Advanced Exploration Systems

Logistics Reduction and Repurposing

Trash-to-Gas & Heat Melt Compactor

KSC

Anne J. Caraccio
NASA, NE-L

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Advanced Exploration Systems

Logistics Reduction and Repurposing

Trash-to-Gas

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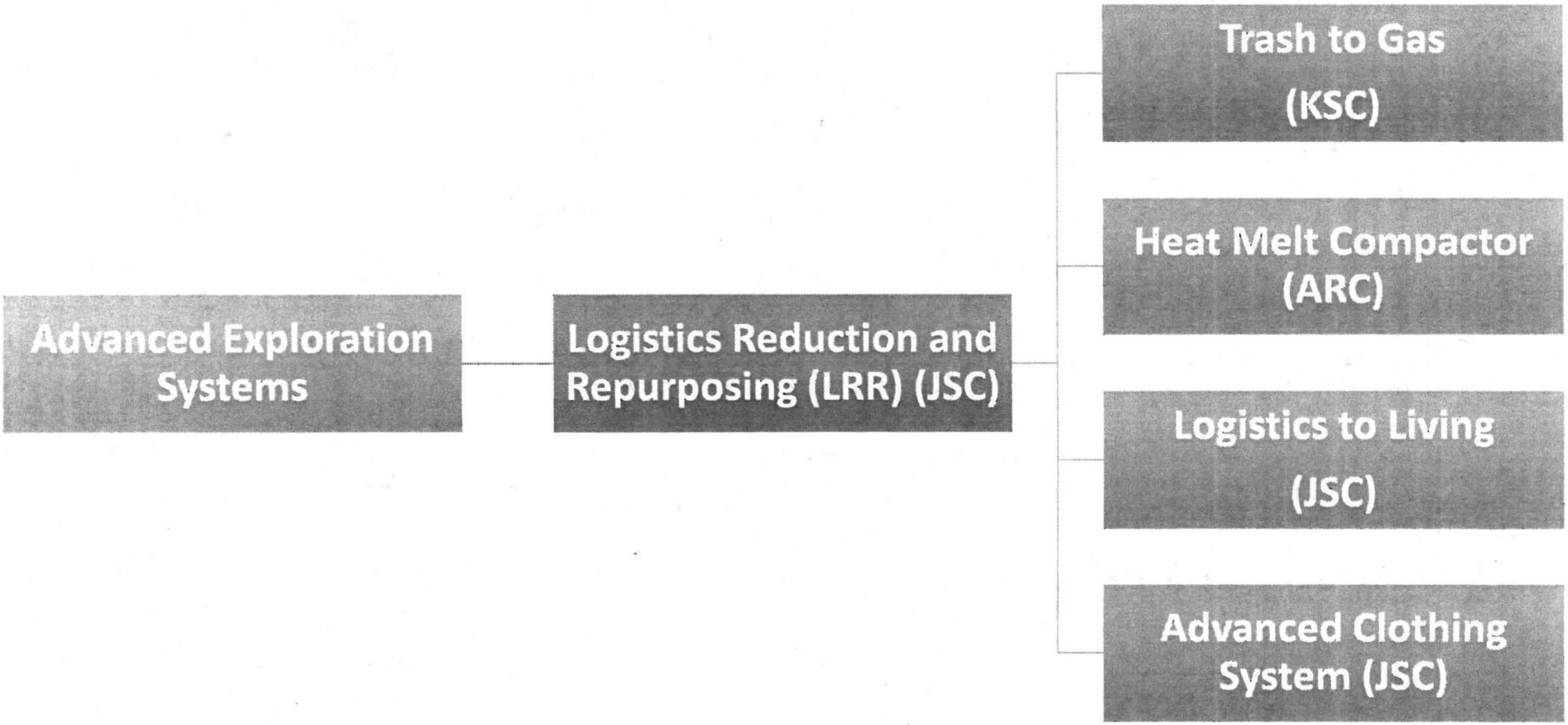
KSC Team: Anne Caraccio, NE-L; Steve Anthony, NE-F; Tony Muscatello, NE-S; Jim Captain, ESC; Bobby Devor, ESC; Doug Tomlin, NE-L; Lashelle McCoy, ESC; John Bayliss, NE-L; Katie Zadjel, GP-L;

Agenda

1. Project Structure
2. "Trash to Gas"
   - *Anne Caraccio, NE-L*
3. "Smashing Trash! The Heat Melt Compactor"
   - *Andrew Lane, NE-M*
4. "Heat Melt Compaction as an Effective Treatment for Eliminating Microorganisms from Solid Waste"
   - *Mary Hummerick, QinetiQ North America*
5. Questions

LRR Project Structure



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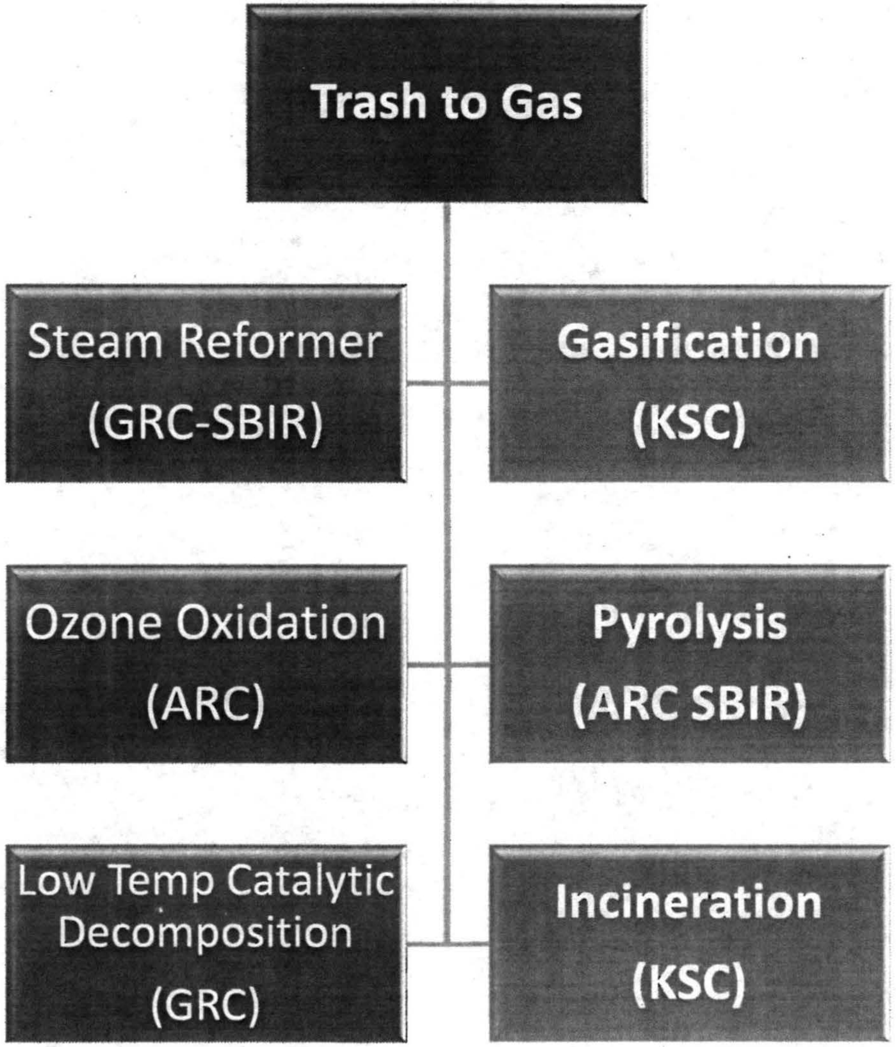
LRR Project Structure

Trash to Gas Project Structure

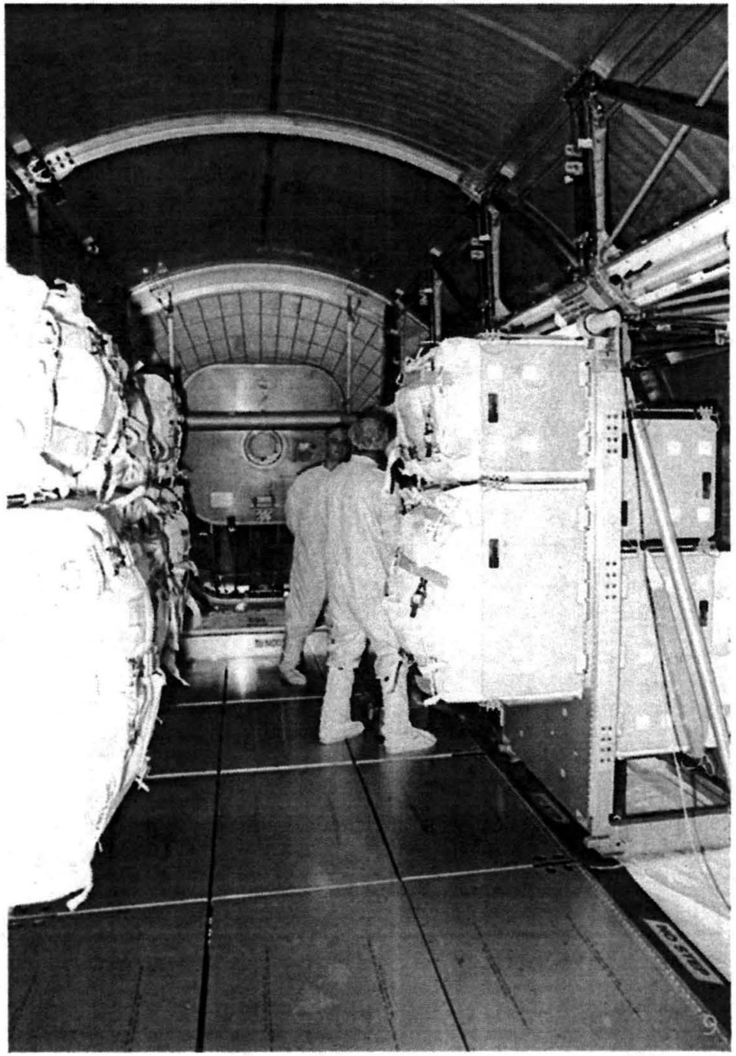
- **Trash to Gas**
  - Steam Reformer (GRC-SBIR)
  - Gasification (KSC)
  - Ozone Oxidation (ARC)
  - Pyrolysis (ARC SBIR)
  - Low Temp Catalytic Decomposition (GRC)
  - Incineration (KSC)

Trash to Gas Project Structure

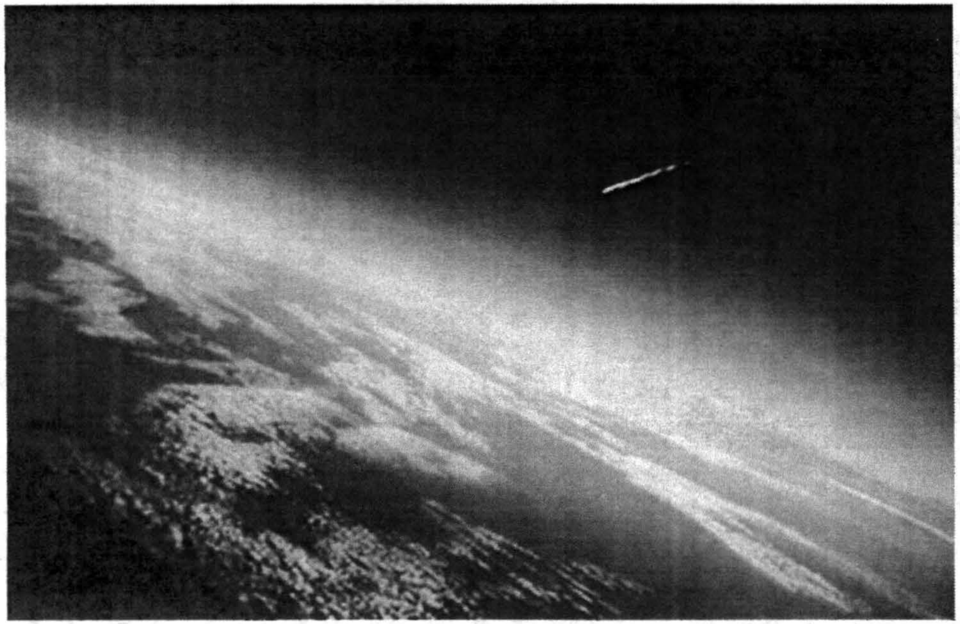


Why?

Mass & Volume



Where Does the Trash Go?



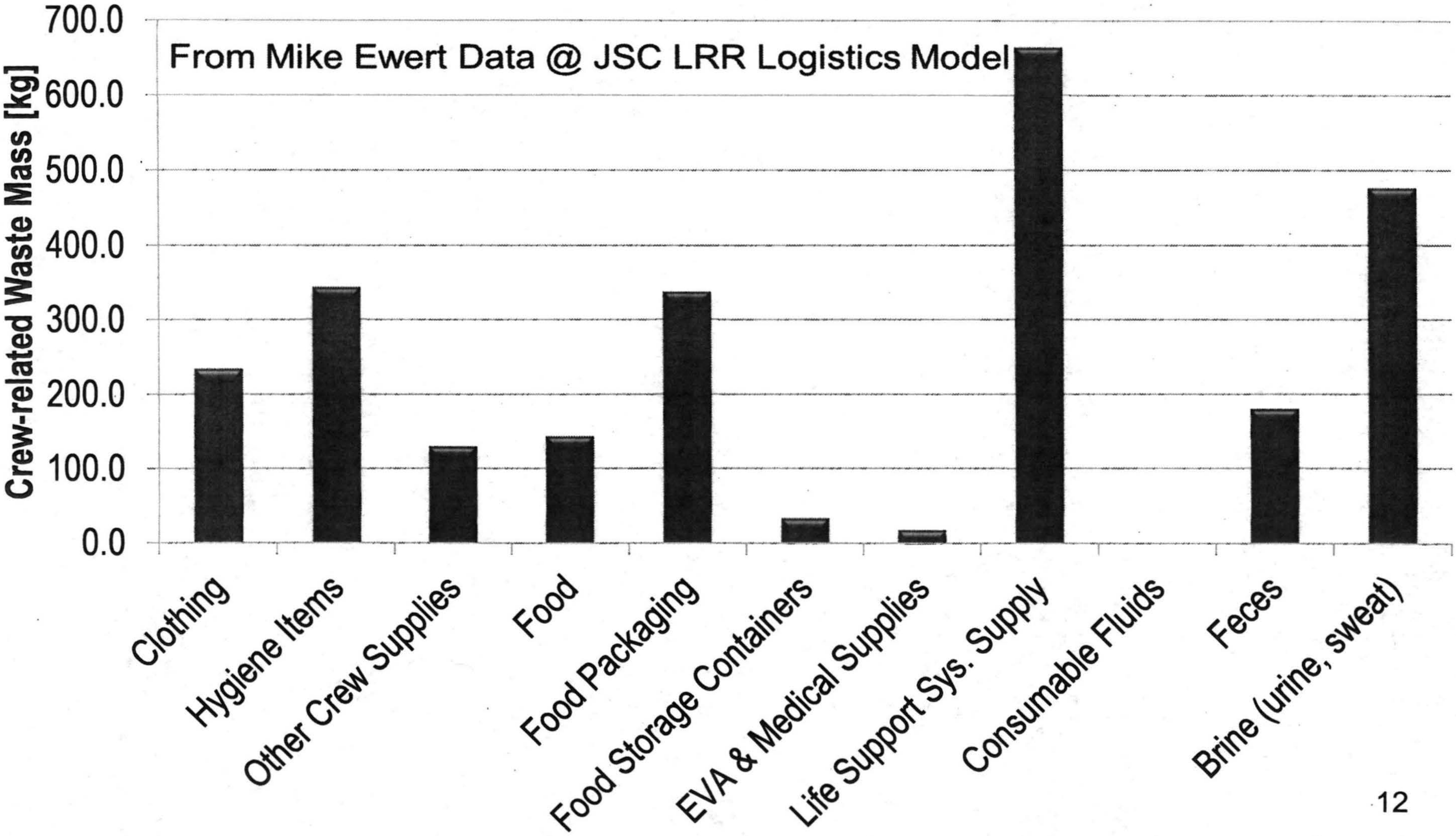
Waste Processing Objectives

- Propellant (methane)
- Environmental control and life support system gas (water and oxygen)
- ISRU/Utilizing resources wisely
- Volume reduction
- Resitojets

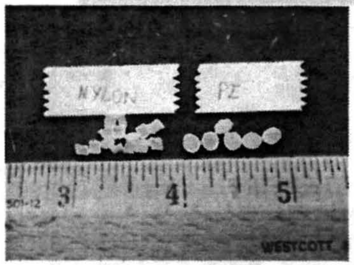
$$TRASH \rightarrow H_2O + CO_2 + Ash$$

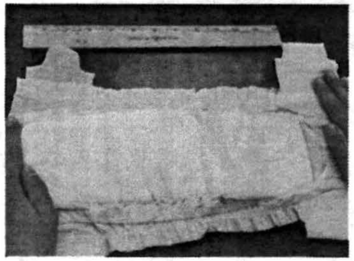
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

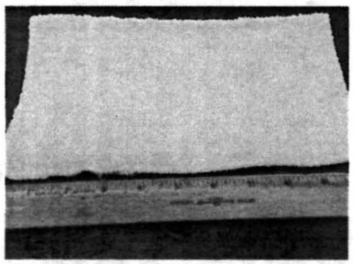
Waste produced by a crew of 4 on a 360 day exploration mission (by mass), ~2500kg/yr



Waste Simulants







Low Fidelity

- Polyethylene

Medium Fidelity

- Low Fidelity listed materials
- MAGs, (diapers with sodium polyacrylate)
- Combinations of Nylon, PET, Polyamide, Al
- Cotton towels

High Fidelity

- Medium Fidelity listed materials
- Simulated human wastes
- Simulated food wastes


Coffee
w/Cream & Sugar
ffee
w/Cream & Sugar

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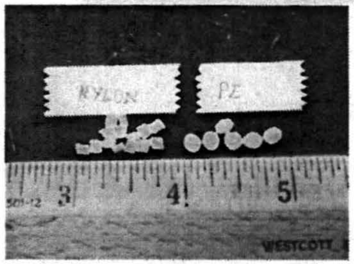
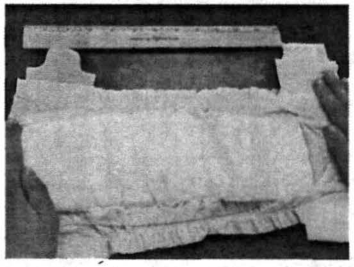
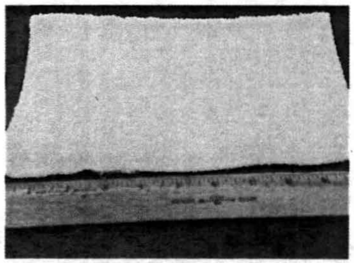
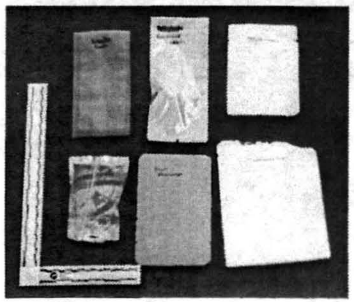
Waste Simulants









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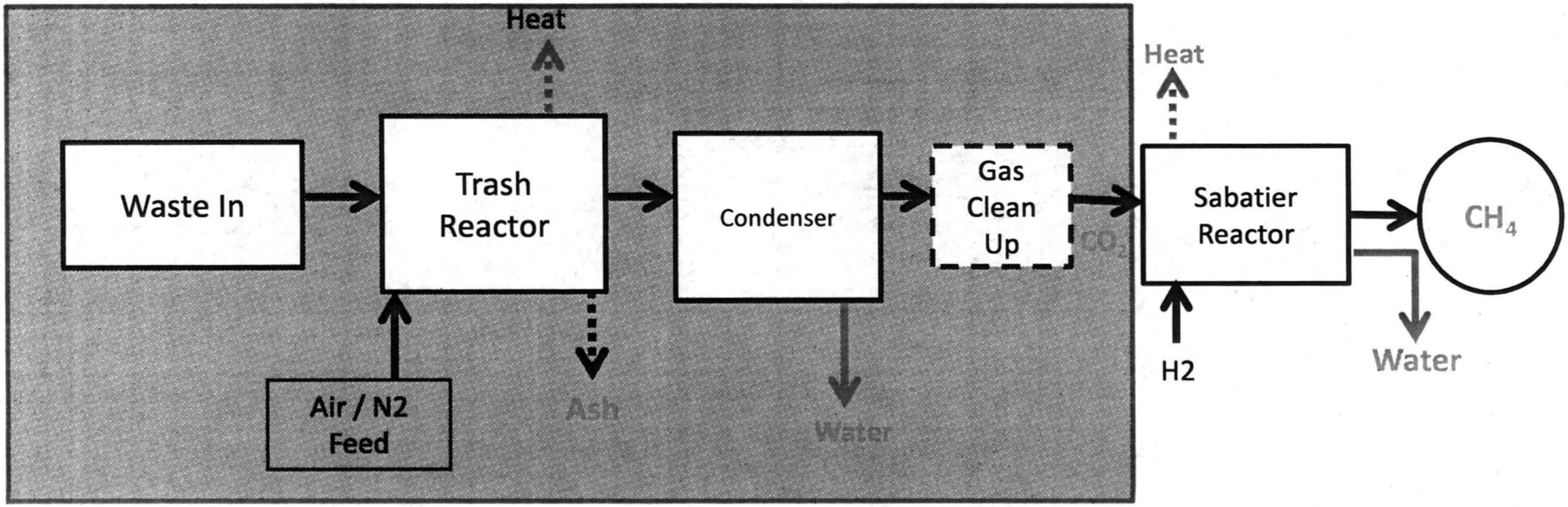
High Fidelity

- Medium Fidelity listed materials
- Simulated human wastes
- Simulated food wastes

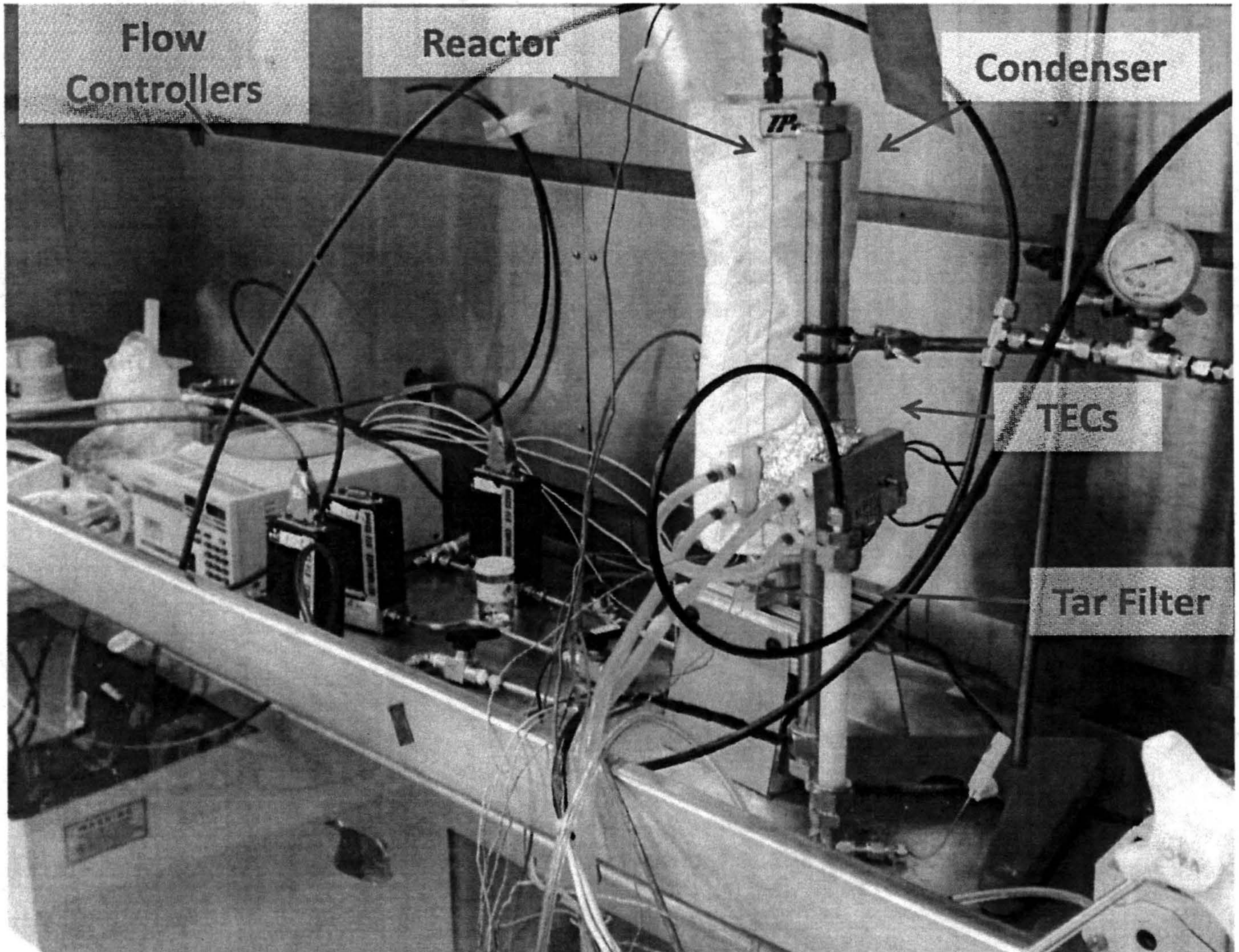
Flow Diagram



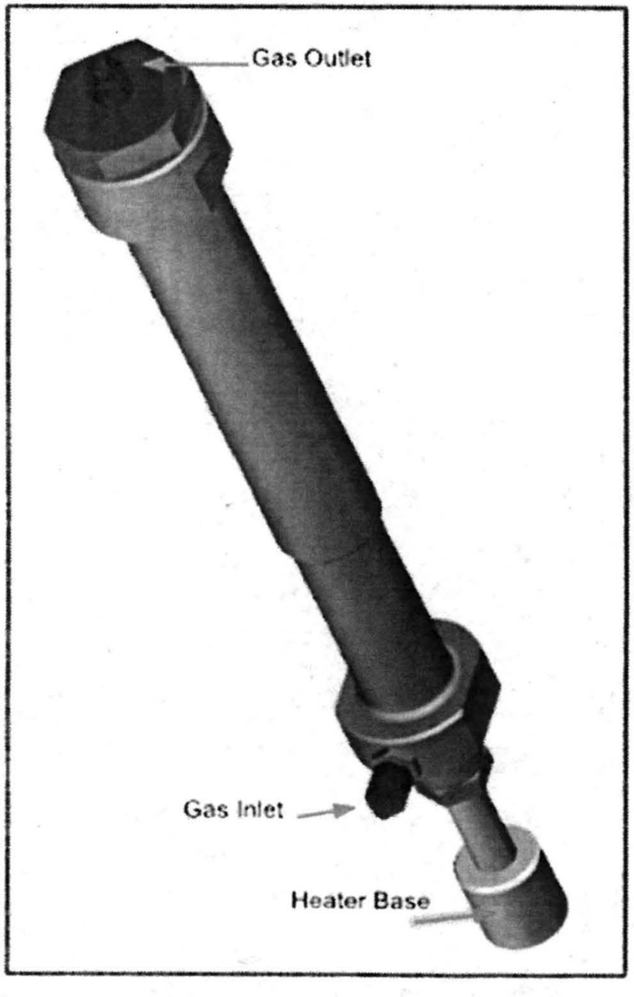
Trash → CO_2

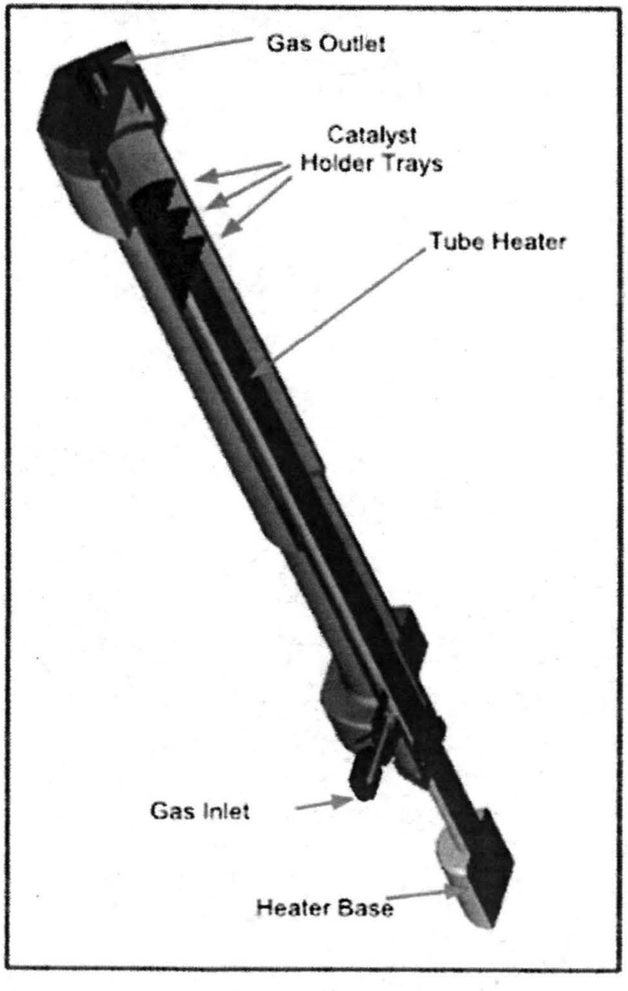
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

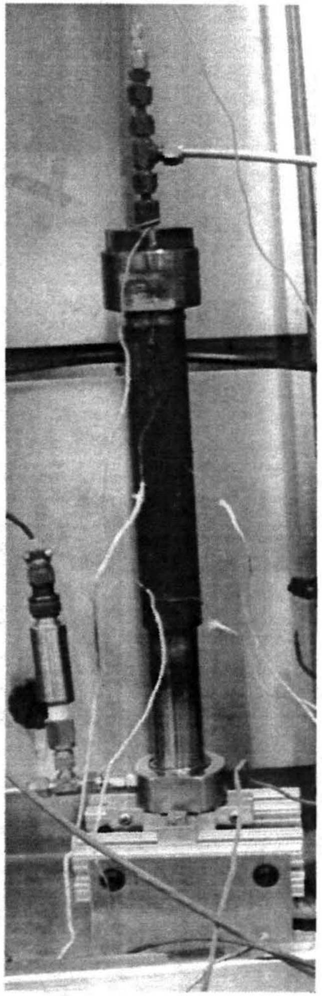
First Generation Reactor Lab Set Up



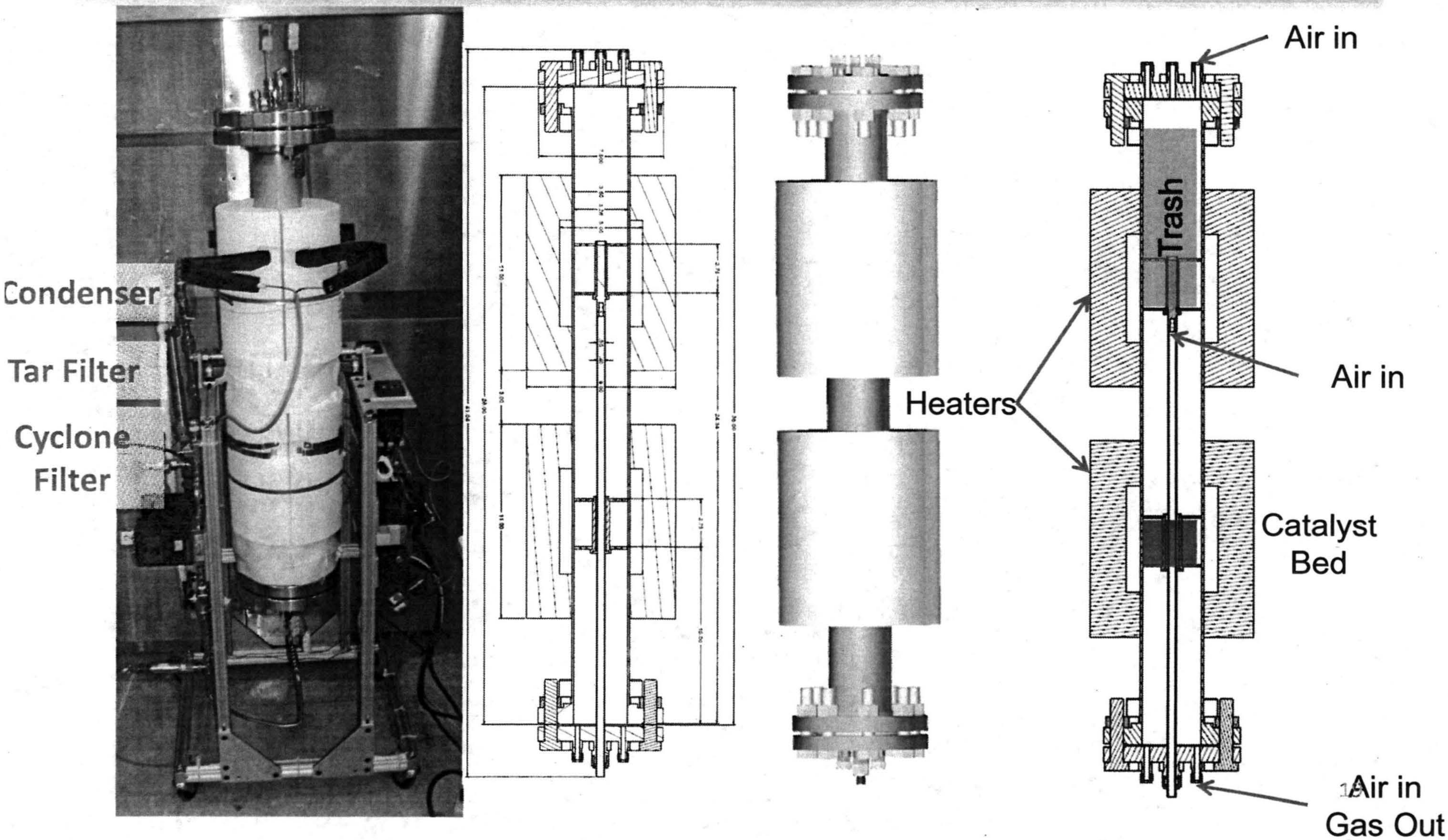
First Generation Reactor







Second Generation Reactor



Test Matrix

- Goal:
  - Maximize CO2
  - Minimize: Reaction time, consumables and power
- Variables
  1. Inlet Flow Rate
     - 1-5 SLM
  2. Inlet Gas Composition
     - $N_{2,}$ N_2/Air, Air
  3. Reactor Temperature
     - 1˚C/min, 10 ˚C/min, 50 ˚ C/min
  4. Waste Simulant
     - Low / Medium / High Fidelity

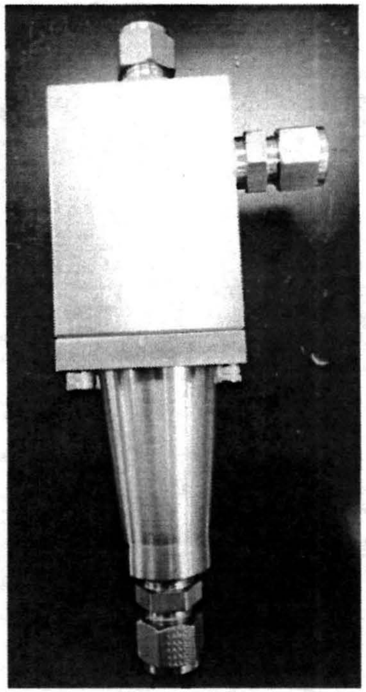
Test Matrix

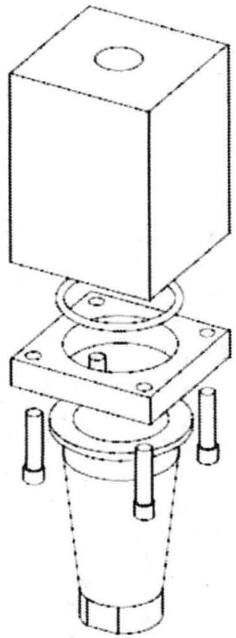
- Favored Test Conditions
  1. Inlet Flow Rate
     - 5 SLM
  2. Inlet Gas Composition
     - Air
  3. Reactor Temperature
     - Quickest Ramp to 500 - 600 °C
  4. Waste Simulant
     - High Fidelity

Products

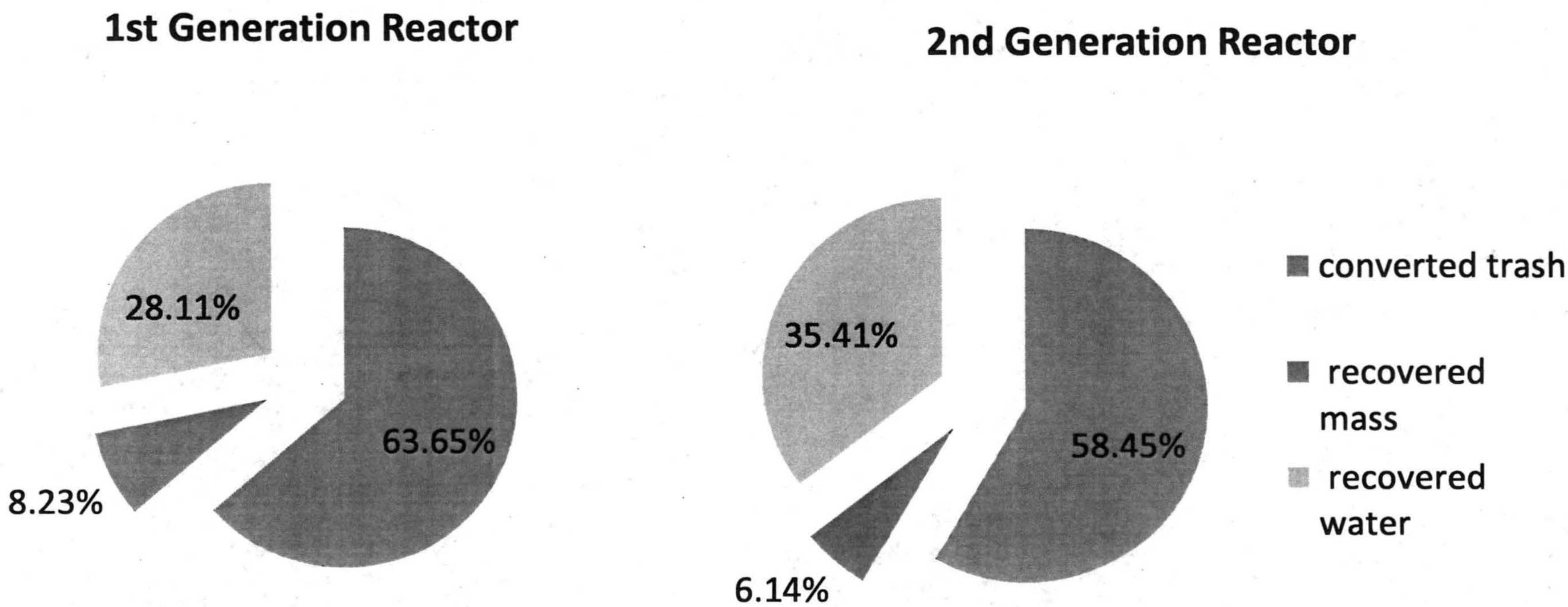
$TRASH \rightarrow H_2O + CO_2 + Al + Ash + Tars$

- Major Products
  - CO_2
- Minor Products
  - CO, CH_4, H_2O, C_2H_4, tar, and ash

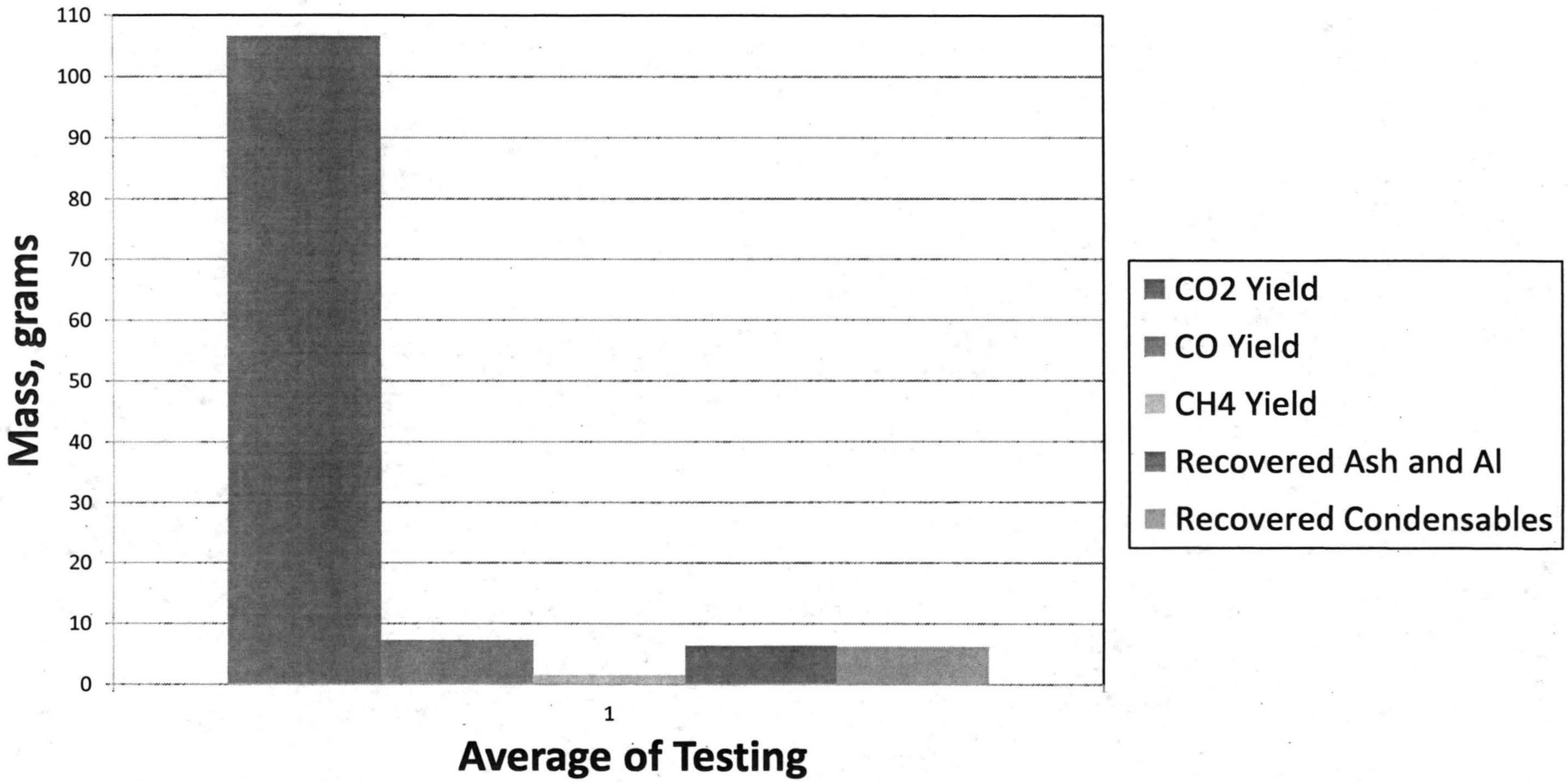




Trash Conversion



2nd Generation Reactor with Air: 5 SLPM and ~100g of trash



Water Analysis

Total Organic Carbon Analysis

Sample	Total Organic Carbon, (ppmC)
Tap Water	2.2
2nd Gen Reactor	33399
2nd Gen Reactor **with cyclone filter, granular activated carbon, heated tubes**	3949
2nd Gen Reactor with cyclone filter, granular activated carbon, heated tubes, **Dolomag catalyst**	2698

Microincinerator determined not flammable.

Elemental Analysis Results to come….

Production

PRODUCTS	AIR FEED (SLM)	1st Generation Reactor (~10g trash)	2nd Generation Reactor (~100g trash)
		kg/yr	kg/yr
CO_2	5	128.49	393.09
CO	5	15.59	26.83
THEORETICAL CH_4	5	46.75	143.03

According to *NASA's Exploration Systems Architecture Study* estimates, approximately 4,000 kg per year of O_2/CH_4 (mixture ratio of 3.6:1 by mass) propellant is needed for an ascent stage of a Lunar Exploration Mission.

Possible Theoretical Production

- 800 – 1500 kg of methane/year
- At current size not enough for this specific lunar ascent vehicle of LOX/CH4 propellant

Conclusions

- Thermal degradation of trash reduces volume while creating water, carbon dioxide and ash.
- CO_2 can be fed to Sabatier reactor for CH_4 production to fuel LOX/LCH4 ascent vehicle.
- Optimal performance: HFWS, full temperature ramp to 500-600˚C
- Tar challenges exist
- Catalysis: Dolomag did eliminate allene byproducts from the product stream.
- 2nd Gen Reactor Studies
  - Targeting power, mass, time efficiency
  - Gas separation,
  - Catalysis to reduce tar formation
  - Microgravity effects
- Downselect in August will determine where we should spend time optimizing the technology

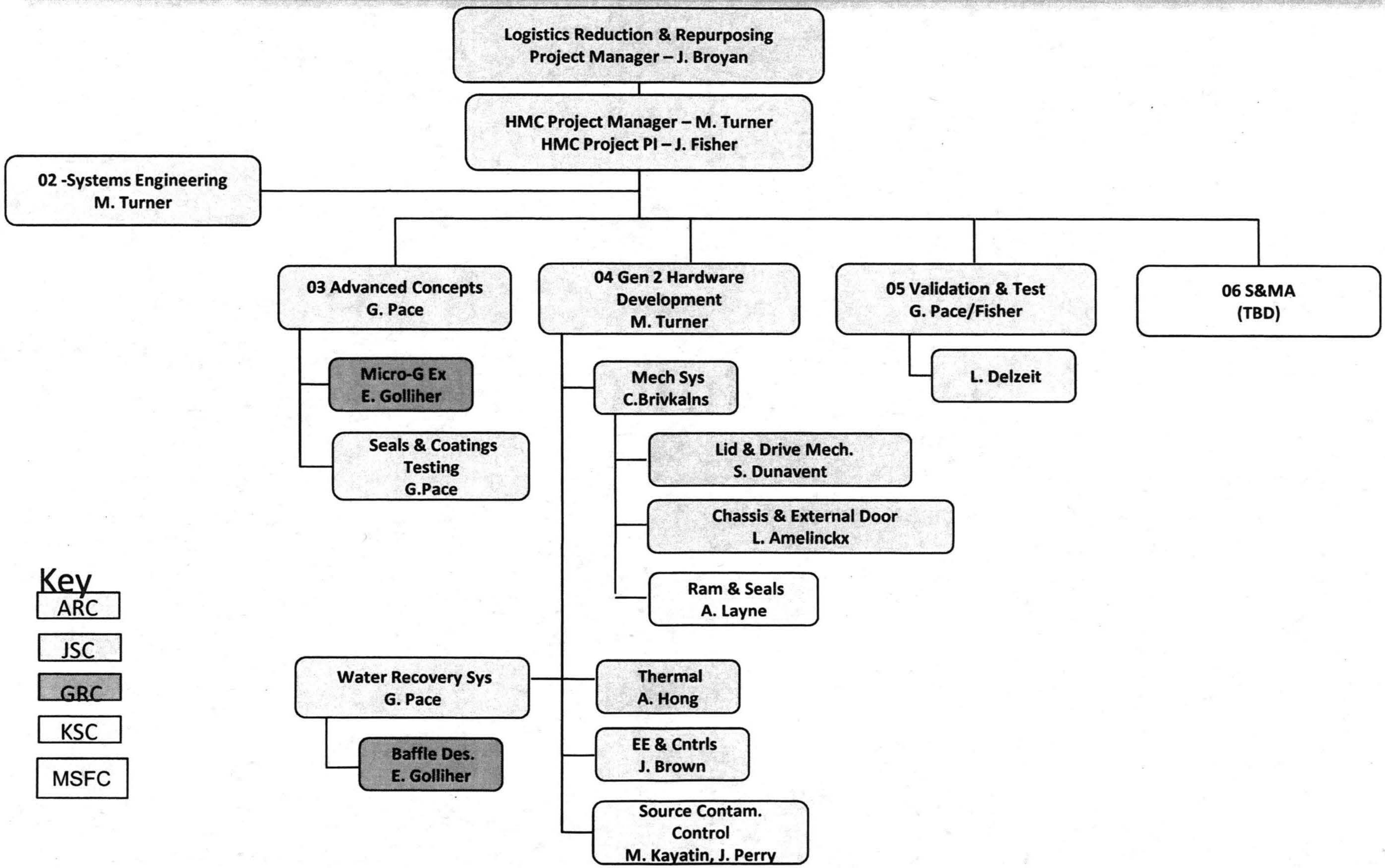

Logistical Reduction and Repurposing: Trash-to-Supply-Gas

Smashing Trash!

The Heat Melt Compactor.

Andrew Layne, NE-M2

HMC Project Organization

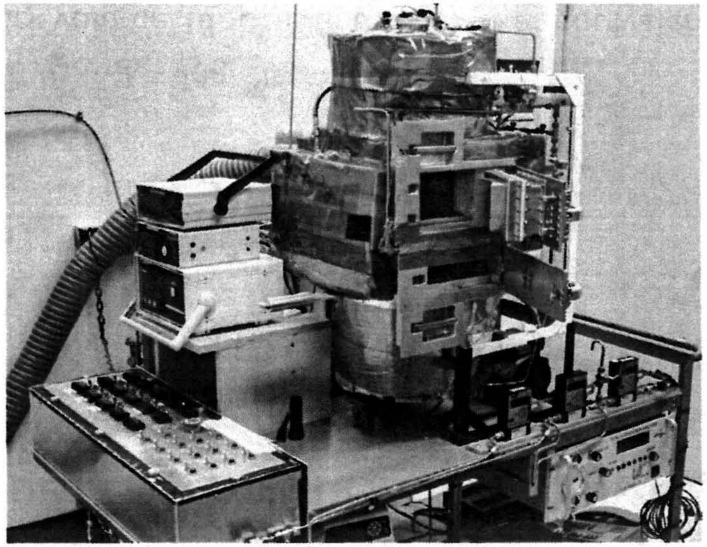


HMC Project Goals

- The project shall develop a prototype Heat Melt Compactor (HMC) for ground based experimentation that will:
  - ❑ Demonstrate the feasibility of compacting trash (10:1) into a sterile puck that can be used for radiation shielding.
  - ❑ Demonstrate the feasibility of compacting trash within the constraints of the ISS/express Rack environment
    - Power
    - Heat rejection
    - Acoustic limits
    - Human Factors
    - Safety – Toxicity/off-gassing/ flammability
    - ISS Express Rack volume (double middeck locker equivalent)

    Note: Future Deep Space Habitats have a high likelihood of being volume and resource constrained as well.

HMC History – Generation 1



HMC Generation 1.

2008 Final assembly and first testing

2009 Testing – volume reduction, water reduction, shuttle waste samples

2010 Converted to vertical orientation. Testing with brine. Technical design review.

2011 Prepared concept of operations. Rough ESM of ancillary hardware. Sterilization runs. Radiation tiles.

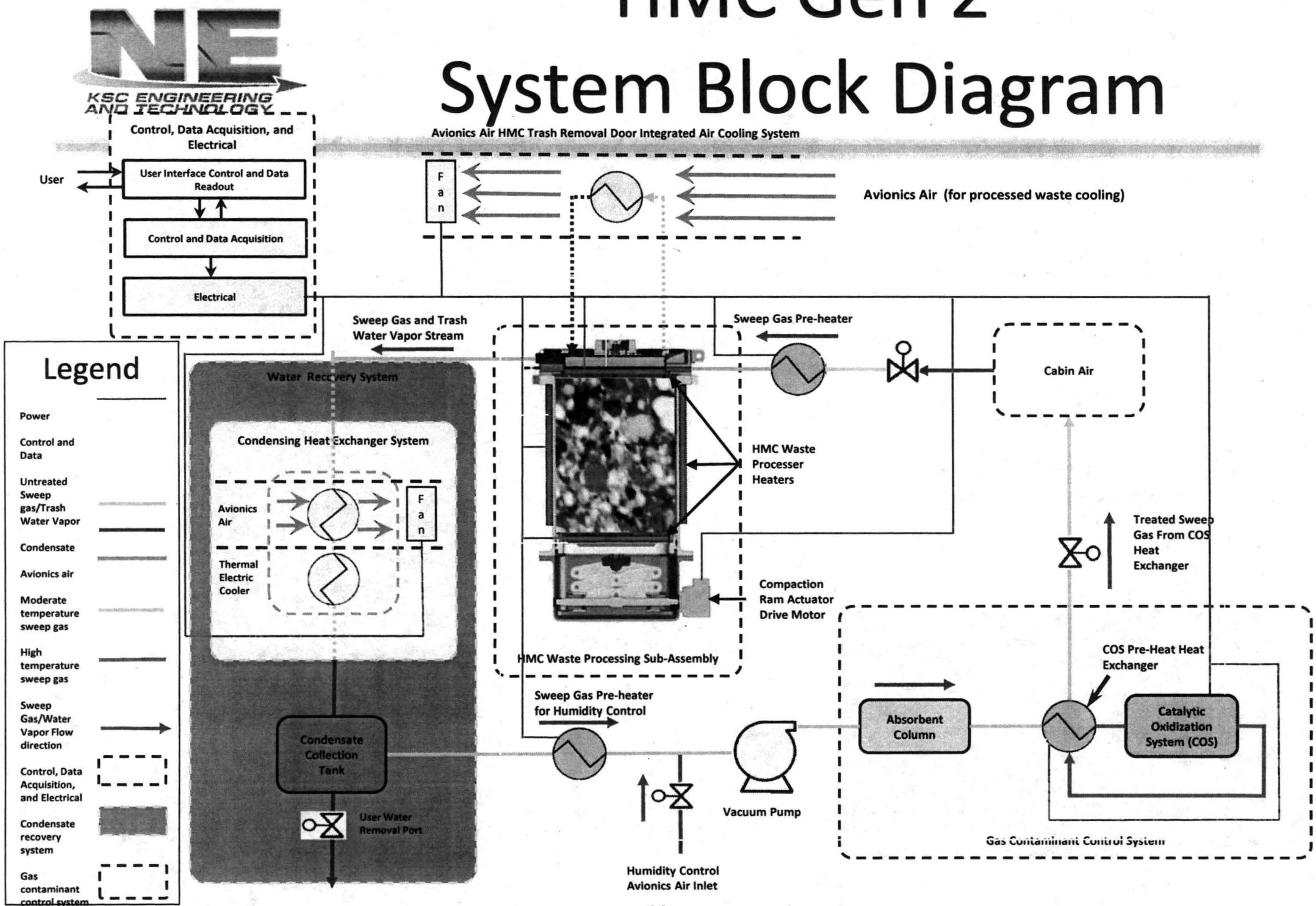
2012 More microbio analysis runs. Minicell foam testing.

2013 Functional limits tests. Gas characterization. Bio characterization. Squeeze tests.

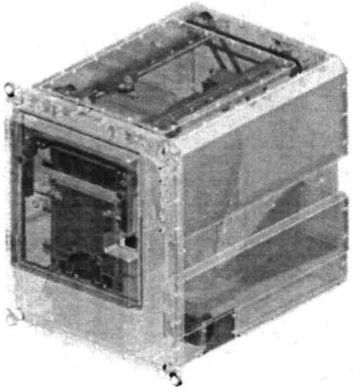
HMC Generation 2.

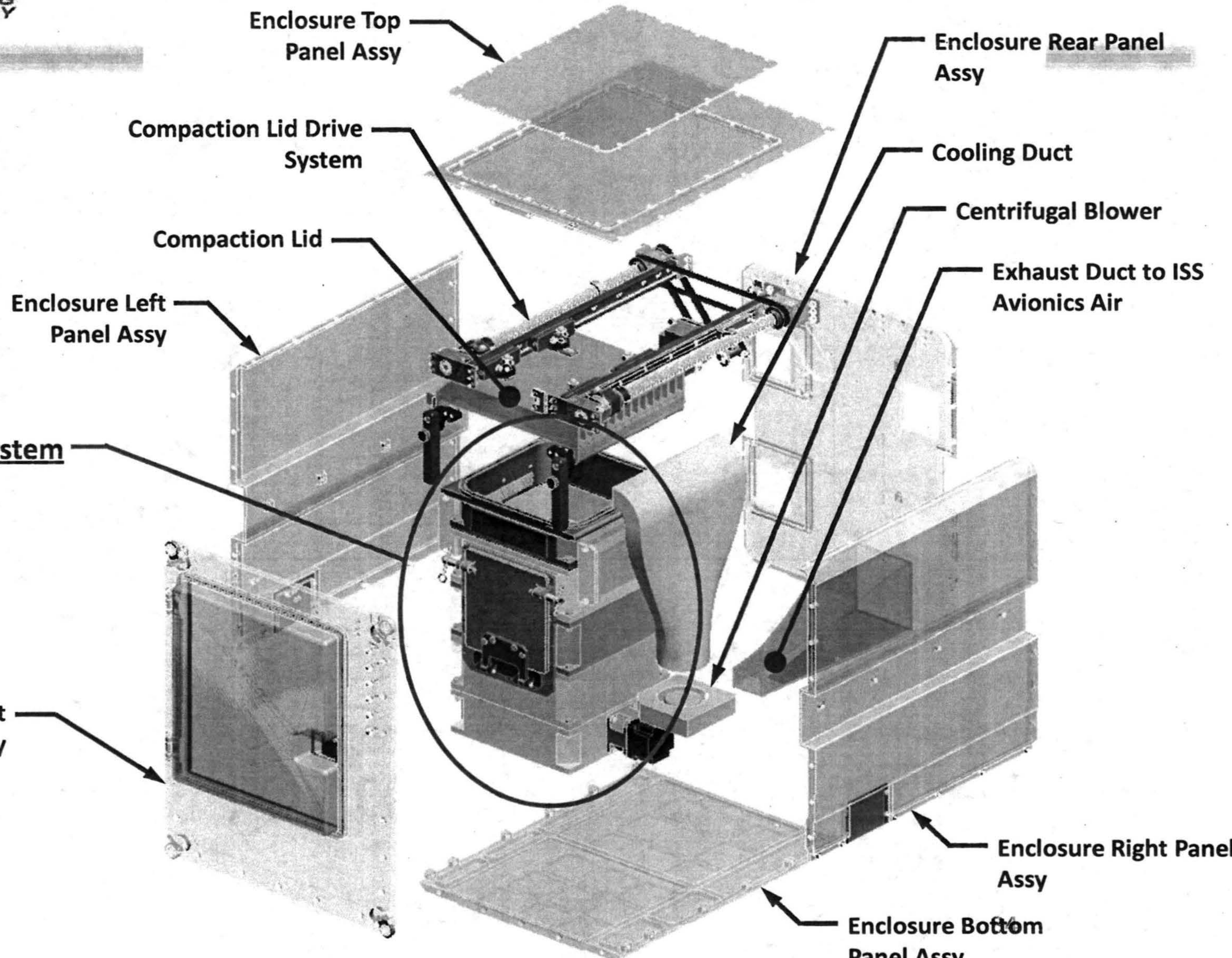
Solids contaminant control, Gas contaminant control, Water recovery, Control and Data acquisition system, Cooling.

HMC Gen 2 System Block Diagram

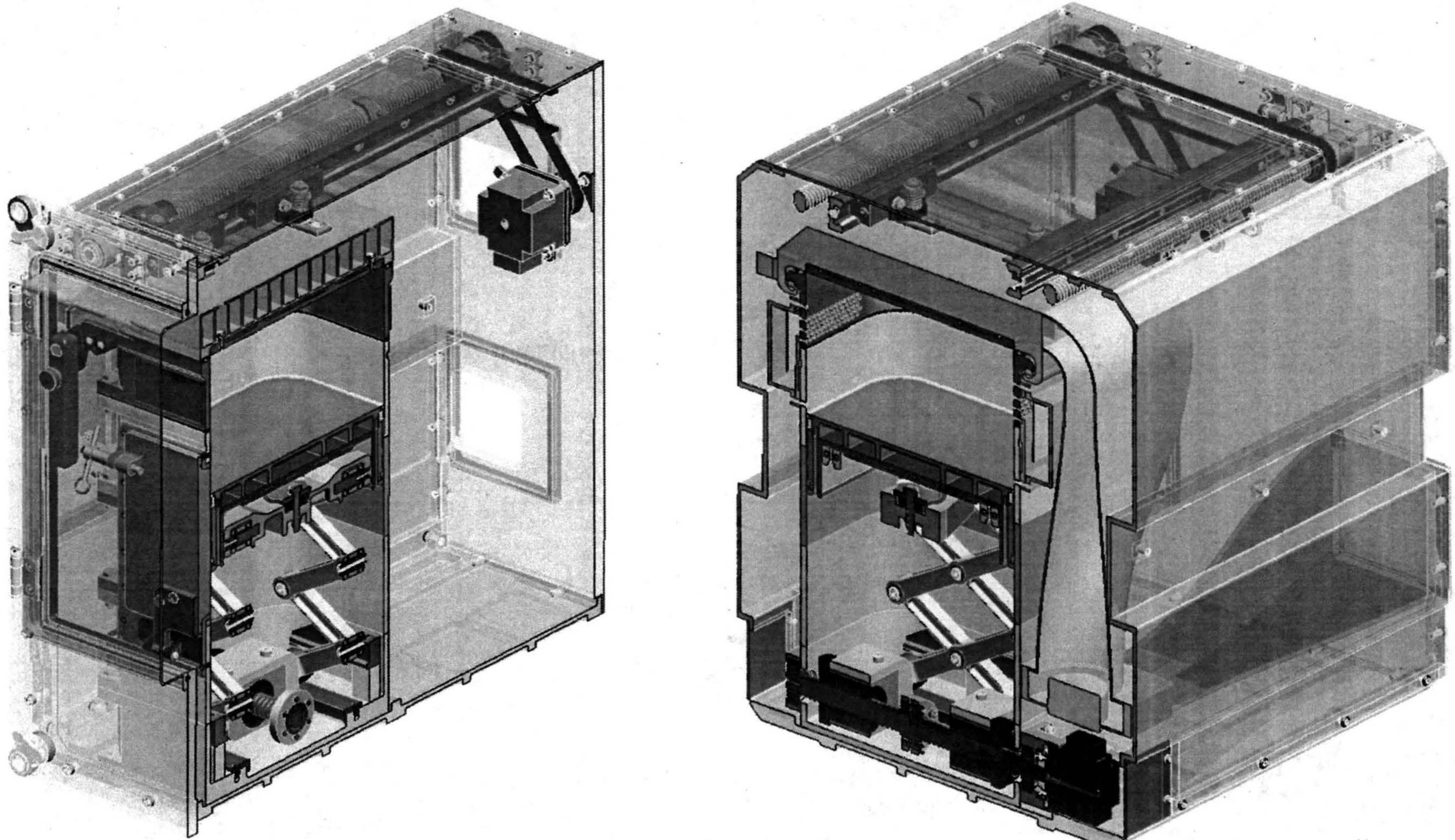


HMC Mechanical Systems Overview (1)





HMC Mechanical Systems Overview (2)



HMC SYSTEM SECTION VIEWS

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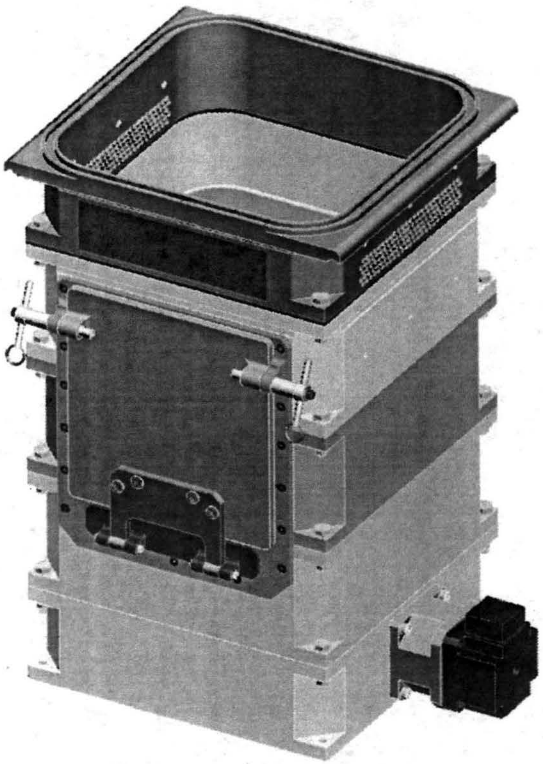
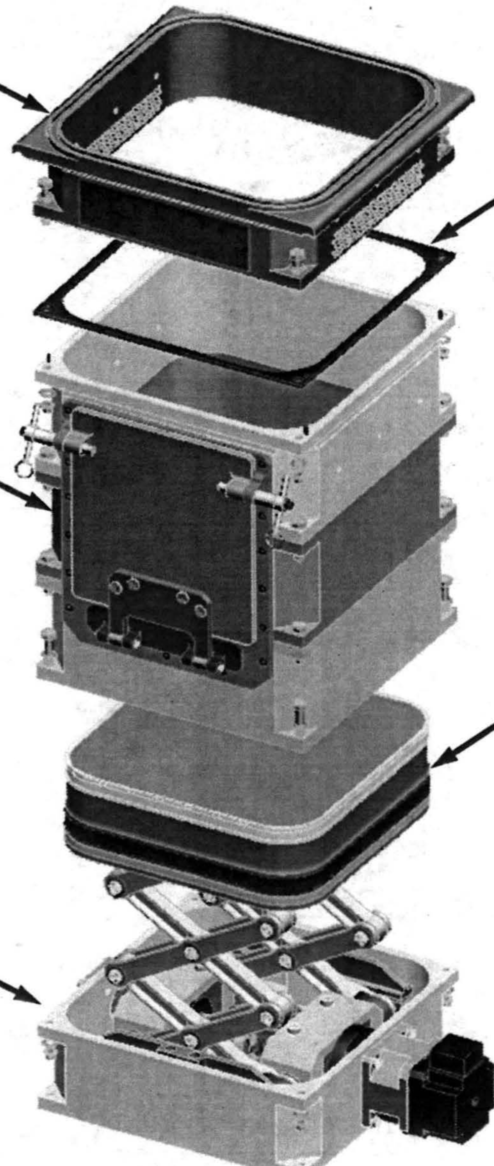
Compaction System



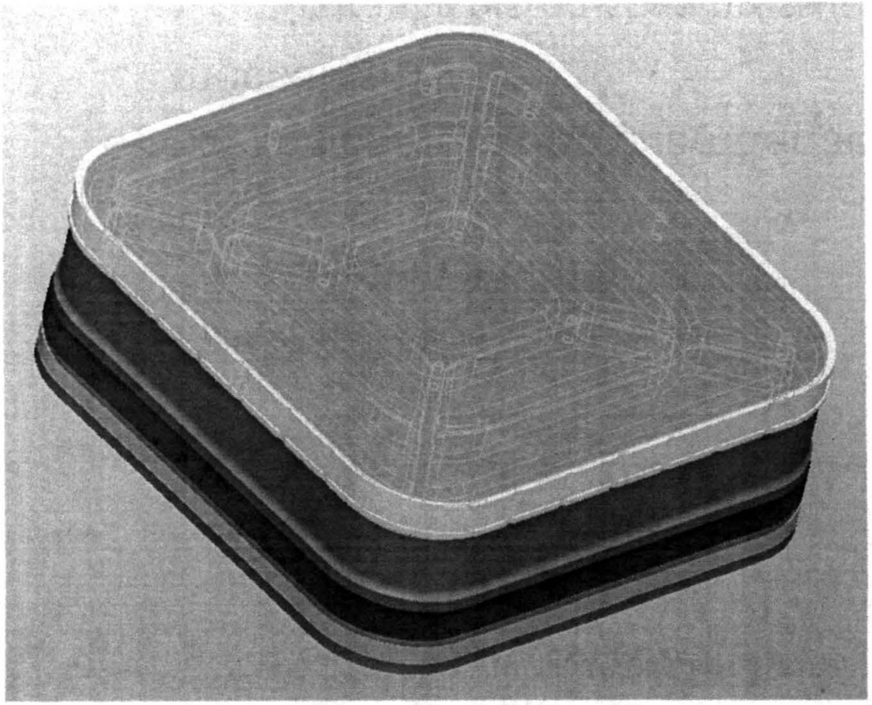


Ram Design - Requirements

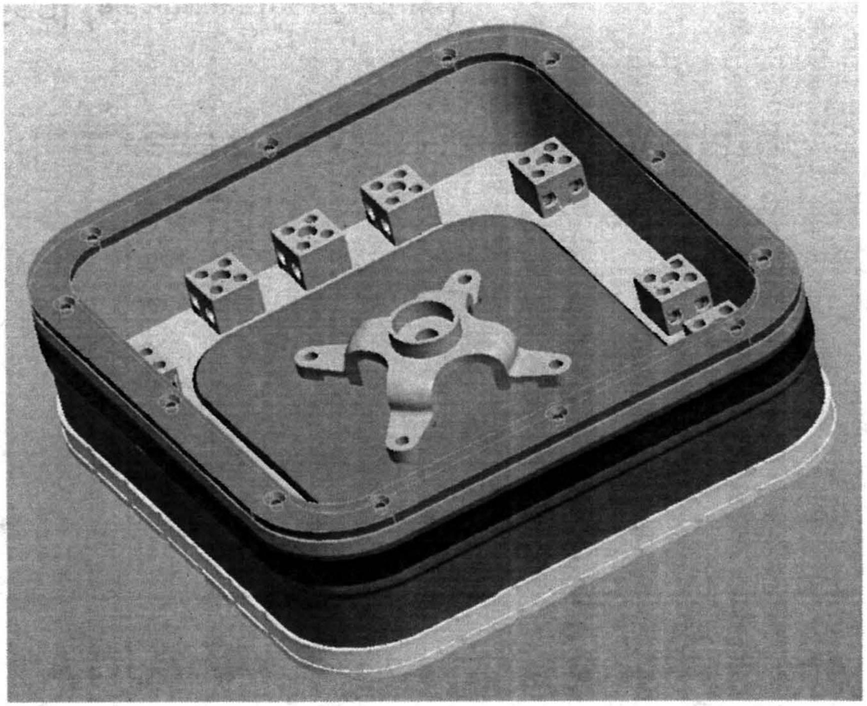
- Ram Requirements
  - Compacting trash
    - Max. Pressure: 182 psia (Based on blocked vapor pressure)
  - Heating trash
    - Max. Temperature: 375 F
  - Sealing compaction chamber and fluid recovery system from actuator mechanism.
    - Hydraulic piston-style pressure Seal (air and water effective)
  - Non-adhesion to trash products (food, molten plastic)
    - Scraper
    - Non-stick surface treatment

Ram Design

Overall Geometry



Front (trash) Side



Back (actuator) Side

Ram Assembly weight: 20.71 lbs

Ram Design – Materials

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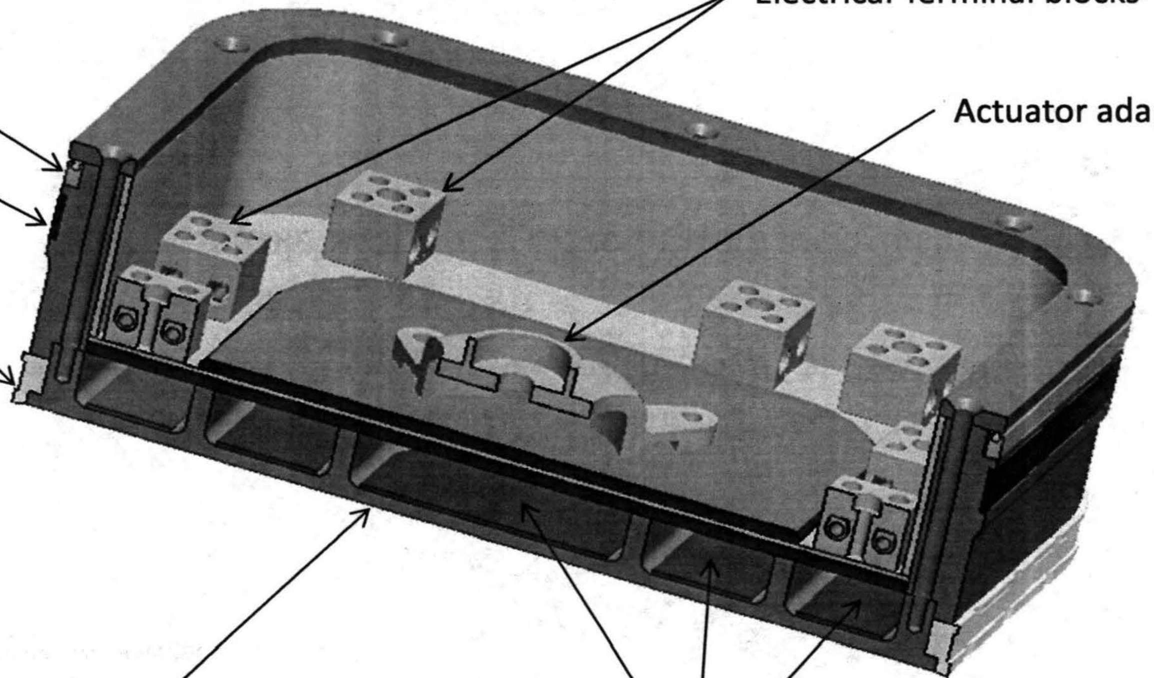
- Materials
- Ram Face-plate

  17-4 PH Stainless Steel – good strength and corrosion resistance. (Alum and Titanium strength down at temp.)
- Ram Skirt/Seal Retainer

  Stainless Steel compatible with face-plate and appropriate stiffness for supporting seals.
- Bearing Plates

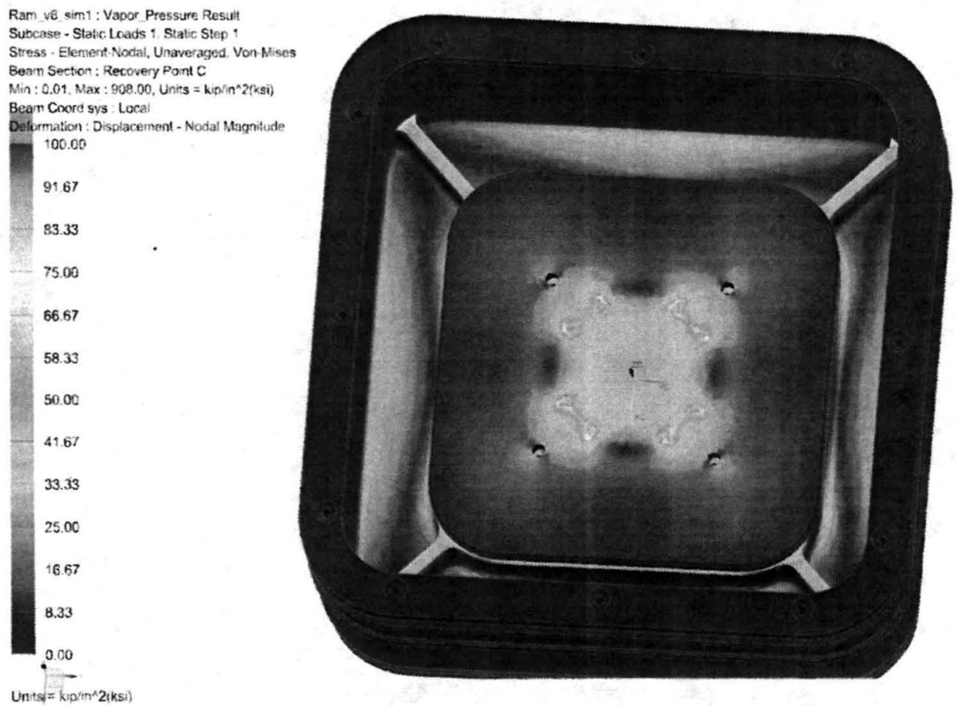
  Titanium – Weight reduction, compatible with actuator adapter.
- Seals (Custom machined by Parker Hannifin Corporation)
  - Scraper: PEEK
  - Wear-ring: PTFE
  - Pressure-seal: PTFE
- Heaters: Custom Silicone pad-heaters (OEM Heater)
- Sensors: RTDs supplied by OEM Heater

Ram Design – Operational Components



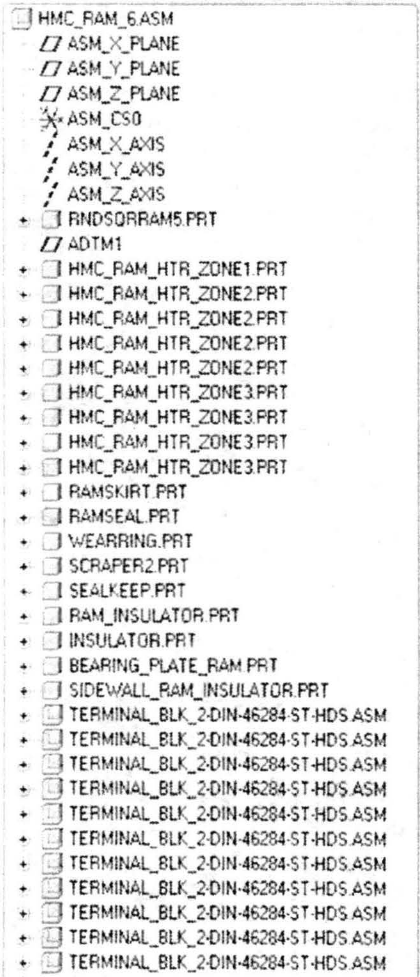
Ram Design - Analysis

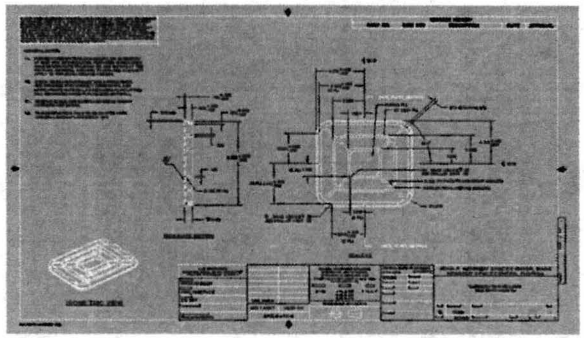
- Structural Analysis
  - Stress plot shown of von Mises Stress given 182 psi pressure load applied to ram surface and restrained at bearing plate and chamber walls.
  - Stainless steel modulus of elasticity used (28,012.6 ksi)
  - Analysis indicates stresses are below allowable.

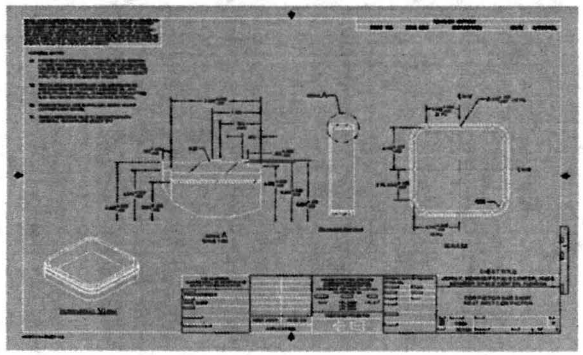


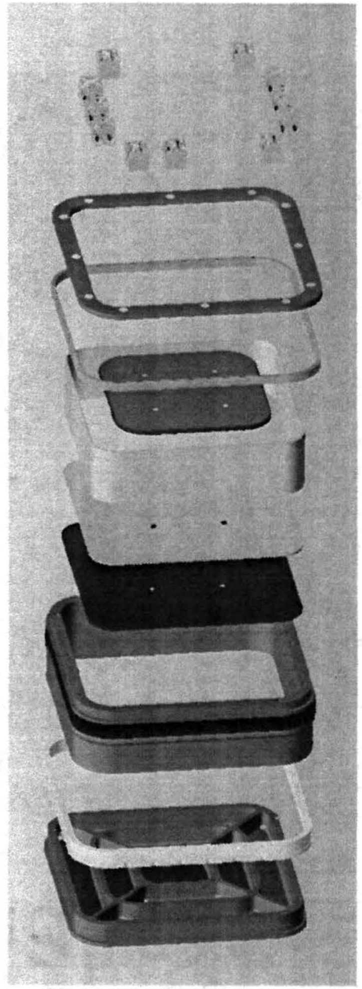
Material Properties Ph17-4 H1025 Plate (4 in thick or less)						
	Str @RM Temp (ksi)	Temp knock down @356F	Str @356F	FS	Allowable (ksi)	Allowable Evaluation
Yield Str-LT	145	0.8875	128.6875	1.25	102.95	Von Mises
Ultimate Str-LT	155	0.905	140.275	1.4	100.20	Max Principle

Parts & Assembly









Heat Melt Compaction as an Effective Treatment for Eliminating Microorganisms from Solid Waste

Mary P. Hummerick, Richard F. Strayer , Lashelle E. McCoy and Jeffrey T. Richards
Engineering Services Contract, Team QNA, Kennedy Space Center
Anna Maria Ruby and Ray Wheeler
NASA, Kennedy Space Center, FL 32899
John Fisher
NASA, Ames Research Center, CA

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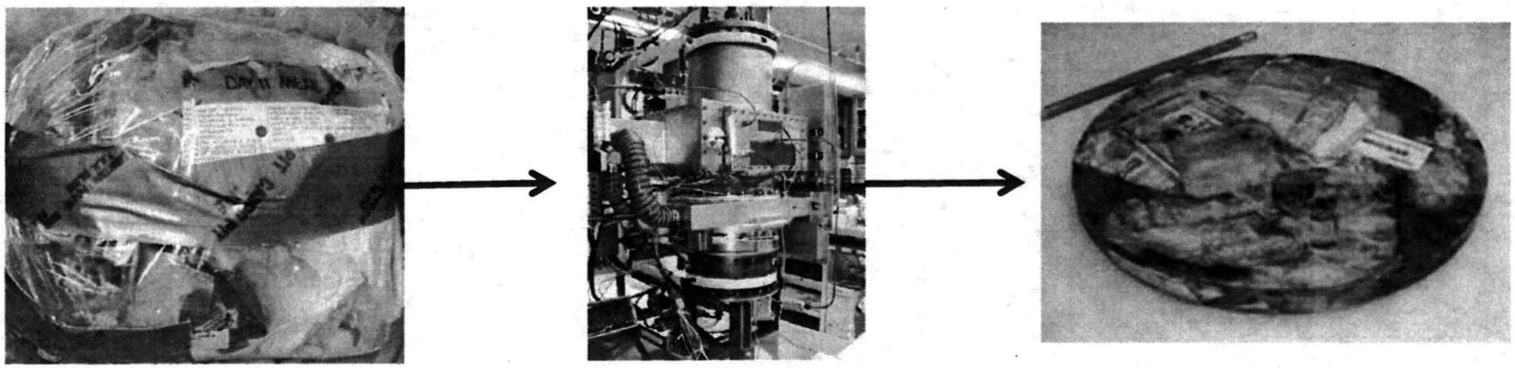
- One of the technologies being tested at NASA Ames Research Center (ARC) for the Advance Exploration Systems program and as part of the logistics and repurposing project is heat melt compaction (HMC) of solid waste.
  - Reduces volume, removes water and renders a biologically stable and safe product.
  - The HMC compacts and reduces the trash volume as much as 90% greater then the current manual compaction used by the crew.



Generated Wastes

- Approximately 1633 gm per crew member per day, 30-45% of that total being water.
- Many of the solid waste components are readily biodegradable organic materials such as food and human solid waste supporting the growth of microorganisms including potential human pathogens.
- Microbial metabolic by-products can also be generated causing unpleasant odors and accumulation of volatile organic compounds (VOCs).

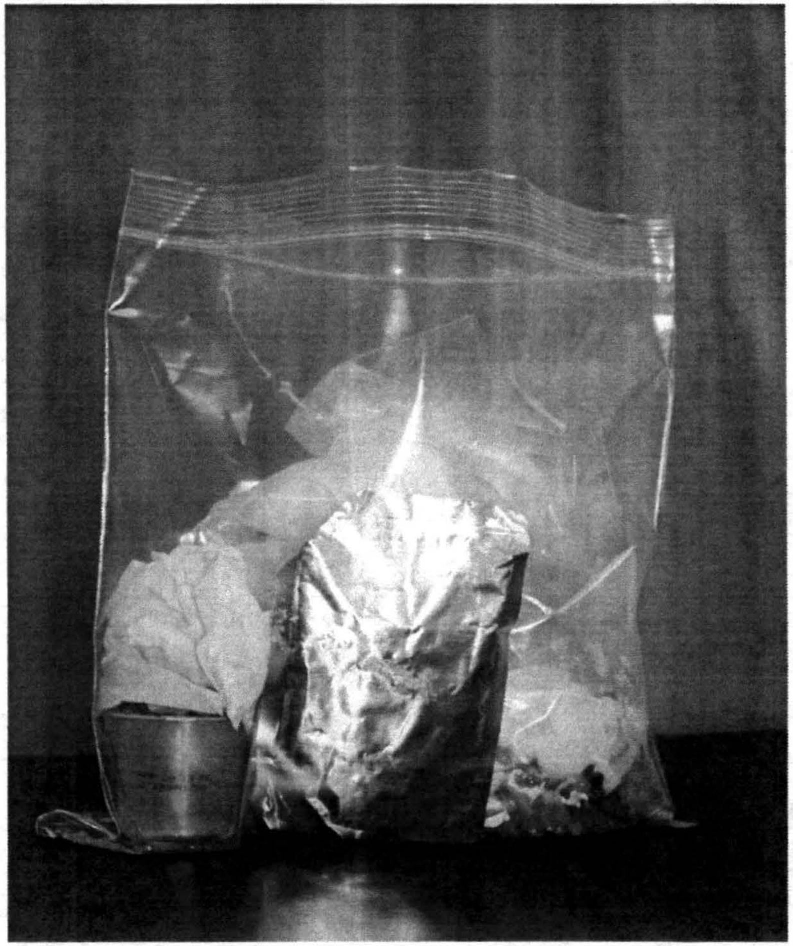
Objectives

The project has three primary objectives.

1. Microbiological analysis of HMC hardware surfaces before and after operation. Are there "cross-contamination issues".
2. Microbiological and physical characterization of heat melt tiles made from trash at different processing times and temperatures.
3. Long term storage and stability of HMC trash tiles or "Do the bugs grow back?"

Objectives 2 and 3.
Preparation of Inoculated Trash

- To perform studies on the survival of microorganisms in waste treated by HMC, waste was:
  - Prepared
  - Sterilized (ETO)
  - Inoculated with a know density of microorganisms that if survive, could be recovered and enumerated. Un-inoculated controls were included.



Inoculum Development

- Three microorganisms were tested for use as an appropriate inoculm.
  - *Bacillus amyloliquifaciens* a spore forming bacteria that has been recovered from shuttle trash,
  - *Rhodotorula mucilagenosa,* a yeast also recovered from shuttle trash
  - *Micrococcus luteus*, a gram positive bacteria commonly found in the environment.

- Bags of "sterilized" trash were inoculated in duplicate with 15 ml of each culture density (10^9, 10^8, 10^7) in 1 ml amounts into 15 different food items in the simulated/ersatz trash

Inoculum recovery

Colony counts (cfu/g of wet trash) from trash samples. Actual recovery is after 24 hr incubation at room temperature.

	Estimated recovery with no growth.			Actual recovery		
Inoculum	*B. amyloliquefaciens*	*M.luteus*	*R.mucilaginosa.*	*B. amyloliquefaciens*	*M.luteus*	*R.mucilaginosa.*
1.00E+09	2.20E+06	4.00E+05	3.00E+05	5.30E+06	3.22E+05	9.65E+05
1.00E+08	3.60E+05	6.60E+05	1.20E+05	1.91E+06	<1.61E+04	1.21E+05
1.00E+07	7.80E+04	3.00E+05	2.00E+05	3.00E+05	<1.69E+04	5.57E+04

- *M. luteus* was below detection from simulated trash samples inoculated with the two lower cell concentrations. *B. amyloliquefaciens* is known to produce bacteriocins and *M. luteus* is sensitive to these antimicrobial compounds.[4] For this reason we eliminated *M. luteus* from the inoculum mixture.

- The calculated recovery estimate assumes no growth during the 24 hr incubation period. Actual counts show an increase in bacterial and yeast numbers after 24 hours incubation at room temperature. Growth of bacteria and yeast during shipping can, thus, be expected.

Objective 1.
Hardware Surface Samples Results

- Varying degrees of microbial growth were found depending on the surface sampled.
  - Generally, the piston surfaces exhibited much lower microbial counts then the groove surface.
- Most of the bacterial species isolated are spore forming Bacillus species resistant to heat.
- Two of the organisms recovered from the surfaces of the compactor, *Bacillus amyloliquefaciens* and *Rhodotorula mucilaginosa* are the organisms used to inoculate the trash for the long term storage studies.

Tile #	Surface	Bacteria	Fungi
10 DL	Comp.Piston	Bacillus amyloliquefaciens[a]	
	Rear Piston	Bacillus subtilis subtilis ATCC=6051	
	Groove	B. amyloliquefaciens	R. mucilagenosa[a]
		B. subtilis subtilis ATCC=6051	Phyllosticta maydis
11 DL	Rear Piston	S. capitis capitis ATCC=27840	Cladosporium cladosporoides
		S. epidermidis	
		S. lugdunensis	
		B. subtilis subtilis ATCC=6051	
		Strep. Salivarius	
	Groove	B. subtilis subtilis ATCC=6051	
		Bacillus atropheus[b]	
12 DL	Wall	B. amyloliquefaciens[a]	None
	Rear Piston	B. amyloliquefaciens[a]	
		B. subtilis subtilis ATCC=6051	
13 DL	None	None	None
7M	Comp. Piston	B. amyloliquefaciens[a]	None
		Bacillus pumilus	
	Wall	B. amyloliquefaciens[a]	
		B. pumilus	
	Rear Piston	B. atropheus[b]	
		Curtobacterium flaccumfaciens	
	Groove	B. subtilis subtilis ATCC=6051	
		Strep. cristatus	
8M	Comp. Piston	B. amyloliquefaciens[a]	None
	Wall	B. amyloliquefaciens[a]	

[a]Organism used for inoculation. [b]BI test strip organism

Objectives 2 and 3. Tile Processing and Sampling

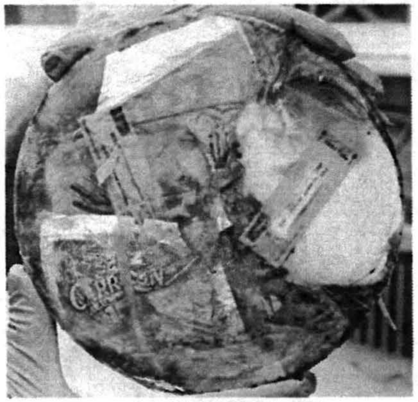


Figure 1. HMC tile showing excised spore strips (arrows).

- BI test strips (NAMSA, Northwood, Ohio) were incorporated into the trash before compaction to test the efficacy of the HMC process in the reduction or elimination of microorganisms

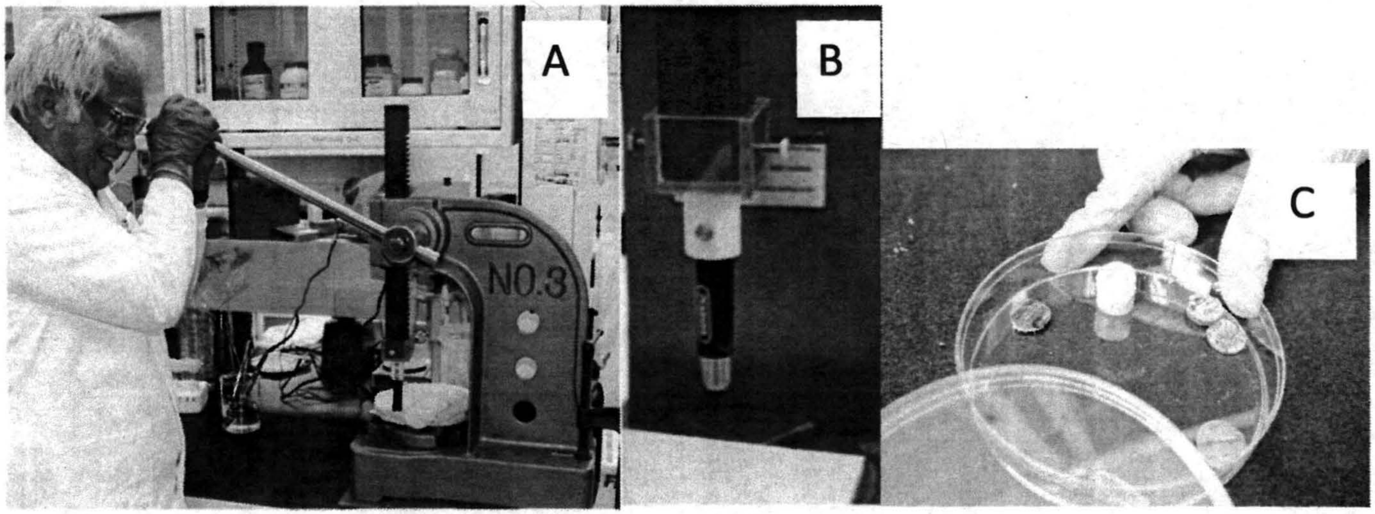


Figure 2. Picture A shows sample procedure using hand press with ½ inch hole punch (B) resulting in a core sample (C).

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Objective 2. Process Parameters

- Simulated, trash was used as the HMC feed to produce the tiles for this study.
- Process parameters (time and temperature) used in these experiments were 130°C for 2 hours, 140°C for 2 and 3 hours and 180°C for 2 hours as determined and processed by ARC investigators.

Process Time and Temperature Studies

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Results of microbial analyses and some physical parameters for core samples cut from HMC product tiles treated at different time and temperature regimes (130° C or 140° C)						
HMC tile number HMC process temperature HMC process duration	10 130°C 2 hrs	11 140°C 2hrs	12 140°C 3hrs	13 130°C 2hrs	7m 140°C 2hrs	8m 140°C 2hrs
Weight loss (%)	24	25	19	16	14	19
Core sample growth	4/10	1/10	6/10	3/10	3/10	5/10
G. stearothermophilus +	3/3	0/2	0	0	NA	NA
B. atrophaeus +	4/4	3/4	0	0	NA	NA
Sterilization time (hrs)	.49	.54	1.5	.54	.52	.52

- Weight loss possibly indicating a loss of water, was inconsistent with temperature treatments.
- Both sets of BI test strips from tile 10 grew after treatment and core samples showed the most diverse growth with the isolation and identification of 9 different species. This tile was subjected to the lowest temperature and shortest sterilization time.

Process Time and Temperature Studies – Microbiology Results

Bacteria and fungi isolated and identified from tile core samples cut from HMC product tiles treated at different time and temperature regimes (130° C or 140° C)					
Tile 10 130°C 2 hrs	Tile 11 140°C 2hrs	Tile 12 140°C 3hrs	Tile 13 130°C 2hrs	Tile 7m 140°C 2hrs	Tile 8m 140°C 2hrs
Brevibacillus agri , *B. subtilis subtilis* *Staphylococcus pasteuri* *Kocuria kristinae* *S. epidermidis* *Streptococcus salivarius* *Bipolaris micropus* *Chaetomium atrobrunneum*	*Penicillium rubrum*	*Neisseria flavescens* *Penicillium chrysogenum,* *Epicoccum nigrum*	*Brachybacterium rhamnosum* *Streptococcus oralis* *Streptococcus mitis* *Streptococcus salivarius*	*Bacillus oleronius* *Moraxella osloensis*	*Penicillium chrysogenum* *Sphingomonas sanguinis*

Objective 3.
Long Term Storage Studies

- HMC processing time and temperature used for the tiles prepared for this study was 180°C for 2 hours and 40 minutes.
- Four time points or storage durations, 0, 45 ,63 and 65 days at ISS like storage conditions (25°C, 50% RH and 3500 ppm CO_2,) were tested for the recovery of the bacterial/yeast inoculant, CO_2, and O_2.
- It was decided to include a study using a longer duration (3.5 hours) at 150° C

Long Term Storage

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Results of microbial analyses and some physical parameters for core samples cut from HMC product tiles (180 C , 2hrs, 40 mins).					
Storage duration (days) and tile number	Uninoc. Control, T=0 (1m)	Inoc. T=0 (3 m)	Inoc.T=45 (4 m)	Inoc. T=63 (5 m)	Inoc. T=65 (6 m)
Weight loss (%)	23	25	30	28	29
Core samples showing growth	7/10	10/10	3/10	4/10	5/10
R. mucilaginosa recovery	Not inoculated	NEG	NEG	POS	NEG
B. amyloliquifaciens recovery	Not inoculated	NEG	NEG	POS	NEG

- Data from tiles 3m-6m indicate incomplete sterilization and survival of bacteria and fungi up to 65 days.
- In processing these tiles, the actual sterilization time (time in which the interior of the tile reached sterilization temperatures) varied.

Long Term Storage Microbiology Results

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Bacteria and fungi isolated and identified from tile core samples cut from HMC product tiles stored for different periods. (180 C , 2hrs, 40 mins).				
Uninoc. Control, T=0 (1m)	Inoc. T=0 (3m)	Inoc.T=45 (4m)	Inoc. T=63 (5 m)	Inoc. T=65 (6m)
No IDs	*Bacillus soli* *B.thuringiensis* *B. alkalitelluris* *P. agaridevorans* *B. megaterium* *B. niacini*	*B.thuringiensis* *Strep. mitis* *Cladosporium cladosporoides* *Penicillium chrysogenum*	*B. amyloliqufaciens*[a] *Strep. mitis* *Strep. salivarius* *Veillonella dispar* *Strep. Parasanguinis* *Neisseria flavescens* *R. mucilagenosa*[a] *P. chrysogenum*	*Strep. Salivarius* *Bacillus mojavensis*
[a]**Organisms used for inoculation.**				

Tile 5, which was in storage for 63 days is the only tile in which we were able to recover the inoculants, *B. amyloliquifaciens and R. mucilaginosa*.

Results of microbial analysis and some physical parameters for core samples cut from HMC product disks. (150° C, 3.5 hrs)			
Treatment and disk number	13M	14M	15M
Weight loss (%)	12%	22%	13%
Core samples showing growth	0/0	0/0	0/0
B. atrophaeus spore strips (Top)	neg	neg	neg
G. stearothermophilis spore strips (Top)	neg	neg	neg
B. atrophaeus spore strips (Bottom)	neg	neg	neg
G. stearothermophilis spore strips (Bottom)	neg	neg	neg
B. atrophaeus spore strips (Middle)	neg	neg	neg
G. stearothermophilis spore strips (Middle)	neg	neg	neg
***R. mucilaginosa* recovery**	neg	neg	neg
***B. amyloliquifaciens* recovery**	neg	neg	neg

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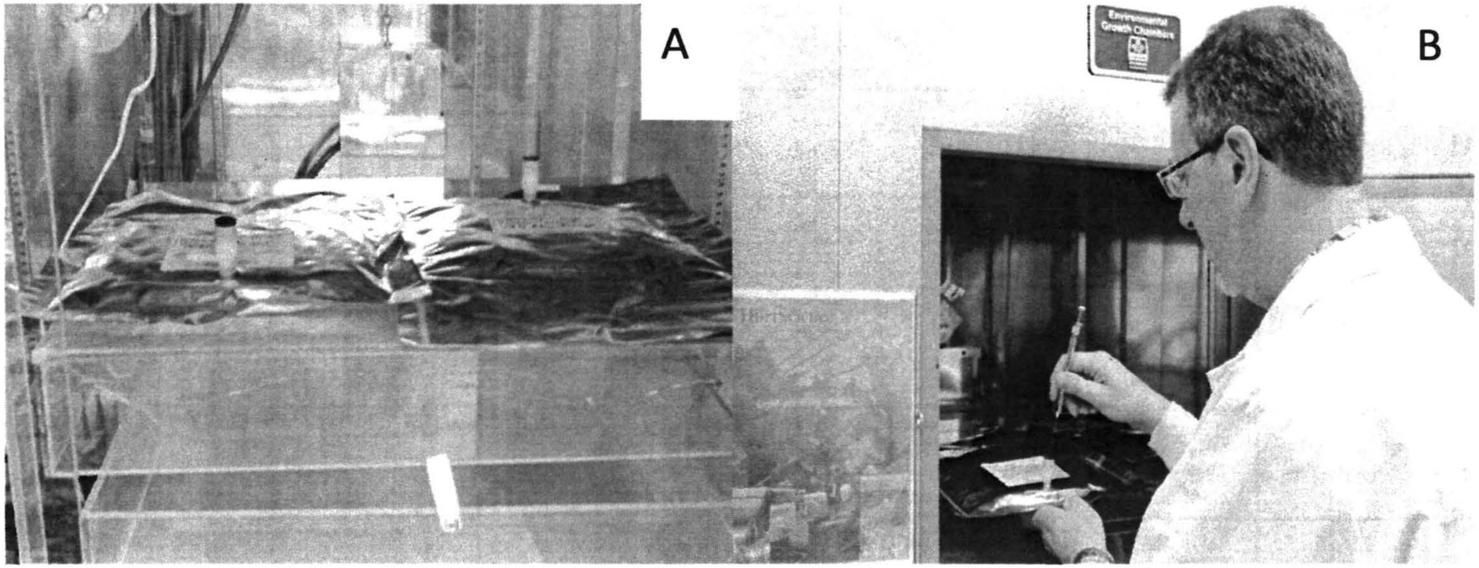
Gas Sampling and Analysis of HMC Tiles



Storage bags used to store HMC prepared tiles. Picture A shows the bags inside the chamber. B shows samples being taken for gas analysis.

No biological activity as indicated by an increase in CO_2 could be detected.

A number VOCs were detected even after 200 days of storage.

Conclusions

- The process of heat melt compaction of ersatz solid waste was tested for it's ability to sterilize the waste and render a biologically stable tile.
- Our analysis showed that organisms inoculated into the waste, *B. amyloliquefaciens* and *R. mucilaginosa* could not be detected in all but one tile after compaction at 180ºC.
- Treatment at 150ºC for 3.5 hours achieved sterility as determined by our testing.
- Finding viable organisms in the core samples of the HMC produced tiles seems contradictory to the negative growth results from the BI spore strips.
  - Heating and exposure to sterilization temperatures in the interior of the tile may be inconsistent so sterilization may not be achieved through the entire tile. Results from tile 5m suggest this possibility, since the organisms in the original inoculum were recovered.
  - Another possibility is post-HMC treatment contamination of the tiles and the ability of the tile components to support microbial life.

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Thank you for attending!

Do you have any questions for us?

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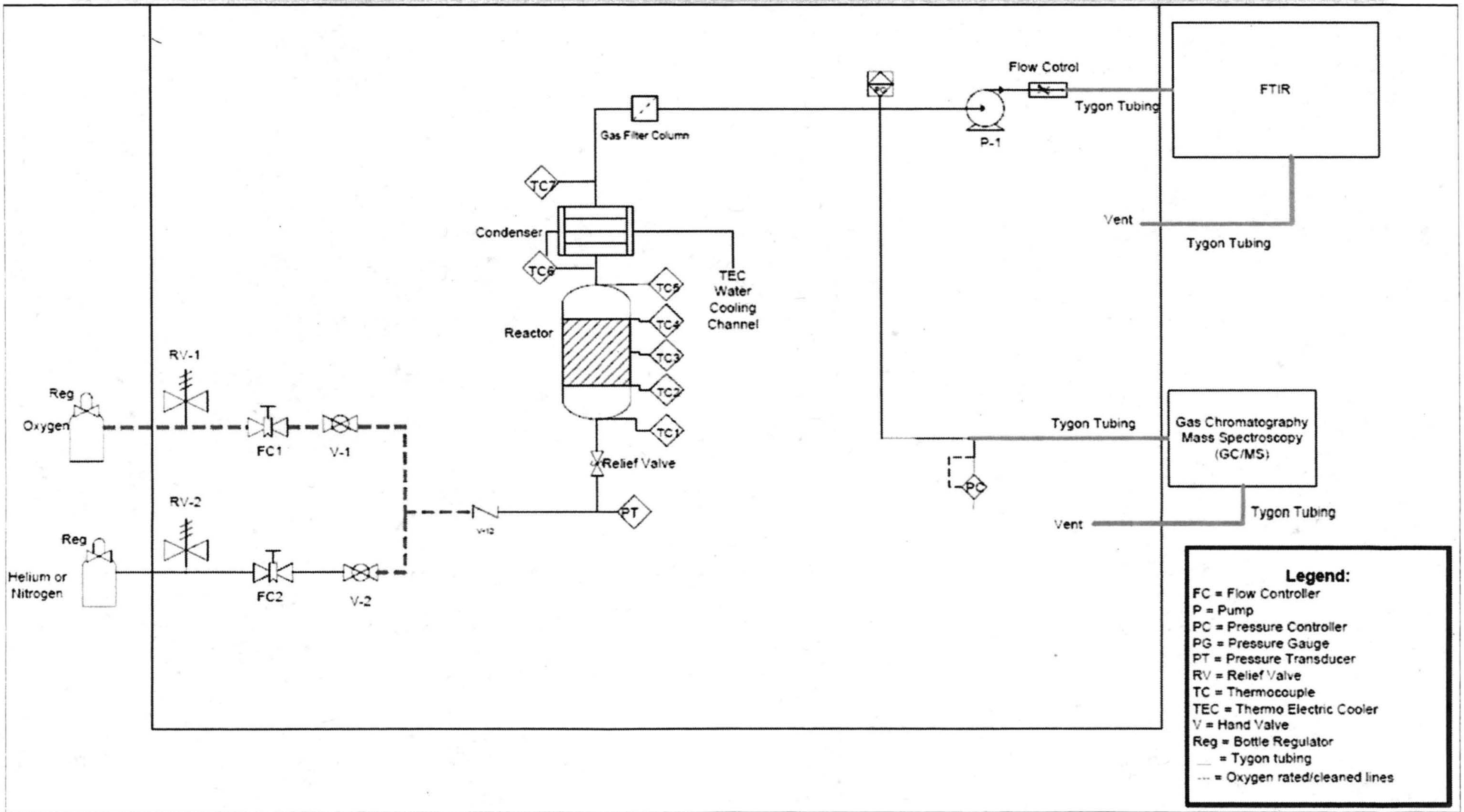
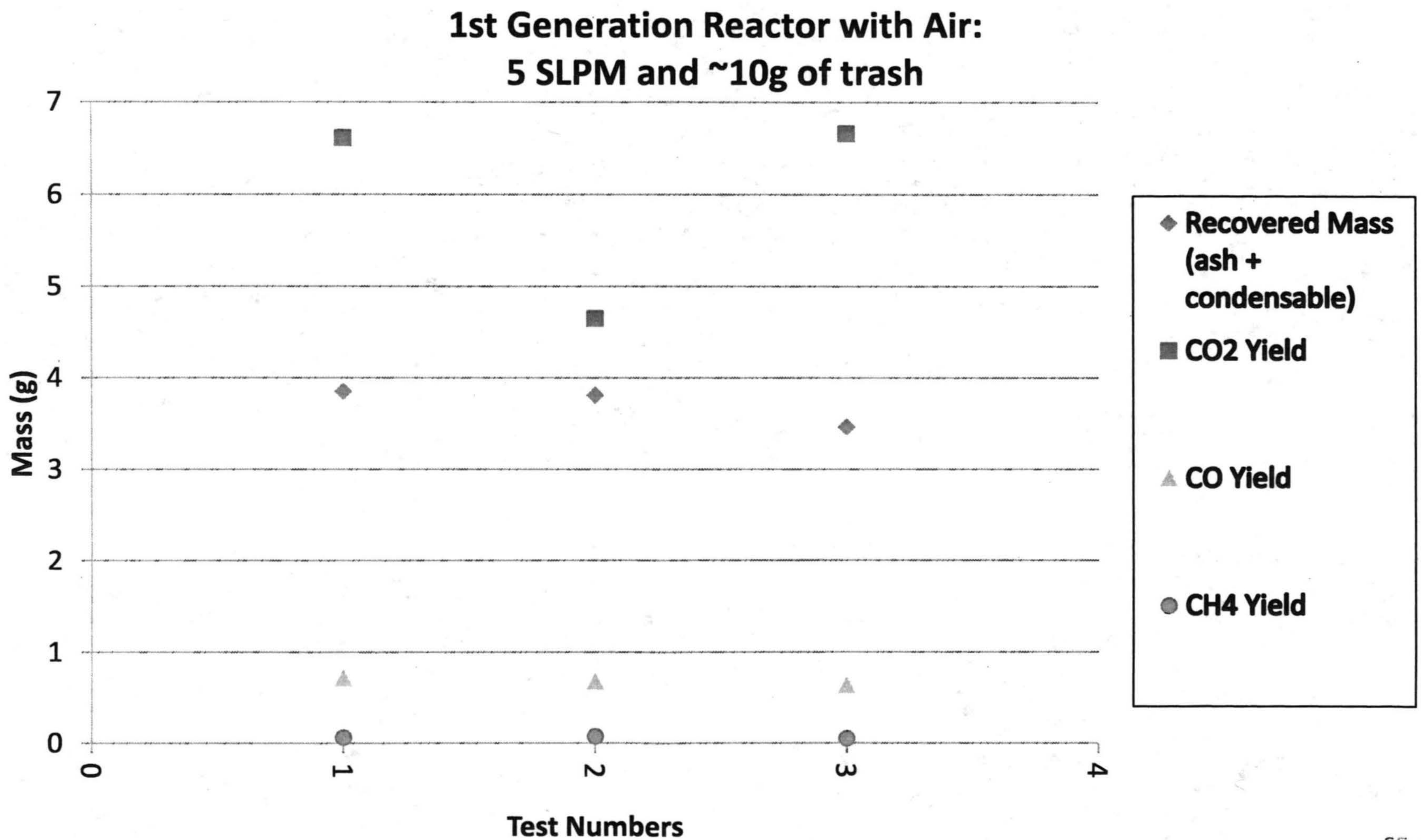
General Flow Diagram

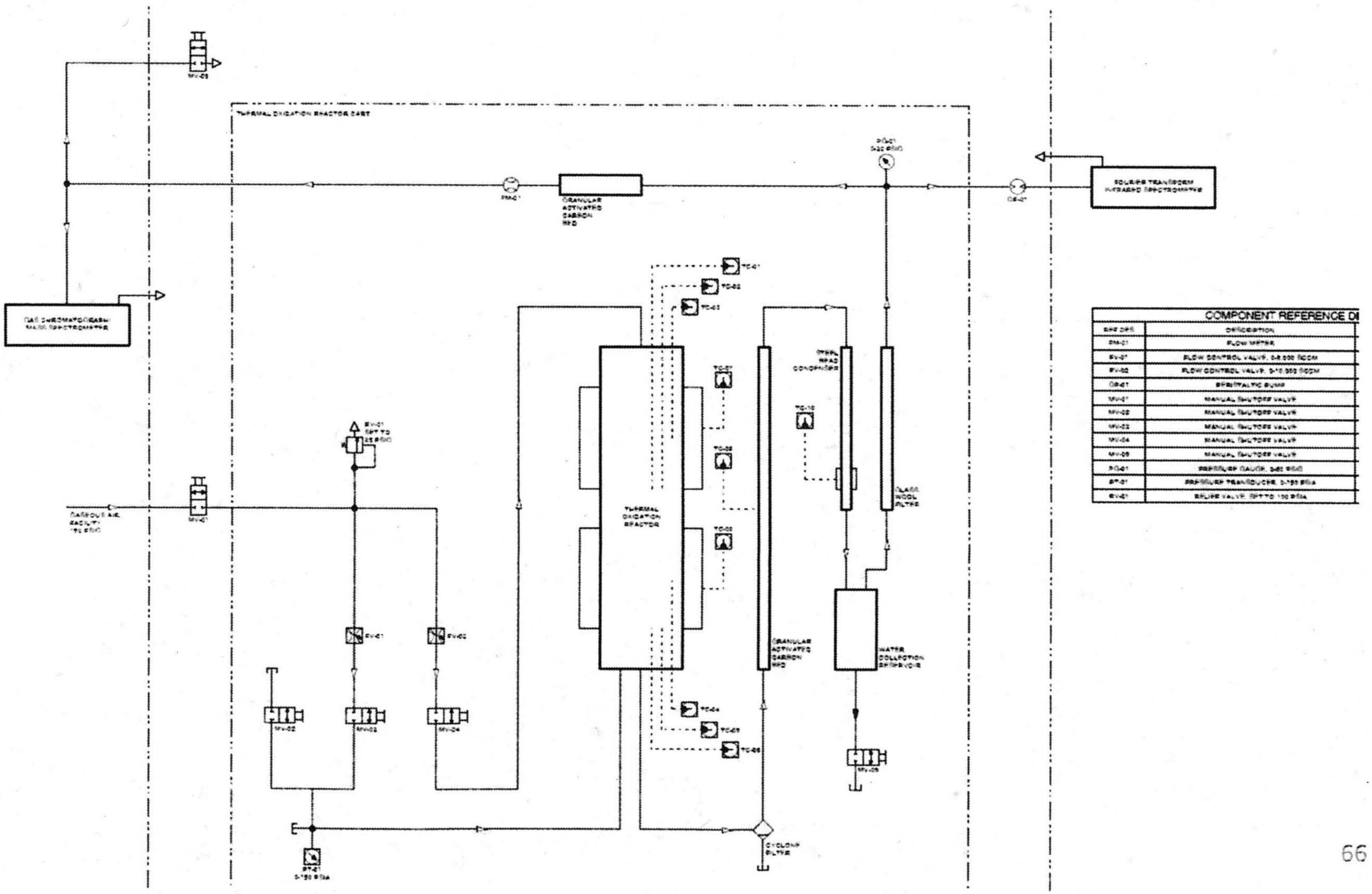


Backup



1st Generation Reactor with Air:
5 SLPM and ~10g of trash
Mass (g)
7
6
5
4
3
2
1
0
0
1
2
3
4
Test Numbers
Recovered Mass (ash + condensable)
CO2 Yield
CO Yield
CH4 Yield

2nd Gen. Reactor Schematic



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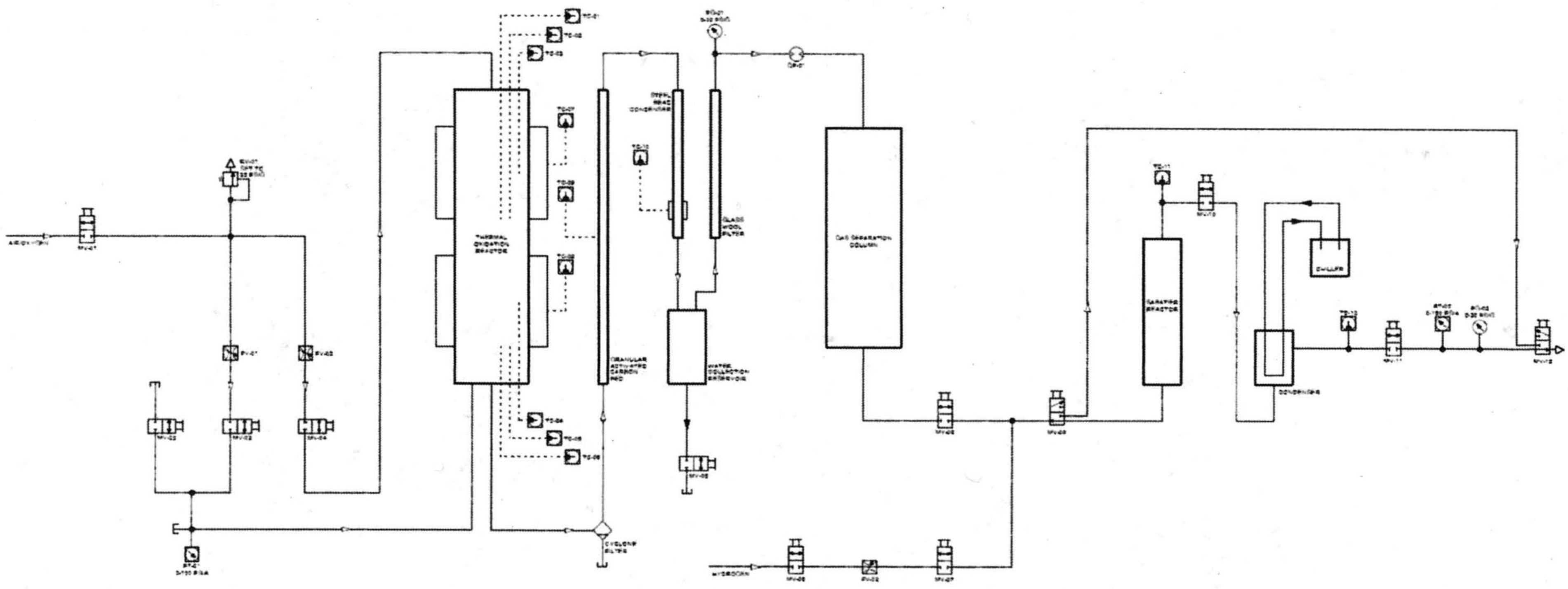
Fully Integrated Schematic



Minor Products Detected on GC/MS 1st Gen. Reactor

CLASS NAME	PROPERTY	REPRESENTATIVE COMPOUNDS
GC-Undetectable	Very heavy tars	
ALKENE	Containing at least one carbon-to-carbon double bond	Acetylene, Allene, 1-Butene, 1-Butene-3-yne, Ethylene, Propene, 2-Methylpropene
ALKANE	Consist only of hydrogen and carbon atoms and are bonded exclusively by single bonds	Ethane, Propane
ALKYNE	Hydrocarbons that have a triple bond between two carbon atoms	Propyne, Ethyne
ALDEHYDE	R-CHO, consists of a carbonyl center (a carbon double bonded to oxygen) bonded to hydrogen and an R group	Acetaldehyde, 2 propenal,
CYCLOALKANE	One or more rings of carbon atoms	Methylenecyclopropane
CYCLIC ETHER	An oxygen atom connected to two alkyl or aryl groups — of general formula R–O–R'	Ethylene Oxide
DIENE	Contains two carbon double bonds	1,3-Butadiene
KETONE	A carbonyl group (C=O) bonded to two other carbon atoms	Acetone