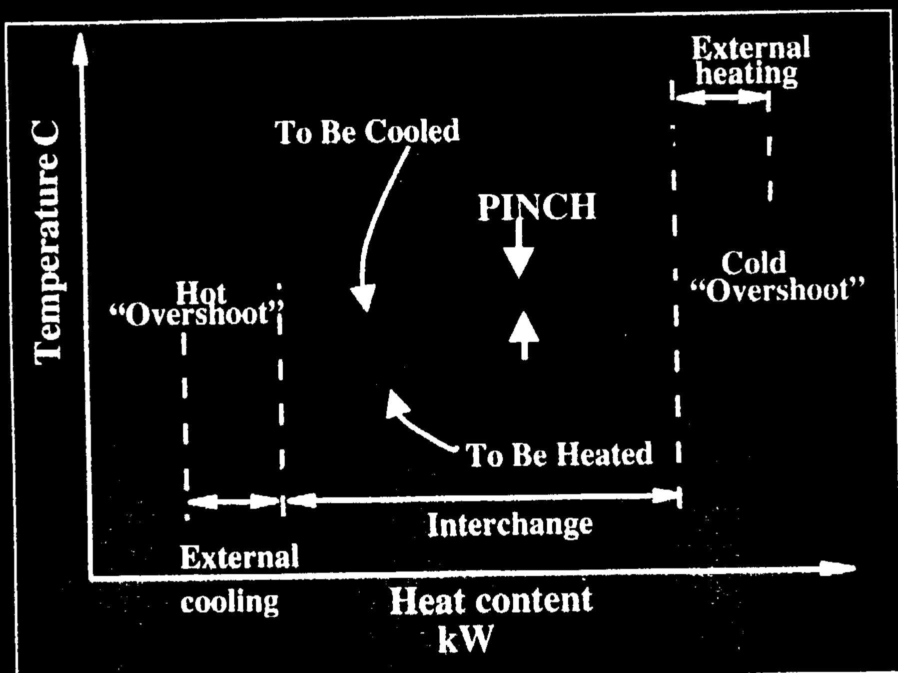


- Design appropriately sized processors and buffers
  - Select technologies based on systems trades

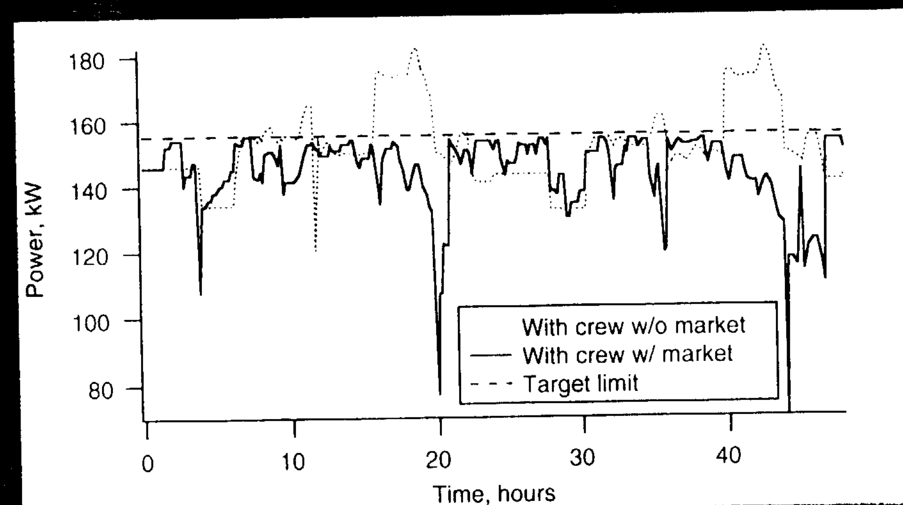


Power Reduction in ALS Systems - NRA

- **Motivation**
  The high power requirement associated with ALS is a key challenge
  Optimization of total system efficiency (not individual processors) is required.
- **Approach**
  - Apply Pinch Analysis technique and Market-based Control strategy



Reduce total system power by optimized reuse of waste heat between hot and cold streams



The market determines which processes receive the power they demand within the target limit
(function of internal process state and power cost)