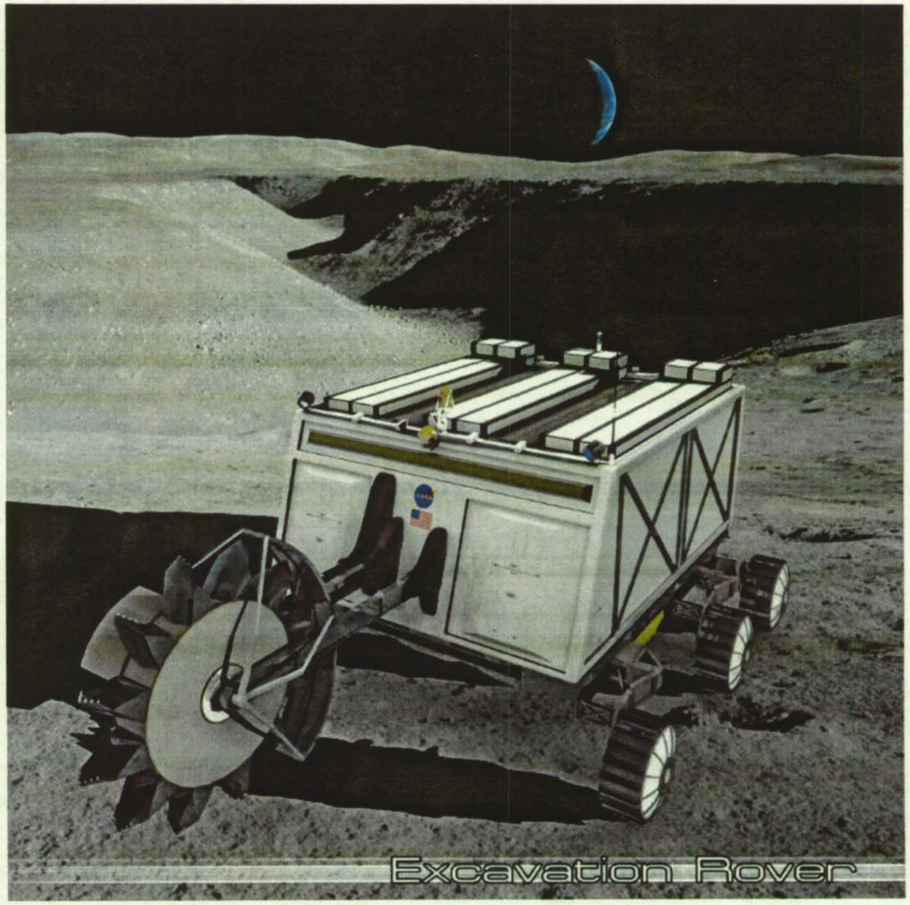
Development of an Integrated RVC-LWRD System for RESOLVE

ISRU Demonstration

- As exploration reaches new destinations, we have a greater need to live off the land

- ISRU plays a role in future mission architectures
  - Manufacture of propellants
  - Manufacture of life support consumables
  - Radiation shielding

- Since ISRU plays a key role, it would be extremely beneficial to demonstrate technology as early as possible



NASA's Exploration Systems Architecture Study -- Final Report

4.2.1.2.4 Key Capabilities and Core Technologies

– Previous NASA architecture studies have included such destinations as the Moon, near-Earth asteroids, Mars, and the moons of Mars. A review of these previous studies illustrates the existence of a common thread of key capabilities and core technologies that are similar between destinations…

– • ISRU: Technologies for "living off the land" are needed to support a long-term strategy for human exploration. Key ISRU challenges include resource identification and characterization, excavation and extraction processes, consumable maintenance and usage capabilities, and advanced concepts for manufacturing other products from local resources;

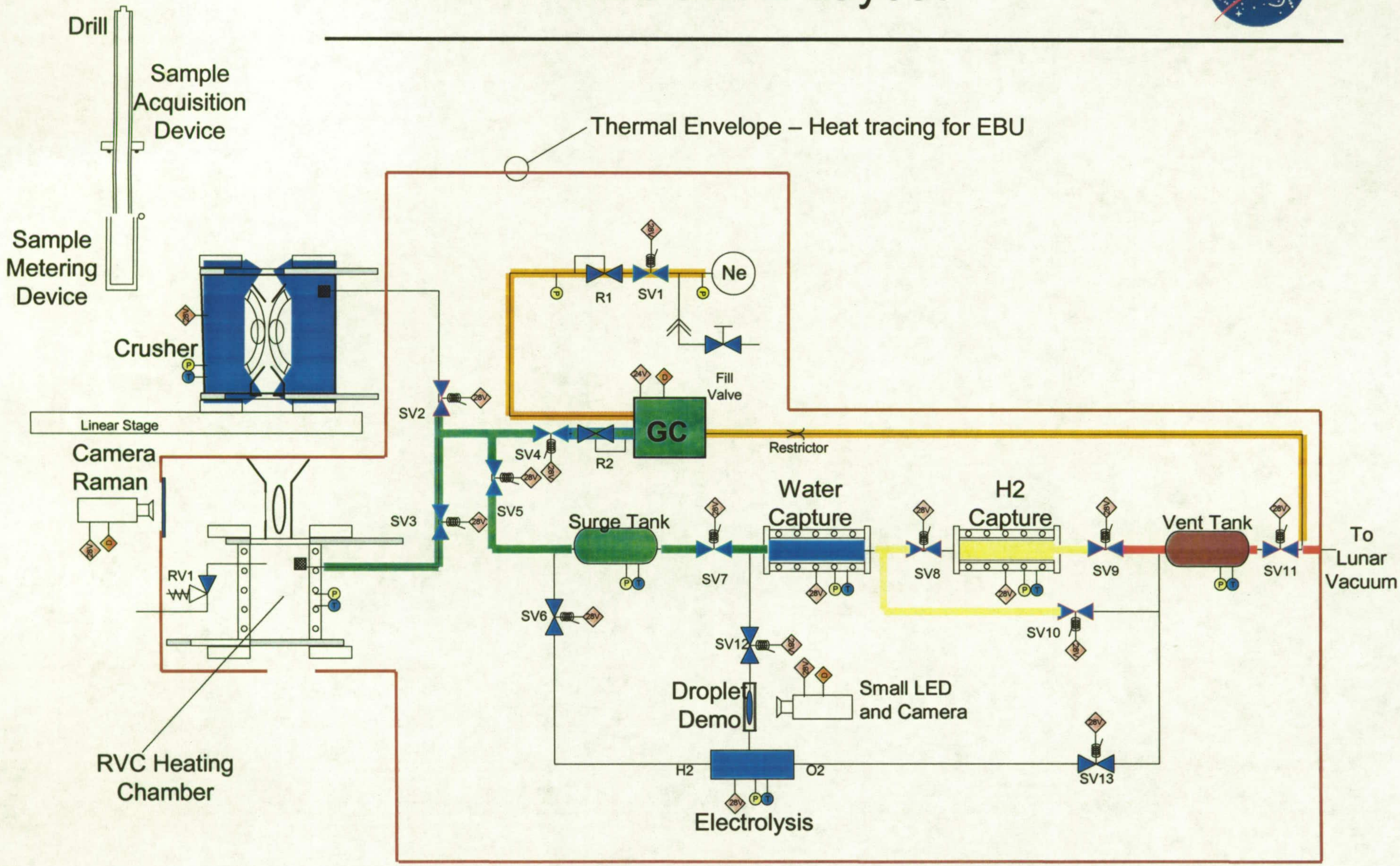
Brief RESOLVE Overview

- **RESOLVE - Regolith & Environment Science and Oxygen & Lunar Volatile Extraction**

- RESOLVE incorporates 5 modules
  - EBRC (Excavation and Bulk Regolith Characterization)
  - ERPC (Environment and Regolith Physical Characterization)
  - ROE (Regolith Oxygen Extraction)
  - RVC (Regolith Volatile Characterization)
  - LWRD (Lunar Water Resource Demonstration)

- Goal – identify and quantify volatiles, demonstrate ISRU, engage the public interest in 'living off the land' technology

RESOLVE Layout

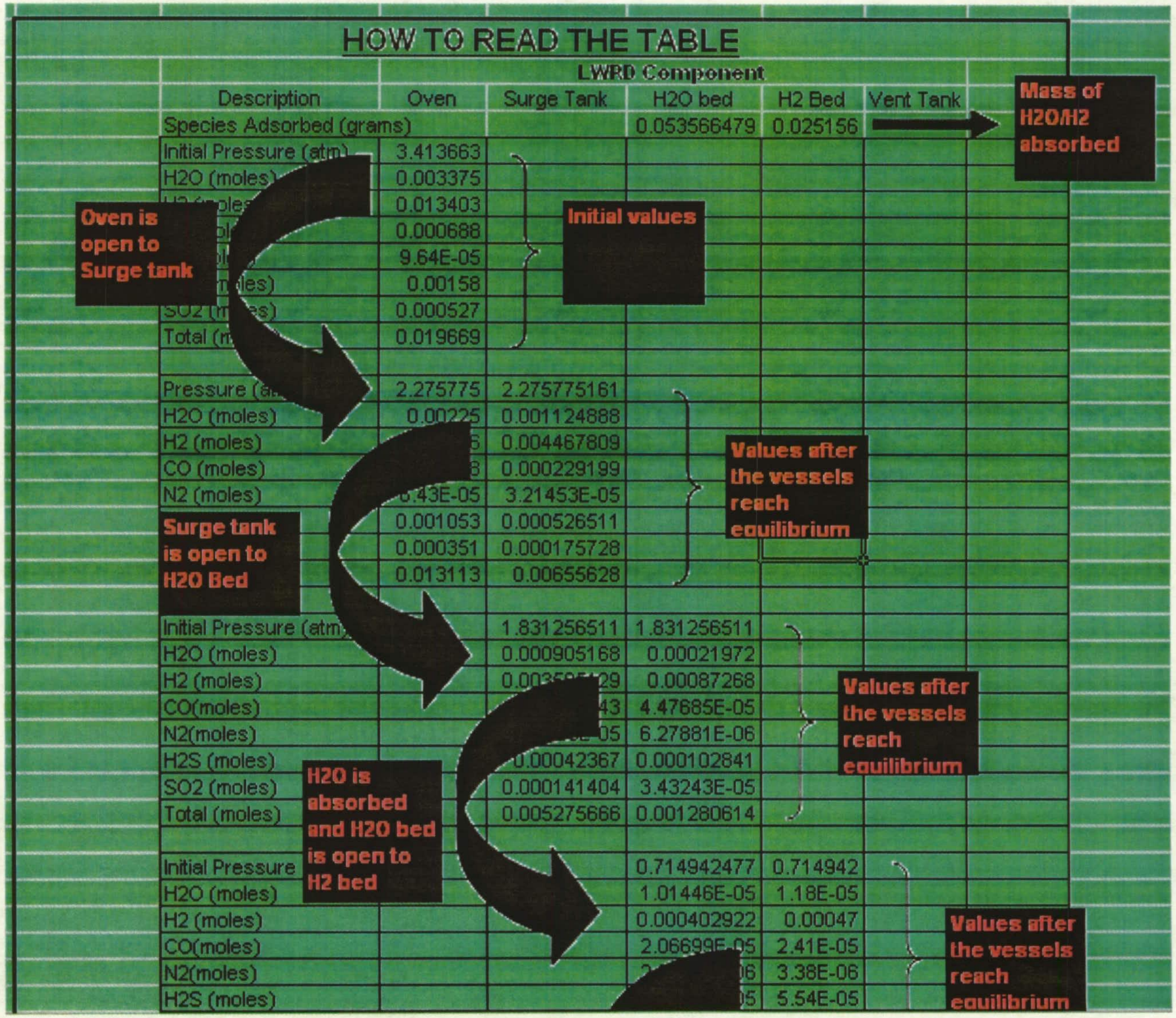


RESOLVE Operational Procedure

- Evaluation of system flow
  - Loop flow
    - Increase capture efficiency, but also increase time required to run the system
  - Straight flow
    - Loss of some efficiency but decrease operational time
  - Timing of solenoid valves
    - Length of time open
    - Time between openings

Model of system

- Model of gas moving through system to provide insight into overall operation of system
- Pressures equalize with each valve opening (assume ideal gas) and calculating resulting pressure if/when adsorption occurs



HOW TO READ THE TABLE

Description	Oven	Surge Tank	H2O bed	H2 Bed	Vent Tank
	LWRD Component				
Species Adsorbed (grams)			0.053566479	0.025156	
Initial Pressure (atm)	3.413663				
H2O (moles)	0.003375				
[illegible]	0.013403				
[illegible]	0.000688				
[illegible]	9.64E-05				
[illegible]	0.00158				
[illegible]	0.000527				
Total [illegible]	0.019669				
Pressure [illegible]	2.275775	2.275775161			
H2O (moles)	0.00225	0.001124888			
H2 (moles)	[illegible]	0.004467809			
CO (moles)	[illegible]	0.000229199			
N2 (moles)	[illegible]E-05	3.21453E-05			
[illegible]	0.001053	0.000526511			
[illegible]	0.000351	0.000175728			
[illegible]	0.013113	0.00655628			
Initial Pressure (atm)		1.831256511	1.831256511		
H2O (moles)		0.000905168	0.00021972		
H2 (moles)		[illegible]	0.00087268		
CO(moles)		[illegible]	4.47685E-05		
N2(moles)		[illegible]	6.27881E-06		
H2S (moles)		[illegible]0.00042367	0.000102841		
SO2 (moles)		0.000141404	3.43243E-05		
Total (moles)		0.005275666	0.001280614		
Initial Pressure			0.714942477	0.714942	
H2O (moles)			1.01446E-05	1.18E-05	
H2 (moles)			0.000402922	0.00047	
CO(moles)			[illegible]	2.41E-05	
N2(moles)			[illegible]	3.38E-06	
H2S (moles)			[illegible]	5.54E-05	

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User Interface – Inputs

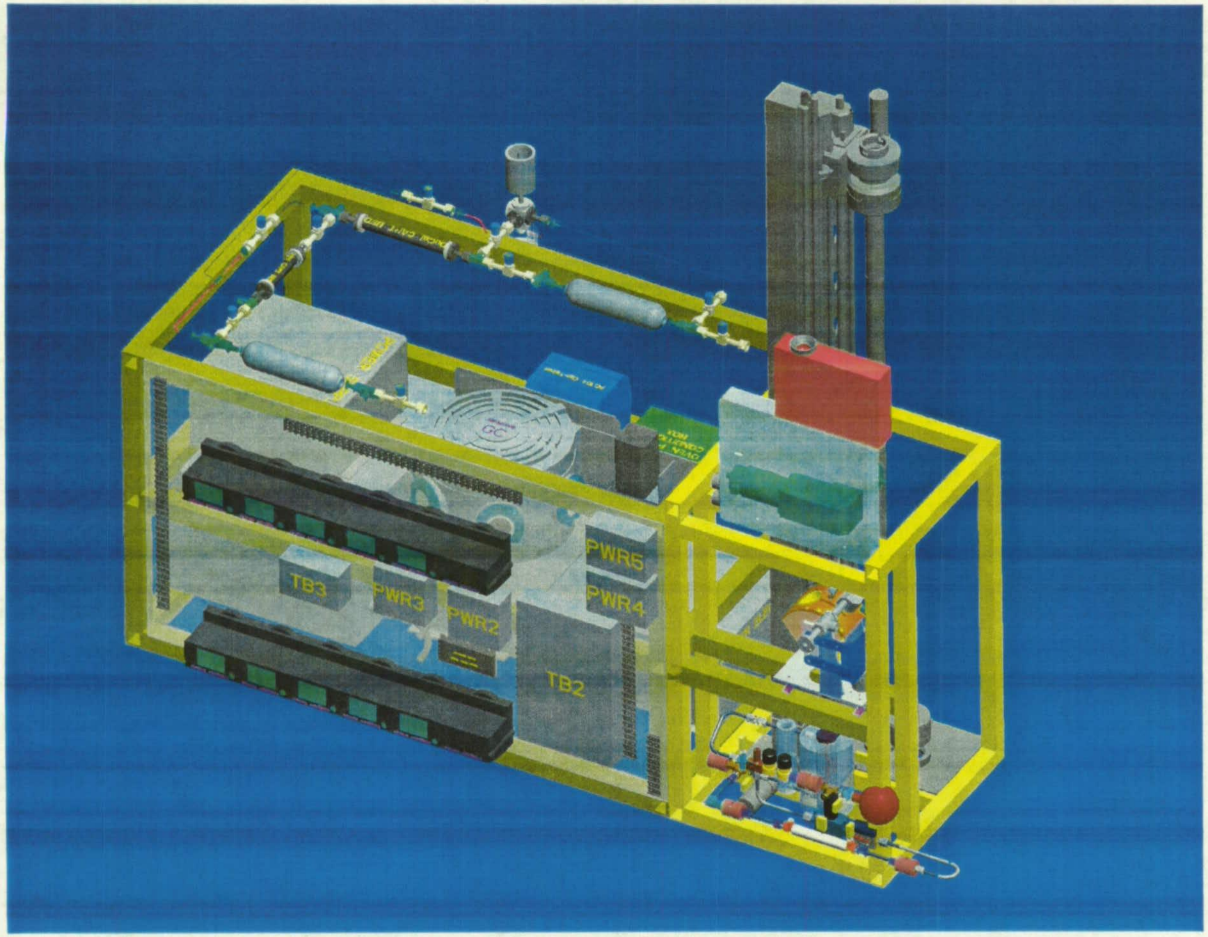
Input Parameter Field

Parameter	Name	Value	Units	Description
Options for Simulation	Simulation Mode	Multiple Loops		
	Minimum H_2O adsorbed	0.05	grams	If H2O adsorbed is not a constrain, this number should be large (i.e. 1e10)
	Minimum H_2 adsorbed	1.00E+10	grams	If H2 adsorbed is not a constrain, this number should be large (i.e. 1e10)
Oven	Volume	200	cm^3	Volume of vessel
	Temperature	423	K	Temperature of vessel
	Minimum Pressure	5	torr	Minimum pressure change to re-pressurize the vessel
Surge Tank	Volume	100	cm^3	Volume of vessel
	Temperature	423	K	Temperature of vessel
	Minimum Pressure	5	torr	Minimum pressure change to re-pressurize the vessel
Dessicant Bed	Volume	20	cm^3	Volume of vessel
	Temperature	298	K	Temperature of vessel
	Minimum Pressure	5	torr	Minimum pressure change to re-pressurize the vessel
	Mass of absorbant	5	gram	Mass of water absorbant
Hydride Bed	Volume	20	cm^3	Volume of vessel
	Temperature	298	K	Temperature of vessel
	Minimum Pressure	5	torr	Minimum pressure change to re-pressurize the vessel
	Mass of absorbant	0.5	gram	Mass of metal hydride
Vent Tank	Volume	200	cm^3	Volume of vessel
	Temperature	298	K	Temperature of vessel
	Minimum Pressure	5	torr	Minimum pressure change to re-pressurize the vessel
	H_2O	900	µg/g-regolith	

Run

Clear

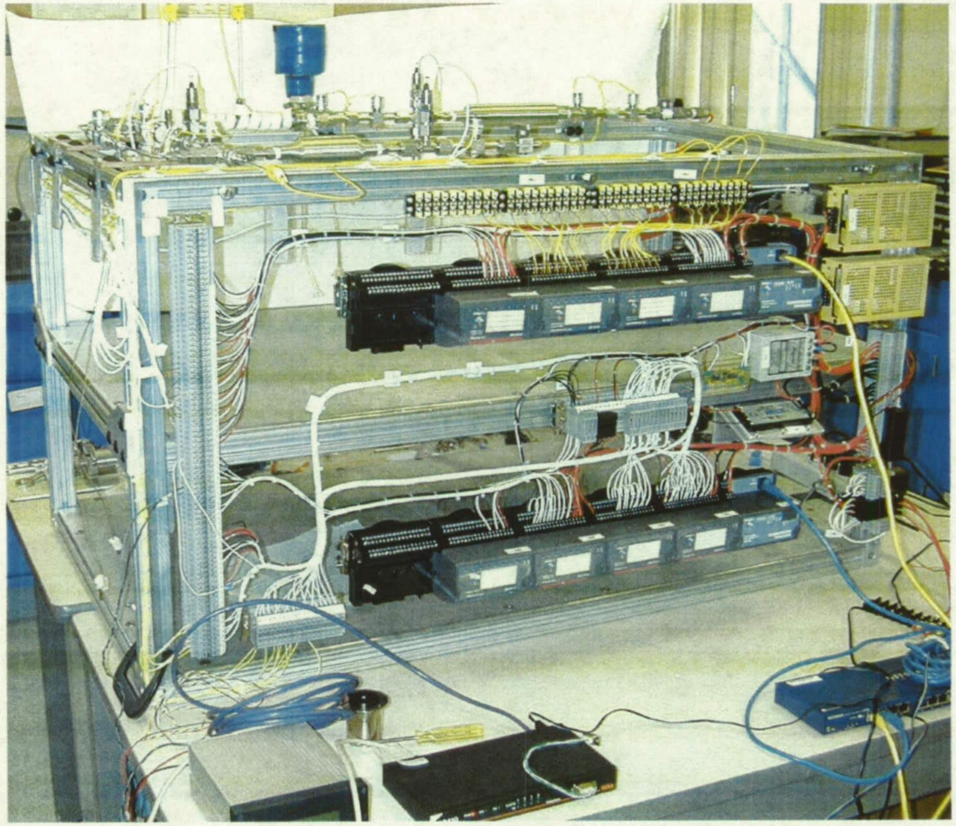
Model of RESOLVE System



Pro-E drawings done by
Victor Spencer - JSC

Engineering Breadboard Unit (EBU)

- Hardware is being assembled
  - GRC – vibrofulidization oven
  - KSC – GC and LWRD
  - NORCAT – drill, crusher
  - JSC – ROE
  - JPL – CHAMP RAMAN
- First cut at an integrated system, finding the kinks
- RVC-LWRD will be integrated and tested at KSC
- Integration will be at JSC in March-April timeframe



Window Viewport for Imaging Chamber

- The window for the RAMAN-CHAMP camera needs to be cleaned between samples to reduce contamination between the samples

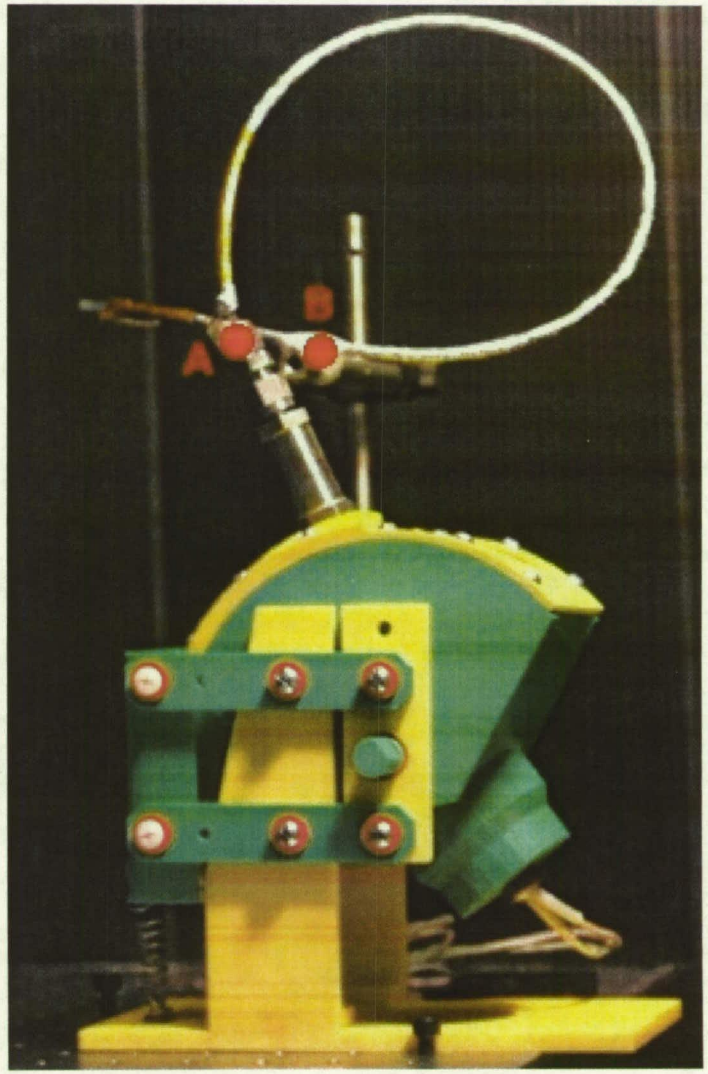
- KSC's electrostatics group (led by Dr. Carlos Calle) has been developing dust removal techniques

- Transparent electrodes made of ITO (Indium Tin Oxide) will be placed on a sapphire window substrate, a voltage will be applied to clean the dust from the window surface

- Technology will be evaulated with real lunar soil

Regolith Volatiles Characterization (RVC) Oven

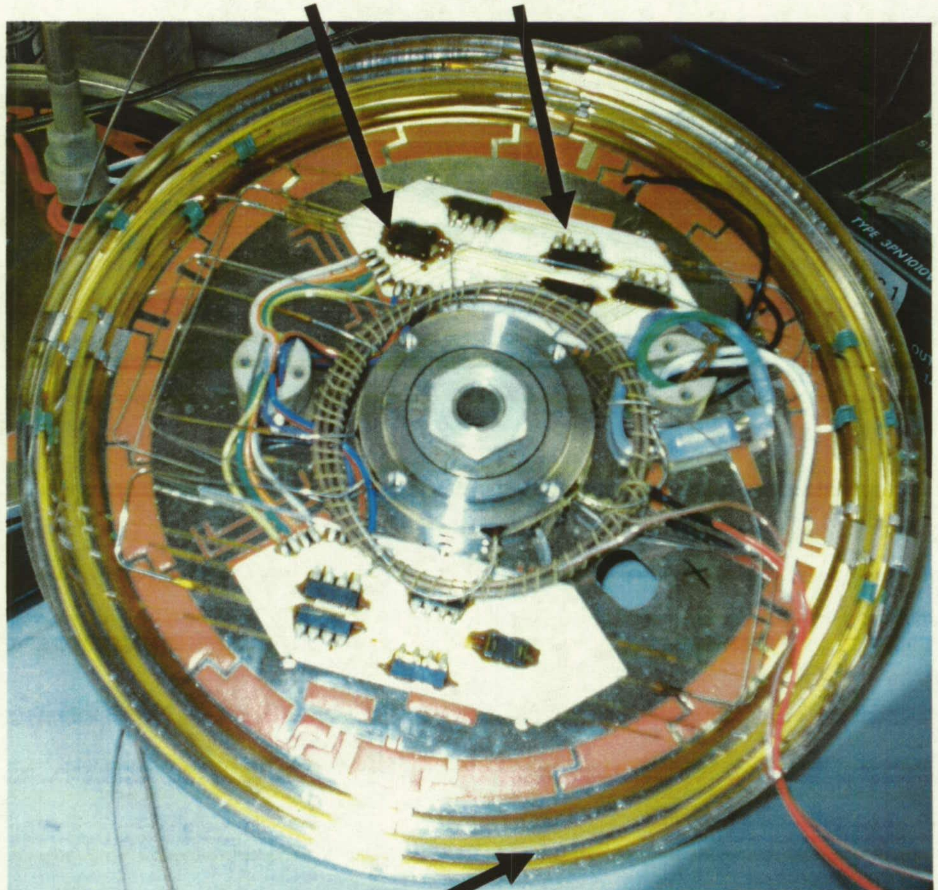
- Crushed regolith will be delivered through RAMAN viewing chamber into vibrofluidization oven
- Oven designed to evenly heat sample,
  - This is important for correlating the volatiles released with the temperature of the regolith
  - The temperature at which the volatiles are released will provide insight into the nature of their bonding
- GRC has done extensive testing on optimizing vibrofluidization parameters



RVC Gas Chromatograph

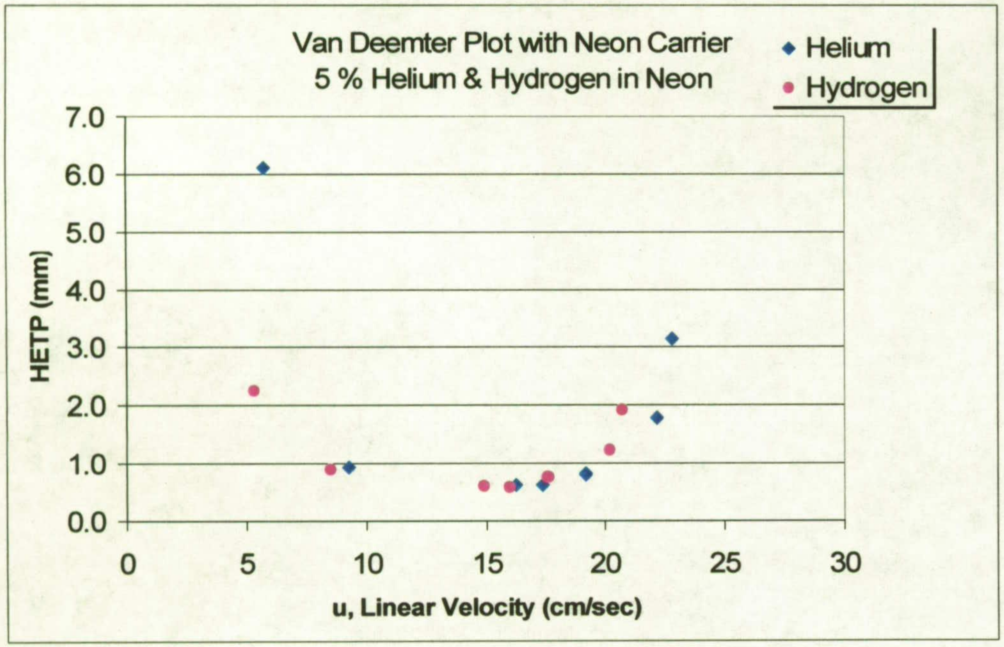
- COTS Siemens GC MicroSAM, converted to Neon carrier gas
- Modified in house to optimize separation and detection of H_2, He, H_2O, O_2, CO, CO_2, CH_4, H_2S
- Water detection was challenging but modifications and heat tracing have allowed for quantitative analysis of concentrations from 1% to 20% of vapor phase composition (current limitation of generation system)
- Water limit of detection corresponds to approximately 0.05 wt % in regolith
- Current testing
  - Optimization of flow
  - Column temperatures

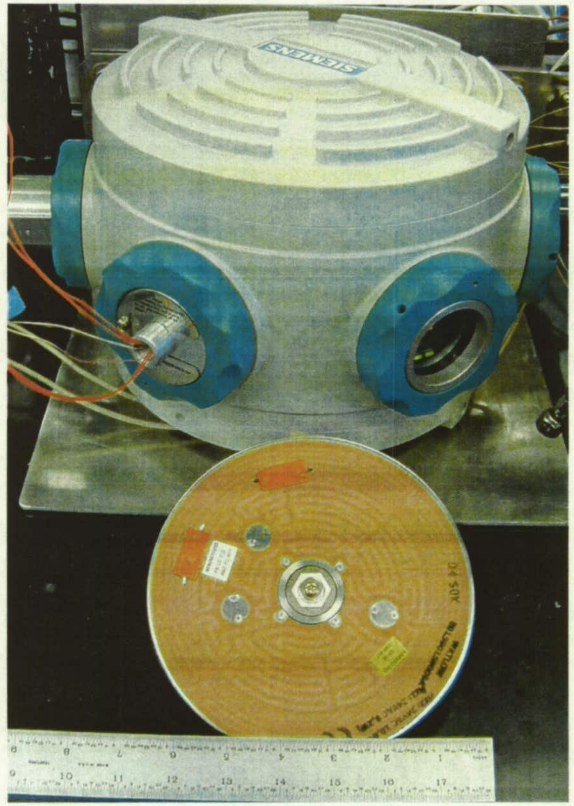
Analysis Module of GC



RVC-GC

- Van Deemter plot generated to optimize pressure driven flows for best separation of components
  - The lower the HETP value, the better the separation on the column (height equivalent of a theoretical plate)





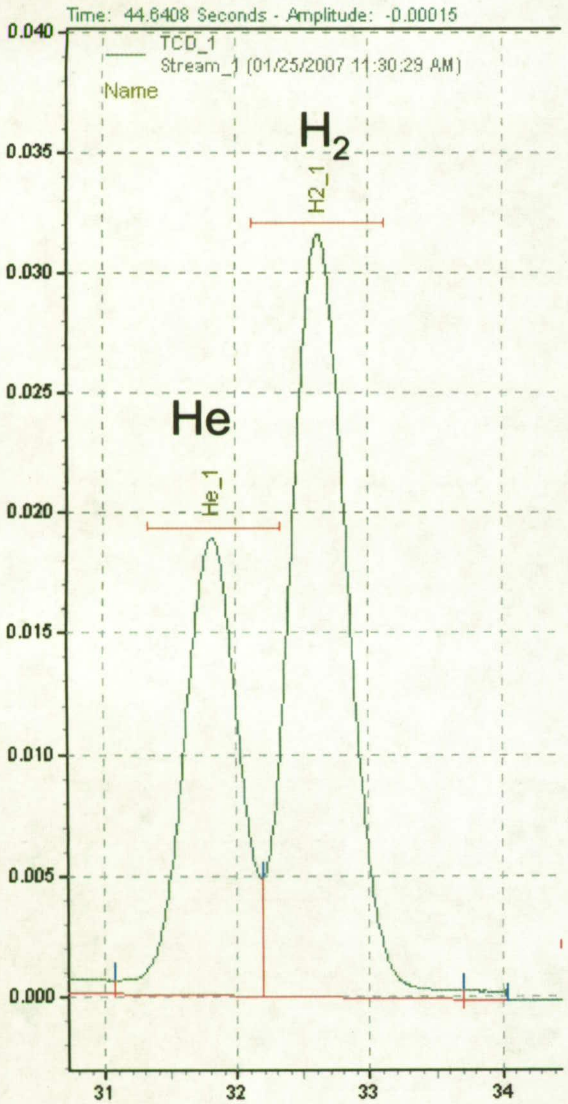
GC with explosion proof case

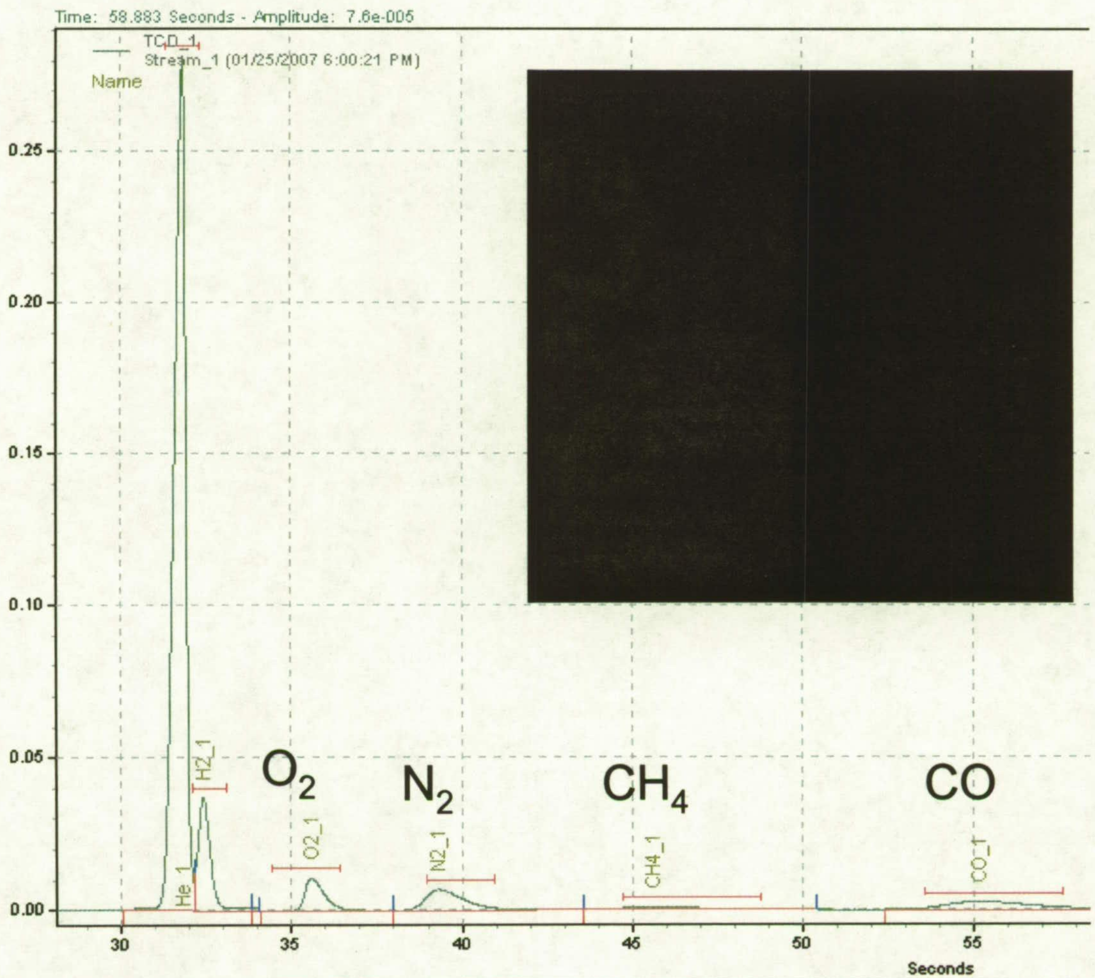
Analysis module

- MicroSAM GC (top) in factory designed case will be stripped and the analysis module (bottom) will be isolated for use in FPU

Sample Chromatograms

- Sample containing He, H_2, O_2, N_2, CH_4, CO, H_2O (inset)



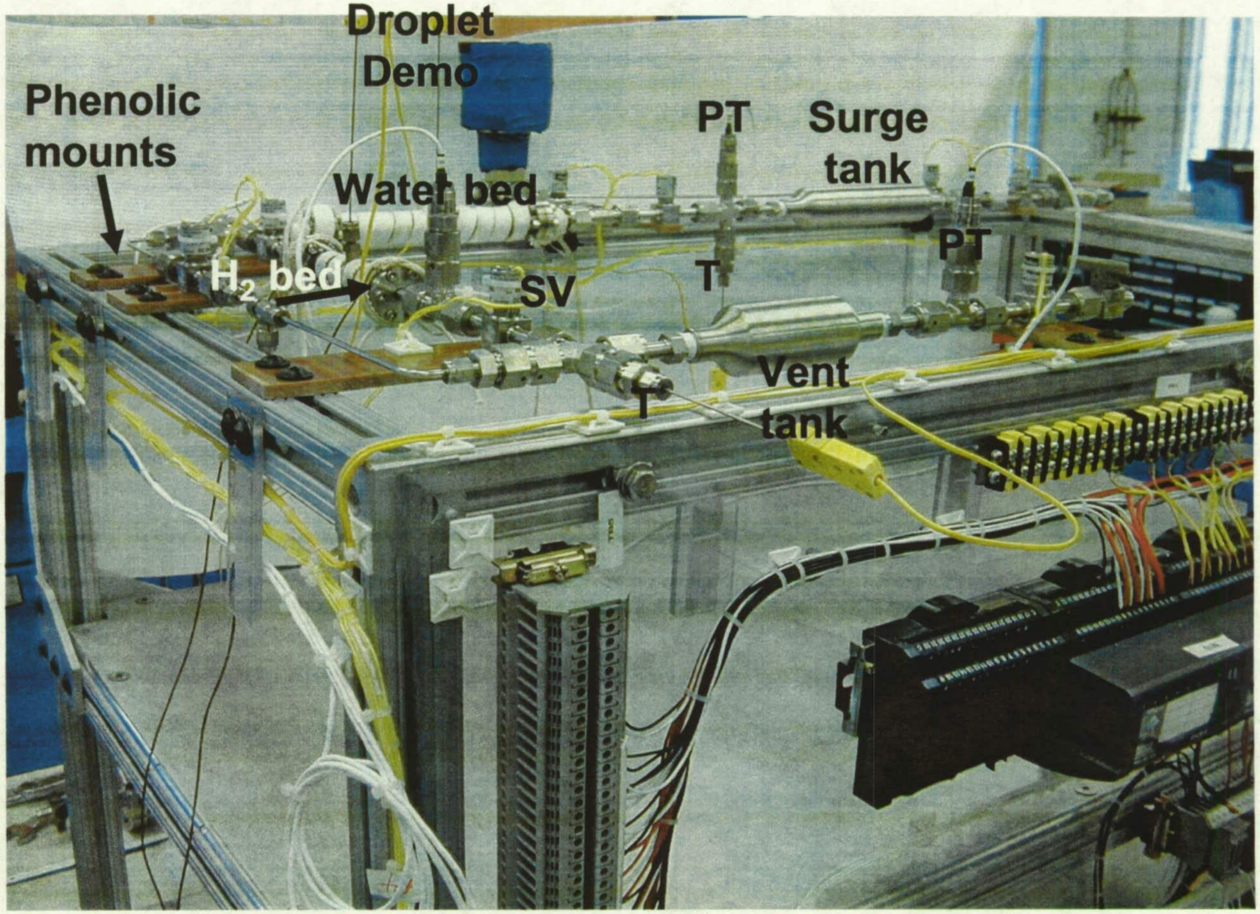


He/H_2 separation (5% each in Ne)

Lunar Water Resource Demonstration (LWRD)

EBU Hardware

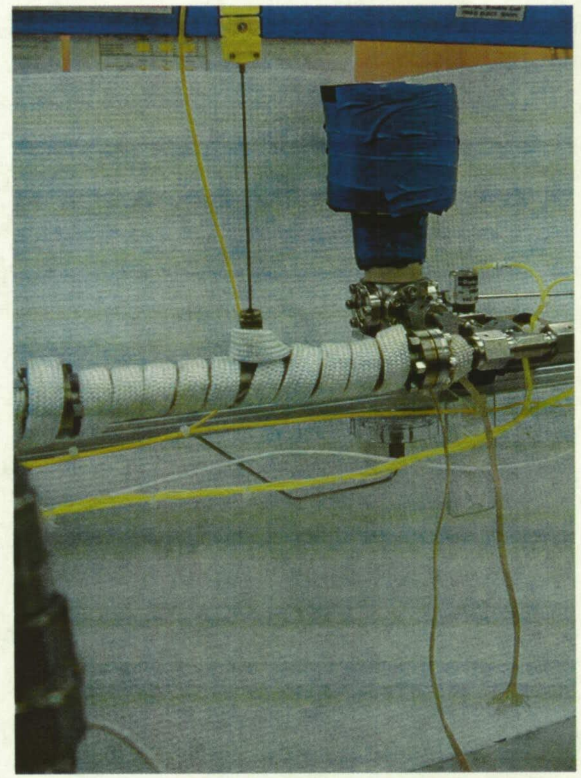
- EBU configuration laid out to allow for easy access to system
  - Wire tracing
  - Leak checks
  - Heat tracing
    - Calculations to estimate power and chose best gauge of wire have been done
  - Insulation
    - Polyimide foam
    - Durablanket (ceramic fiber) high temp insulation



Heat Tracing Challenges

- Goal – prevent condensation of water in system while capturing volatiles
- Cold spots in system would allow for condensation which would skew GC analysis of volatiles
- Thermal imaging camera will be used to analyze heat tracing

- Challenge – solenoid valves (normally closed)
  - maximum operating temp of ~100degC observed when continuously operated, only two must be continuously operated
  - In an insulated system they would overheat, however they need to be heat traced to prevent condensation
  - For FPU latching solenoid valves are preferred to avoid this problem



High temperature heat tape on water capture bed

Water Vapor generation

- Currently Miller Nelson or in house vapor generation system used
- First cut evaluation will be done with mixed gases and injected water with no simulant
  - Preliminary tests with water and simulant indicate clumping will be a problem for vibrofluidization oven
- Goal will be to dope simulant with hydrated salts that release water vapor for analysis at elevated temperatures
- current oven design is limited to 150°C, this puts an upper bounds on the amount of water vapor we'd see in the system (VP of water at 150°C is ~70 psi)

Desorption temps of selected hydrated salts from STA runs

Water Capture

- Several options explored
  - LN_2 cold trap
    - \+ efficiently captures water
    - \- not selective, will condense other volatiles (contamination for electrolysis)
  - Molecular sieves
    - \+ reversible water capture
    - \- capture based on size, not selective
  - Hydrated salts
    - \+ selective adsorption
    - \- slower than LN_2 trap

Integration with ROE – current system will need to capture ~1g of water

Picture of LN2, molecular sieves and hydrated salts

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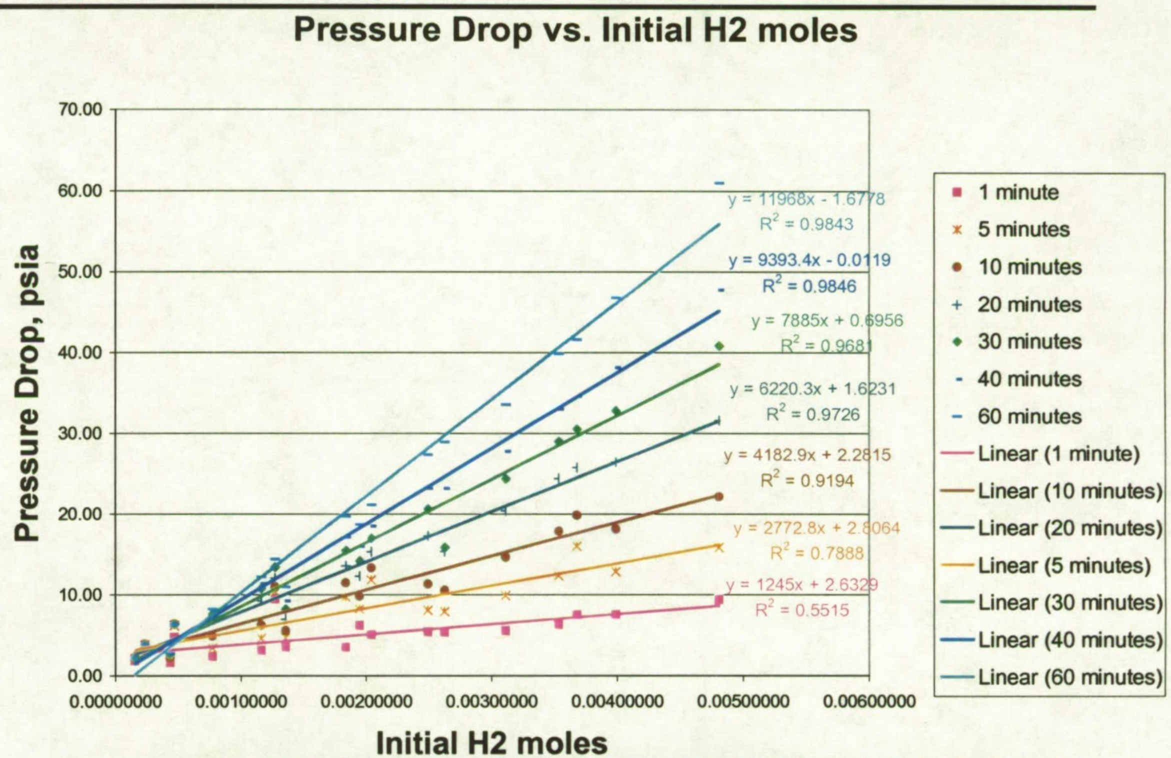
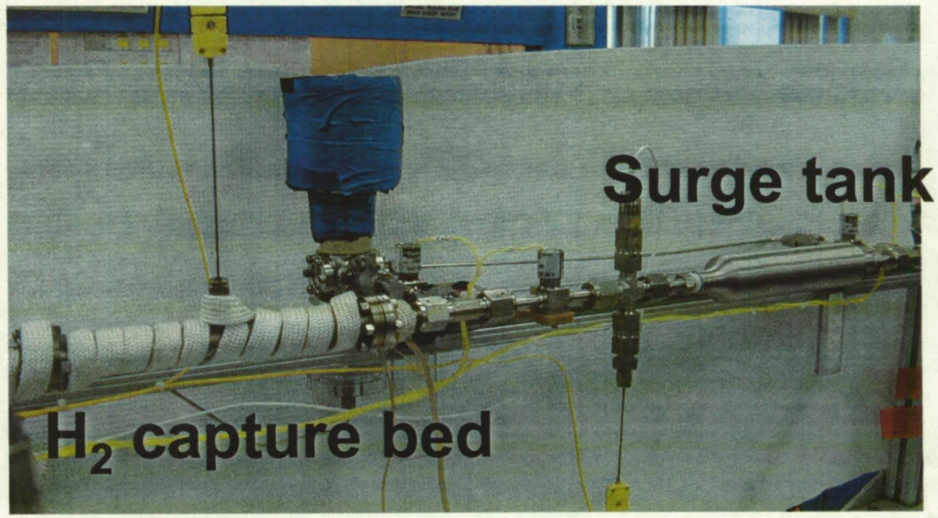
Hydrogen Capture

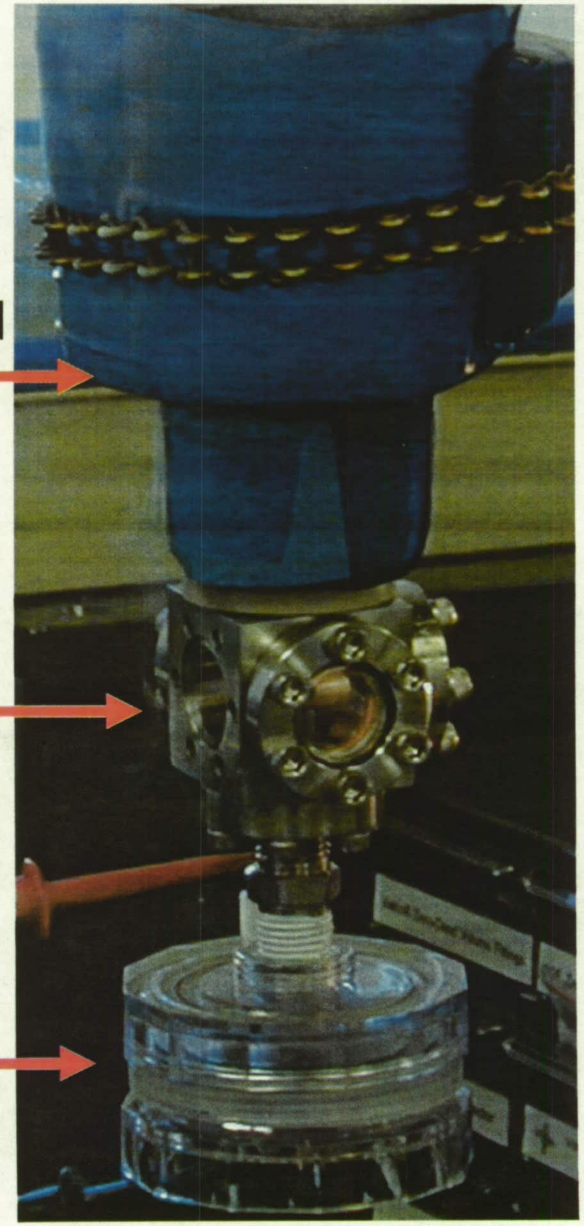
- Metal hydrides explored
  - ZrNi most stable of evaluated hydrides in air, least susceptible to contamination
  - Equilibrium vapor pressure vs desorption temperature trade off explored for ZrNi
  - Kinetics of ZrNi outweigh the slightly higher equilibrium vapor pressure at elevated temperatures, adsorption performed ~160°C





Water Droplet Demo and Electrolysis

- Currently LN_2 used to cool cold finger for water condensation
- Droplet demo tested, when the cold finger is warmed a droplet will form on the tip of the condenser and fall into the electrolyzer
- Electrolyzer records an increase in current corresponding to the time the droplet fell



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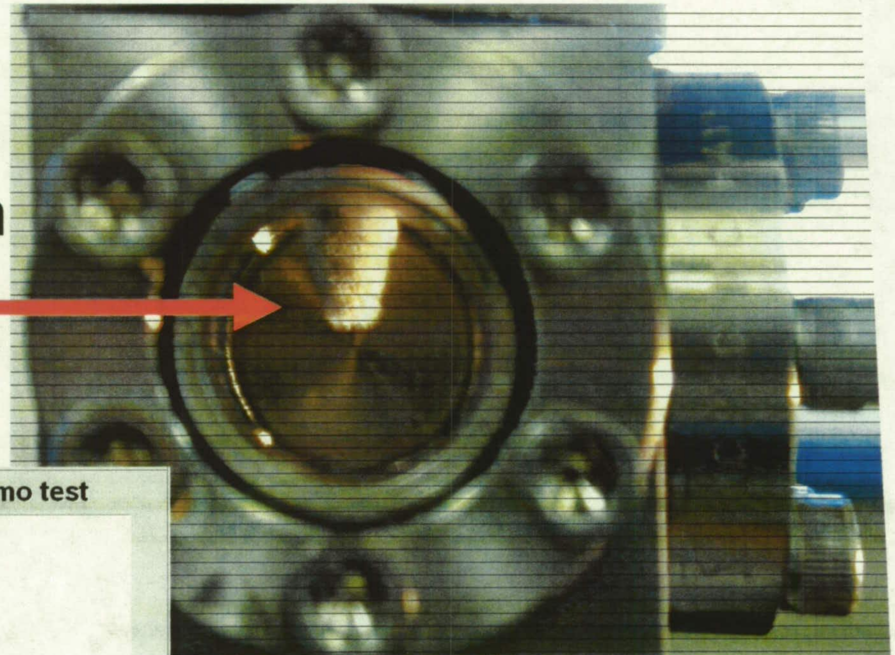
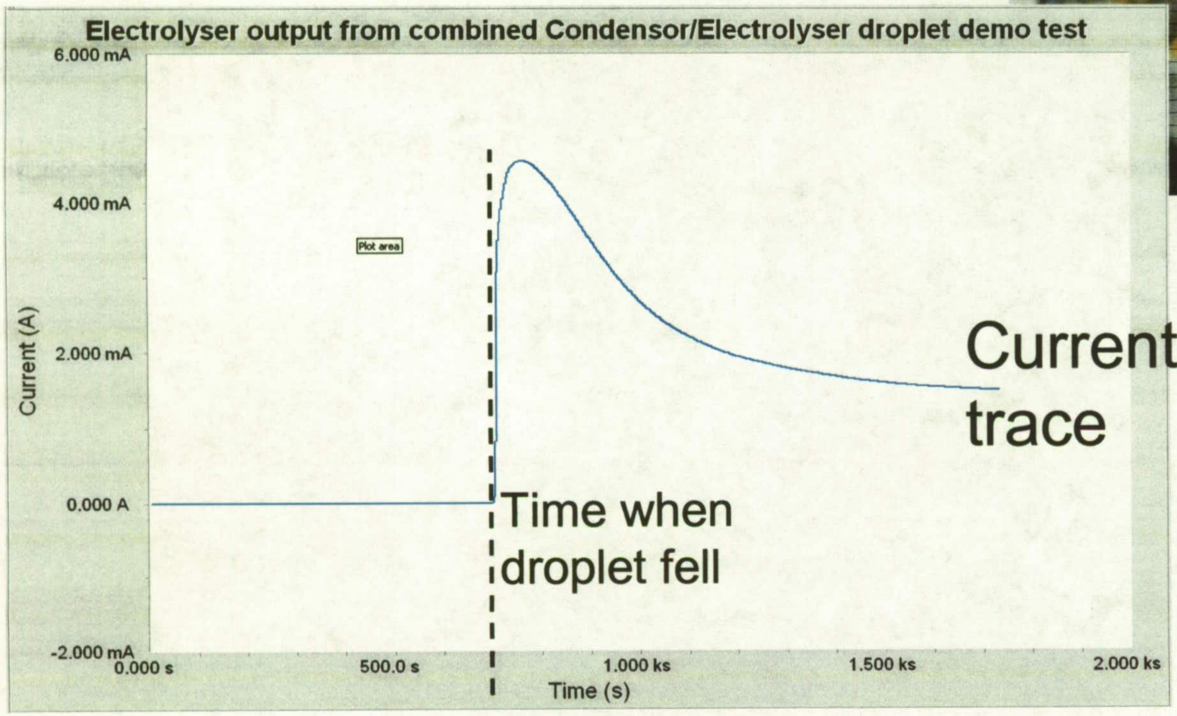
Water Droplet - Electrolyzer

Ice formation on cold finger in droplet demo





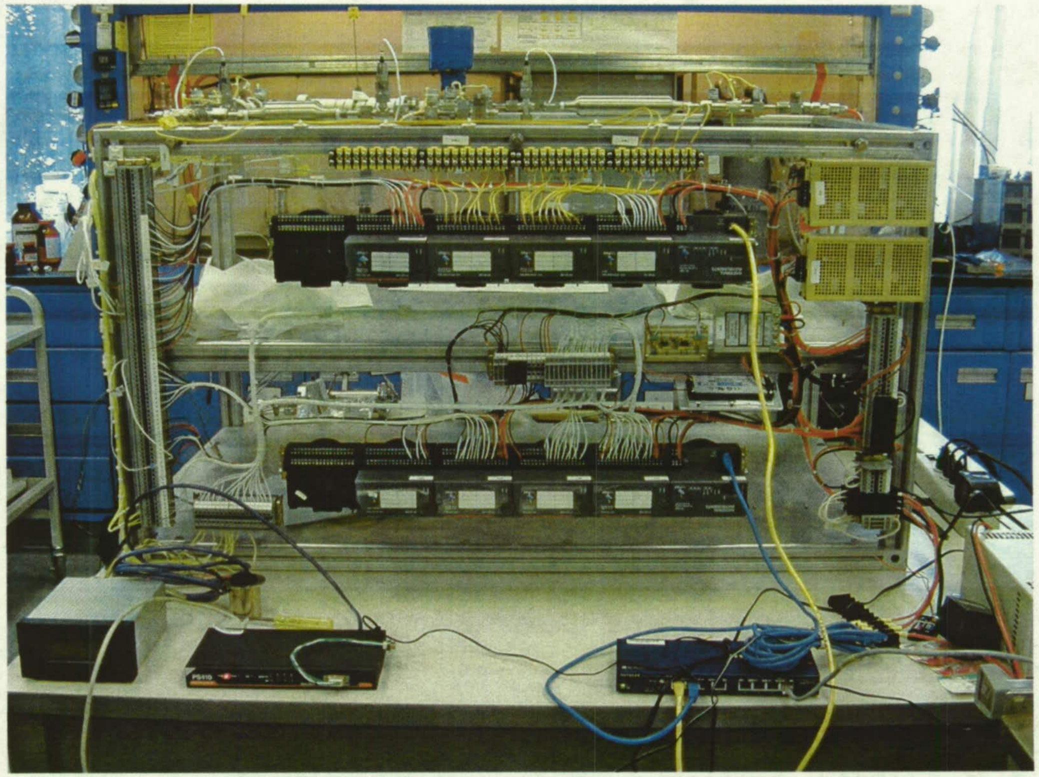
Electrolyzer

- Trade off between designing for a drop vs 1g of water

Pictures of initial electrolyzer designs and testing with 40uL in dry cell

Computer Control

- Documentation has been placed into Microstation (CAD)
- Manual interface is operational and supporting initial testing and data recording
- Process of integrating shaker control software into our system control software



- Next steps
  - Working on heater control loops
  - To integrate system into rover we will need to go to compact fieldpoint ($) or Xiphos ($$$)
  - Flow charts for automated processes are being constructed

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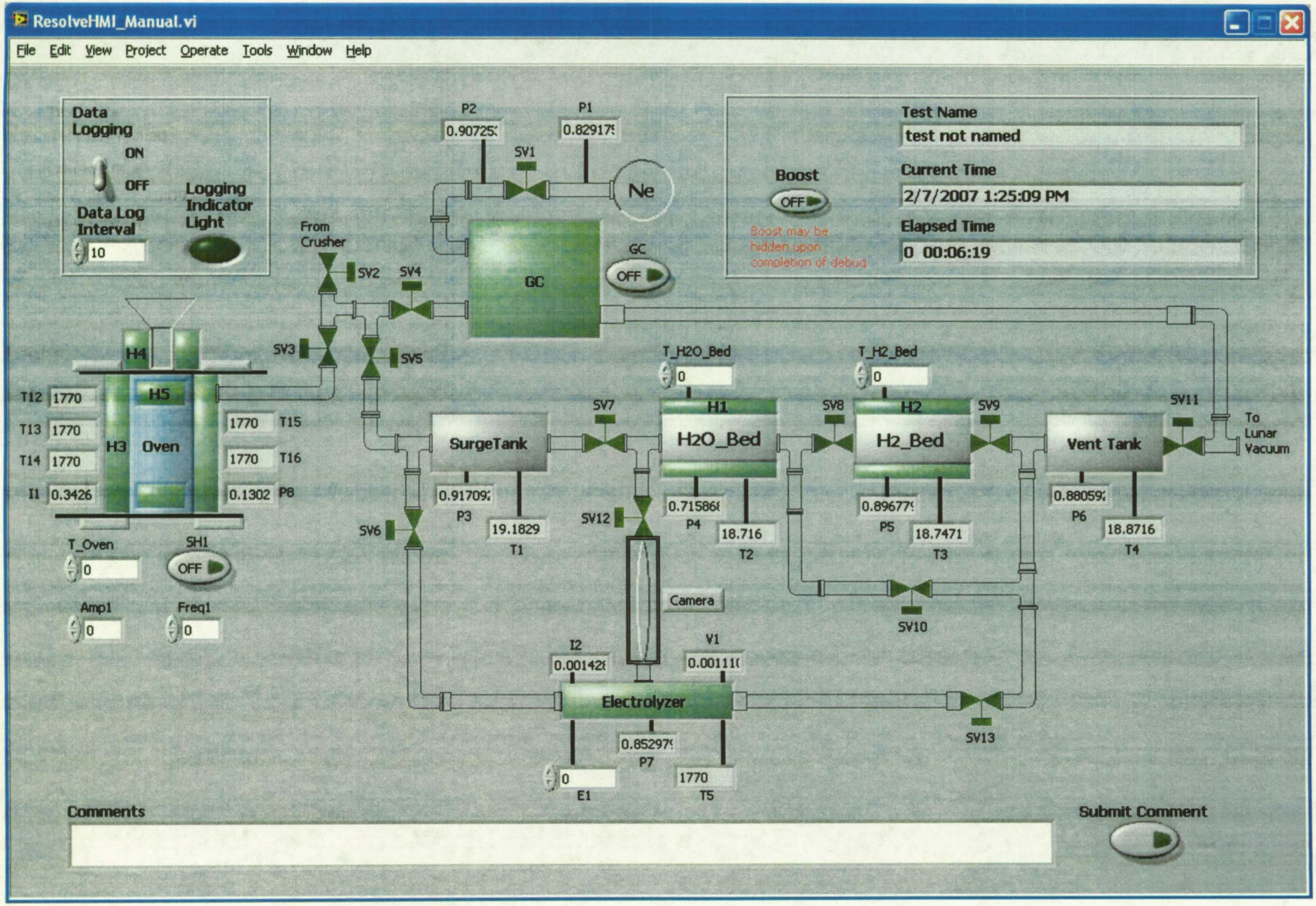
Manual Control Interface

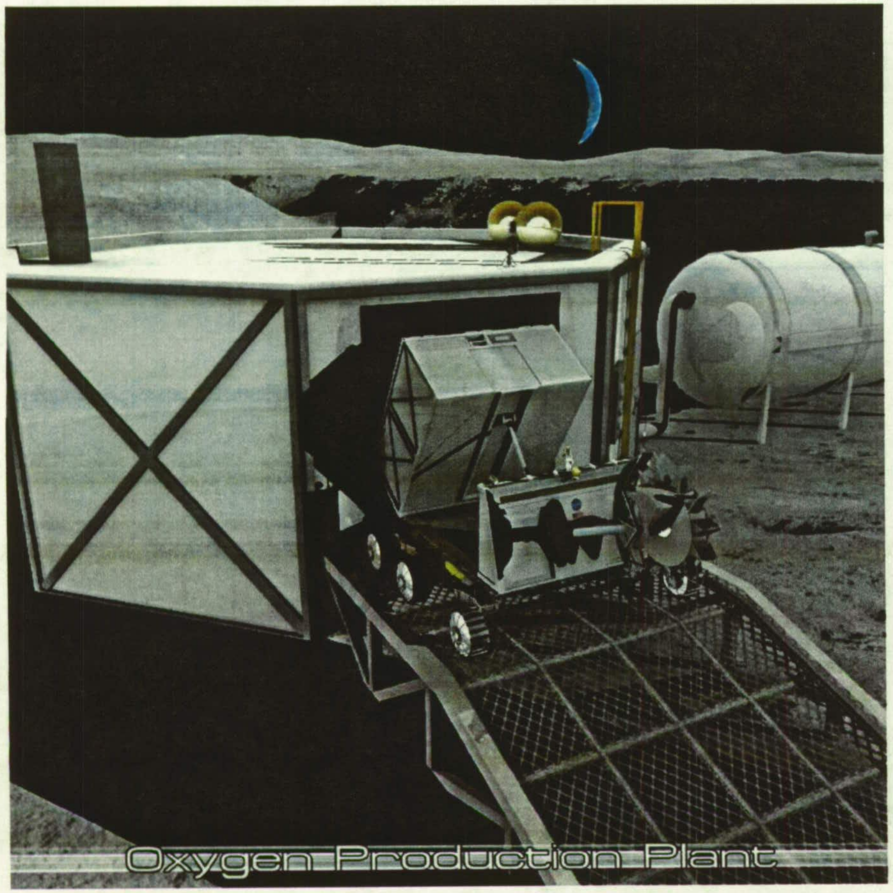


Conclusion

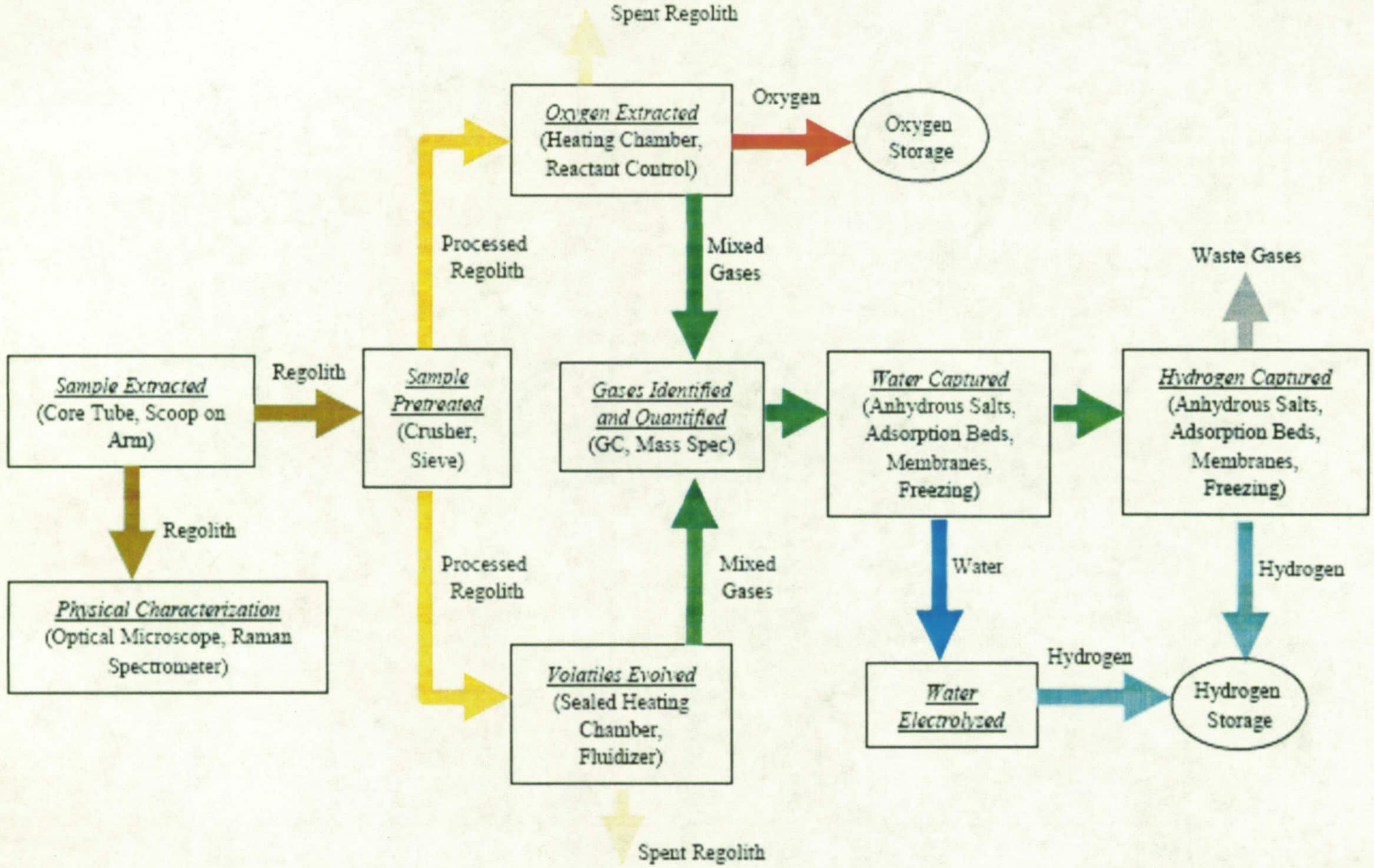
- EBU integration currently in progress
- Future goals and changes required for FPU identified
- Current RESOLVE goals of volatile characterization and demonstration of ISRU will be met with the EBU and optimized for FPU

- **Key Functional Requirements and GR&As**The following key functional requirements and GR&As were used for the study, with emphasis placed on ensuring that the architecture approach was consistent with the Cycle 3 ESAS architecture and mission assumptions.
- ISRU: Capable of utilizing locally produced propellants.

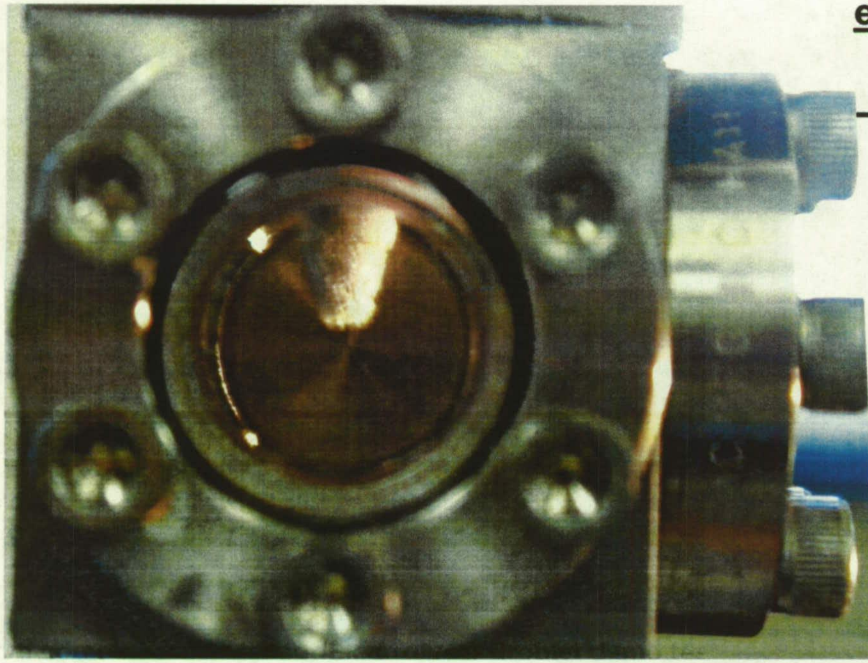
- This initial strategy corresponds to the "pointer" location shown in **Figure 4-54** (which appears later in the report in **Section 4.3.5**, **Lunar Surface Traffic Model**), and serves as a starting point for the analysis of outpost deployment strategies. A number of key a
- Precursor missions have accomplished the following tasks:
- • Demonstrated ISRU technologies such as O2 production, H2/H2O extraction, and excavation of regolith; and
- • Developed an enhanced lunar gravity potential model.

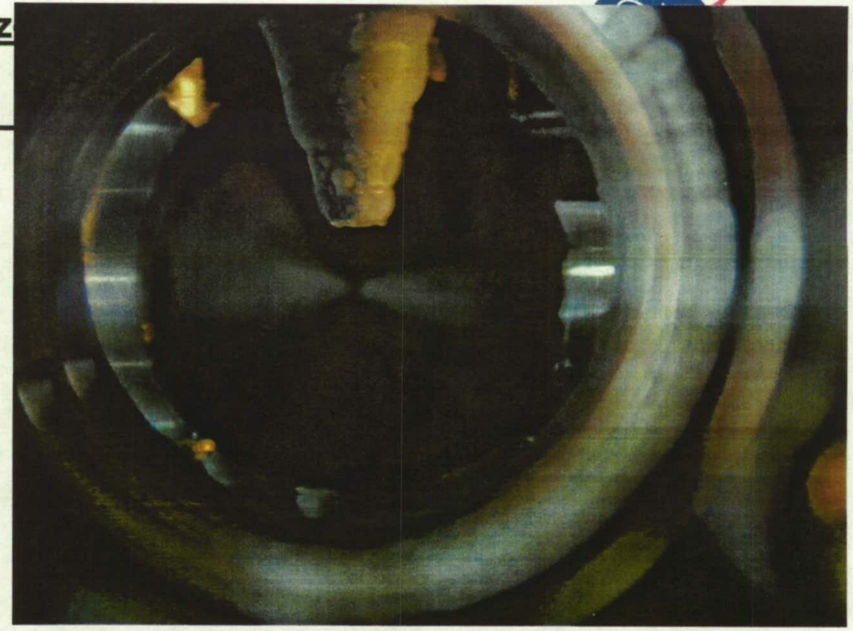

Oxygen Production Plant

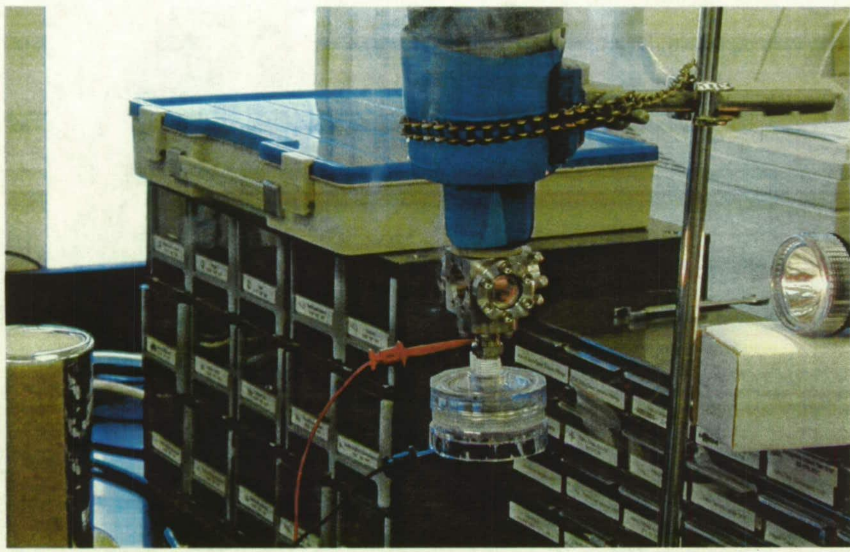

Water Extractor

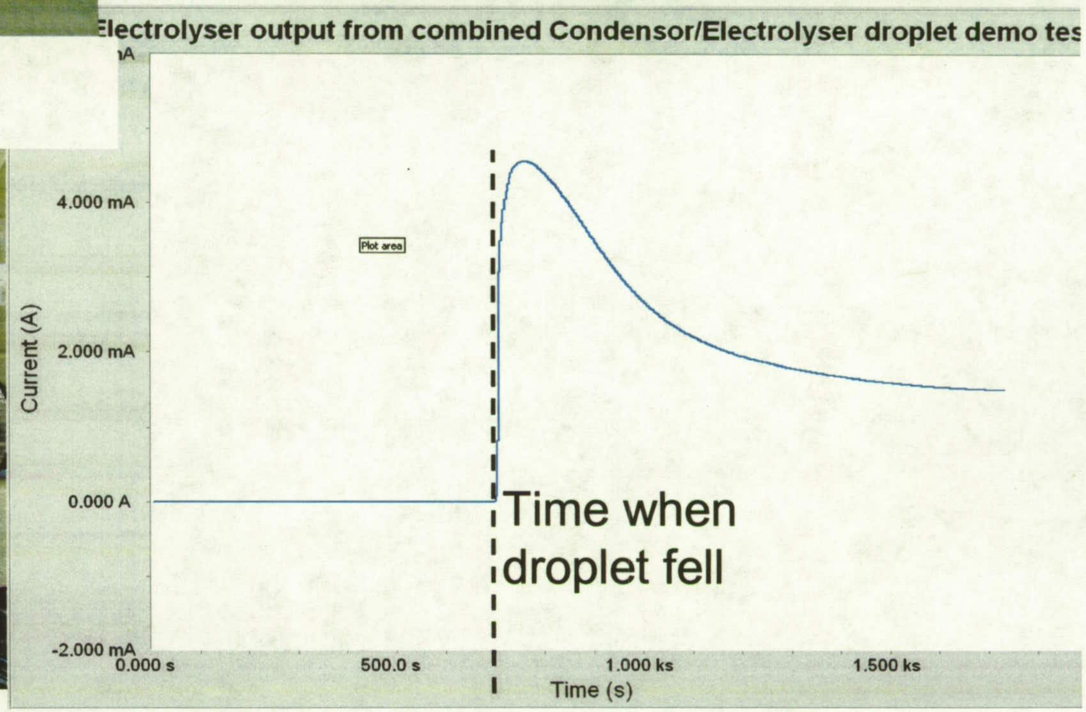

Spent Regolith
Oxygen Extracted
(Heating Chamber, Reactant Control)
Oxygen
Oxygen Storage
Processed Regolith
Mixed Gases
Waste Gases
Sample Extracted
(Core Tube, Scoop on Arm)
Regolith
Sample Pretreated
(Crusher, Sieve)
Gases Identified and Quantified
(GC, Mass Spec)
Water Captured
(Anhydrous Salts, Adsorption Beds, Membranes, Freezing)
Hydrogen Captured
(Anhydrous Salts, Adsorption Beds, Membranes, Freezing)
Regolith
Processed Regolith
Mixed Gases
Water
Hydrogen
Physical Characterization
(Optical Microscope, Raman Spectrometer)
Volatiles Evolved
(Sealed Heating Chamber, Fluidizer)
Water Electrolyzed
Hydrogen
Hydrogen Storage
Spent Regolith

electrolyz








Electrolyser output from combined Condensor/Electrolyser droplet demo tes
4.000 mA
2.000 mA
0.000 A
-2.000 mA
Current (A)
Plot area
Time when
droplet fell
0.000 s
500.0 s
1.000 ks
1.500 ks
Time (s)