In-Situ Space Resource Utilization

By

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And The

AIAA Space Colonization Technical Committee

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Introduction

In-Situ Resource Utilization

The Concept

The production of commodities on other planetary bodies using locally available resources.

The Benefits

By "living off the land" mission mass and costs can be dramatically reduced, enabling self-sufficient missions

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In-Situ Resource Utilization Is Enabling

Make what you need there instead of bringing it all the way from Earth

"Living off the Land"

In-Situ Resource Utilization

Mass Reduction

- Reduces Earth to orbit mass by 20 to 45%
- Estimated 300 MT/yr reduction in Earth logistics

Cost Reduction

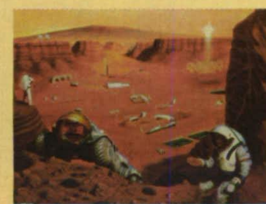
- Reduces number and size of Earth launch vehicles
- Allows reuse of landers

Risk Reduction

- Reduces dependence on Earth supplied logistics
- Enables self-sufficiency
- Provides backup options & flexibility
- Radiation Shielding

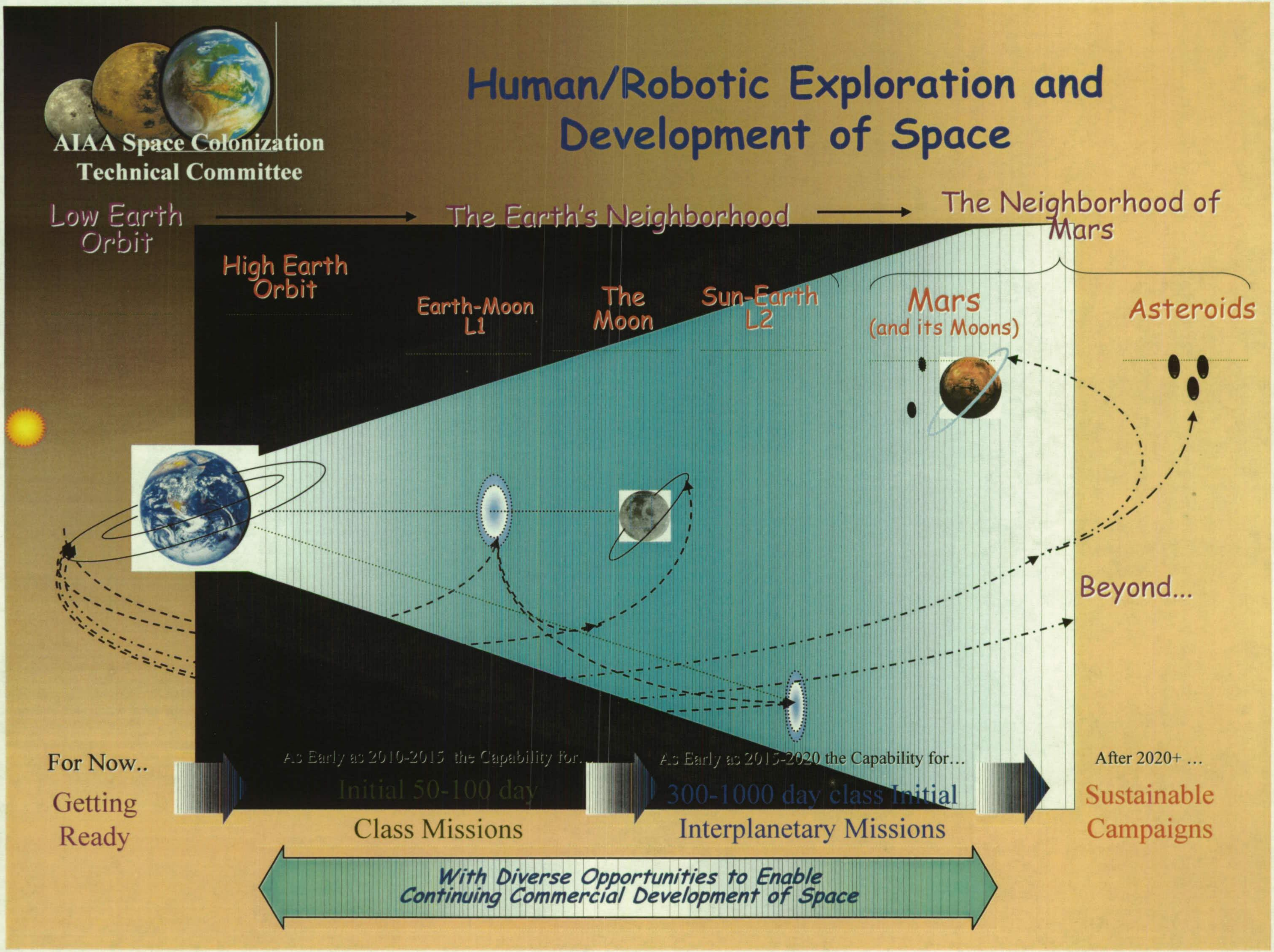
Expands Human Exploration & Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.



Enables Space Commercialization

- Develops material handling and processing technologies
- Provides infrastructure to support space commercialization
- Earth, Moon, & Earth-Moon space manufacturing, and product/resource development, resupply, & transportation



Human/Robotic Exploration and Development of Space
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Low Earth Orbit
The Earth's Neighborhood
The Neighborhood of Mars
High Earth Orbit
Earth-Moon L1
The Moon
Sun-Earth L2
Mars (and its Moons)
Asteroids
Beyond...
For Now..
Getting Ready
As Early as 2010-2015 the Capability for...
Initial 50-100 day
Class Missions
As Early as 2015-2020 the Capability for...
300-1000 day class Initial
Interplanetary Missions
After 2020+ ...
Sustainable Campaigns
With Diverse Opportunities to Enable Continuing Commercial Development of Space

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Planetary Resources and Products

Planetary Body	Space Resource	Potential Products
Moon	Atmosphere: Vacuum @10^{-9} to 10^{-12} torr Regolith: Pyroxene [$CaSiO_3$, $MgSiO_3$, $FeSiO_3$, Al_2SiO_5, $TiSiO_4$] (50%), Olivine [$MgSiO_4$, Fe_2SiO_4] (15%), Anorthite [$CaAl_2Si_2O_8$] (20%), Ilmenite [$FeTiO_3$] (15%) + traces [C <30 ppm , <200 ppm Cl, <400 ppm F, <100 ppm He, <10 ppm Ne, <10 ppm Ar] Potential: H_2O in permanently shadowed poles and ^3He on sun exposed surfaces	O_2, H_2, H_2O, Al, Mg, Ti, Fe, Ca, SiO_2 Bulk regolith (radiation shielding, building material) CaO, Al_2O_3, MgO, TiO_2, Ne, S, F, Cl (misc. reagents) ^3He (potential fusion applications) Surface and orbit solar electric and thermal power Photovoltaic cells
Mars	Atmosphere: CO_2 (95.5), N_2 (2.7), Ar (1.6), O_2 (0.15), CO (0.07), H_20 vapor (210 ppm), NO (100 ppm), Ne (2.5 ppm), Kr (0.3 ppm) @ 5.2 to 7.5 torr Regolith: SiO_2 (43.5), Fe_2O_3 (18.2), SO_3 (7.3), Al_2O_3 (7.3), MgO (6.0), Cl (0.8), TiO_2 (0.6), TBD (16.3) Surface/subsurface: deposits of frozen H_20 ice and CO_2	O_2, H_2, H_2O,Fe, Mg, Ti, Si Bulk regolith (radiation shielding, building material) MgO, TiO_2, N_2 , Ar, CO_2 Solar electric power

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Planetary Resources and Products (cont)

Near Earth Asteroids Aten asteroids Apollo asteroids Amor asteroids	Atmosphere: Vacuum @10^{-9} to 10^{-12} torr Regolith: Variable depending on type A - Olivine (or olivine-metal) C, F - Hydrated silicates, carbon, organics Q - Olivine, pyroxene, metal S - Metal, Olivine, pyroxene V - Pyroxene, feldspar (basalt) [Note: Metals include: Fe, Ni, Co with traces of Mn, Cr, Ti, Ca, Al]	Use as orbit to orbit transfer station and depot Specific products depend on physical makeup of the particular asteroid O_2, FeO, MgO, Si, Ni, Co, Mn, Cr, Ti, Ca, Al Zero/micro gravity and vacuum manufactured materials
Phobos (Mars)	Atmosphere: Vacuum @10^{-9} to 10^{-12} torr Regolith: hydrated silicates, carbon, organics (surface covered in 3' layer of fine powder. Subsurface ice possible)	O_2, H_2, H_2O, Si, SiO_2, hydrocarbon distillates, plastics Zero/micro gravity and vacuum manufactured materials
Demos (Mars)	Atmosphere: Vacuum @10^{-9} to 10^{-12} torr Regolith: hydrated silicates, carbon, organics; subsurface ice possible	O_2, H_2, H_2O, Si, SiO_2, hydrocarbon distillates, plastics Zero/micro gravity and vacuum manufactured materials
Titan (Saturn)	Atmosphere: N_2 (90 to 95%), CH_4 (5 to 10%), H_2 (0.3), and traces of hydrocarbons, water vapor, and nitrides @ 1.5 bar Regolith: water ice, silicates, liquid hydrocarbons	N_2, CH_4, hydrocarbon distillates, plastics

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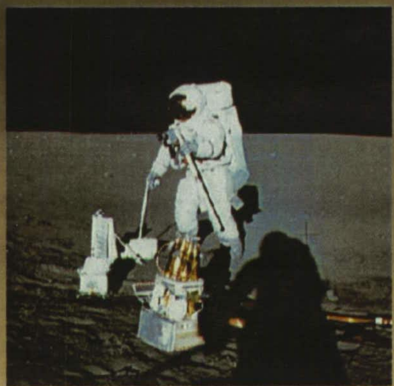
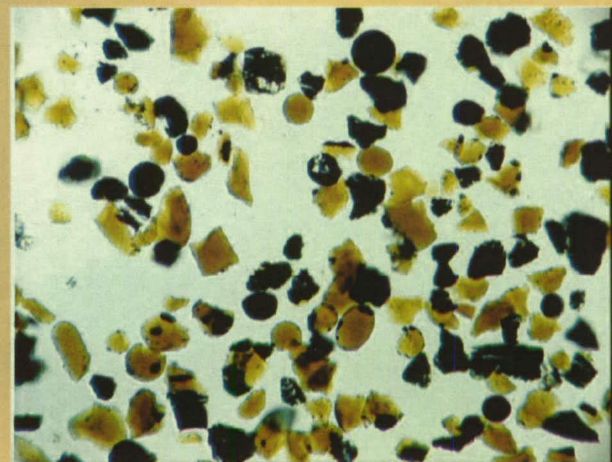
Lunar Environment Micrometeoroids, Abrasive Soil & High Vacuum

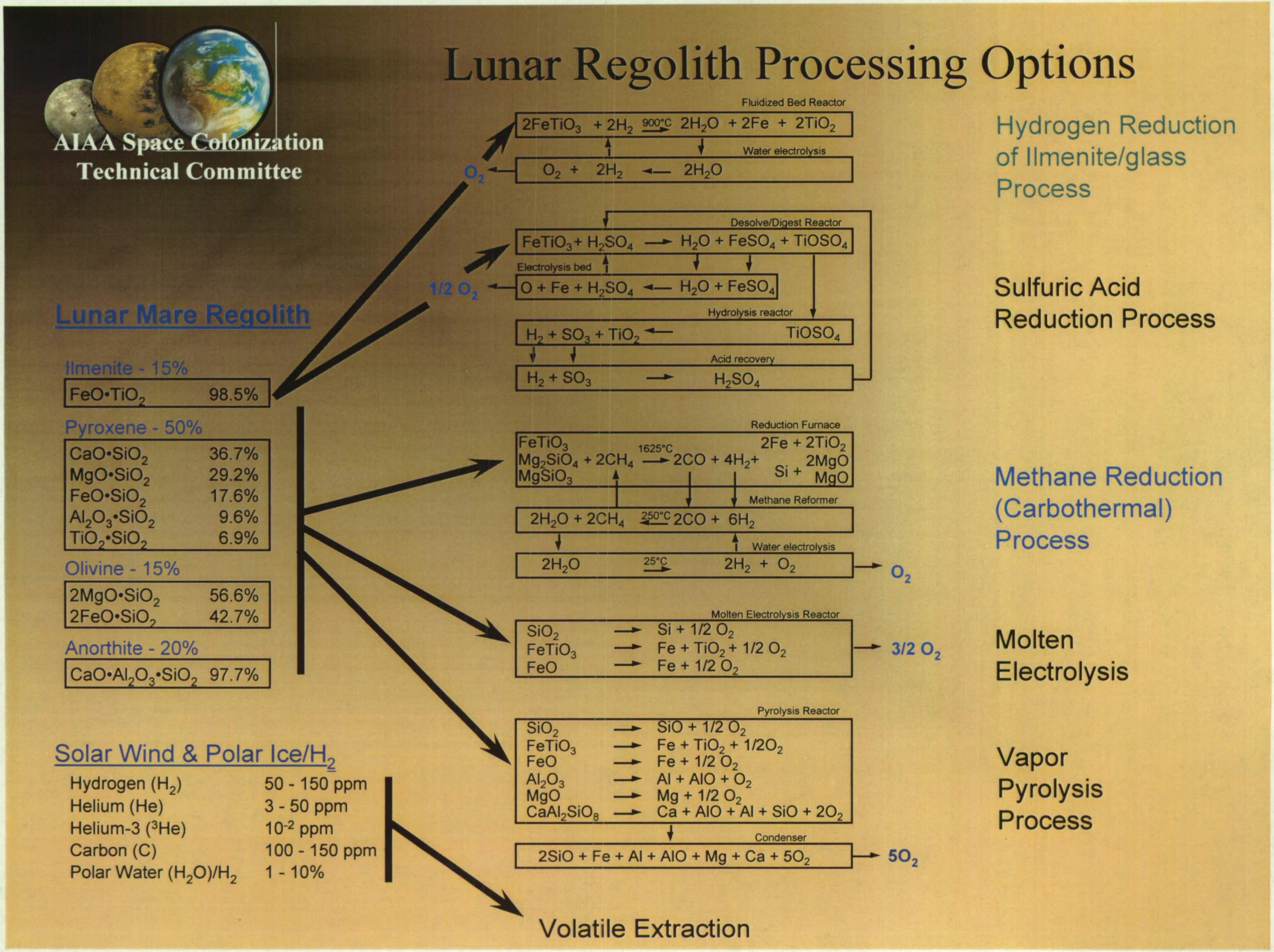


- Equipment will be under constant micrometeoroid bombardment.
  - Thin walled equipment components preferred for their low mass, will need an erosion-resistant coating.



- Lunar soil is extremely abrasive due to the lack of weathering.
  - Problem is increased by the tendency of the soil to carry a significant electrical charge which causes it to stick to everything.
  - Dust will likely have serious effects on humans, electrical systems, and mechanisms.

- Development of materials and cleaning methodologies will be important to any long-term mission.



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Lunar Regolith Processing Options
Fluidized Bed Reactor
2FeTiO3 + 2H2 900°C → 2H2O + 2Fe + 2TiO2
Water electrolysis
O2 ← O2 + 2H2 ← 2H2O
Hydrogen Reduction of Ilmenite/glass Process
Desolve/Digest Reactor
FeTiO3 + H2SO4 → H2O + FeSO4 + TiOSO4
Electrolysis bed
1/2 O2 ← O + Fe + H2SO4 ← H2O + FeSO4
Hydrolysis reactor
H2 + SO3 + TiO2 ← TiOSO4
Acid recovery
H2 + SO3 → H2SO4
Sulfuric Acid Reduction Process
Lunar Mare Regolith
Ilmenite - 15%
FeO•TiO2 98.5%
Pyroxene - 50%
CaO•SiO2 36.7%
MgO•SiO2 29.2%
FeO•SiO2 17.6%
Al2O3•SiO2 9.6%
TiO2•SiO2 6.9%
Olivine - 15%
2MgO•SiO2 56.6%
2FeO•SiO2 42.7%
Anorthite - 20%
CaO•Al2O3•SiO2 97.7%
Reduction Furnace
FeTiO3 / Mg2SiO4 + 2CH4 / MgSiO3 1625°C → 2CO + 4H2 + 2Fe + 2TiO2 / Si + 2MgO / MgO
Methane Reformer
2H2O + 2CH4 250°C ← 2CO + 6H2
Water electrolysis
2H2O 25°C → 2H2 + O2 → O2
Methane Reduction (Carbothermal) Process
Molten Electrolysis Reactor
SiO2 → Si + 1/2 O2
FeTiO3 → Fe + TiO2 + 1/2 O2
FeO → Fe + 1/2 O2
→ 3/2 O2
Molten Electrolysis
Pyrolysis Reactor
SiO2 → SiO + 1/2 O2
FeTiO3 → Fe + TiO2 + 1/2O2
FeO → Fe + 1/2 O2
Al2O3 → Al + AlO + O2
MgO → Mg + 1/2 O2
CaAl2SiO8 → Ca + AlO + Al + SiO + 2O2
Condenser
2SiO + Fe + Al + AlO + Mg + Ca + 5O2 → 5O2
Vapor Pyrolysis Process
Solar Wind & Polar Ice/H2
Hydrogen (H2) 50 - 150 ppm
Helium (He) 3 - 50 ppm
Helium-3 (3He) 10-2 ppm
Carbon (C) 100 - 150 ppm
Polar Water (H2O)/H2 1 - 10%
Volatile Extraction

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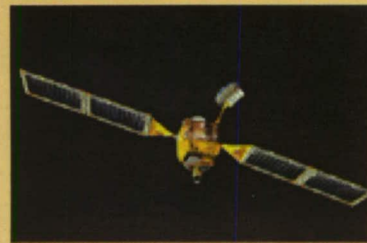
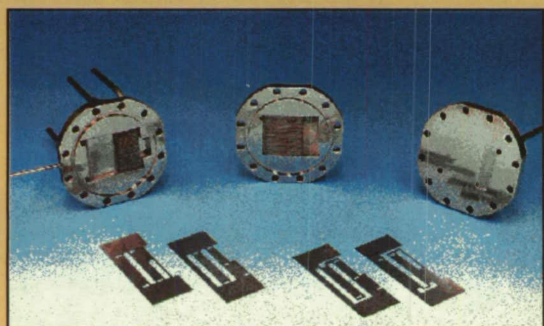
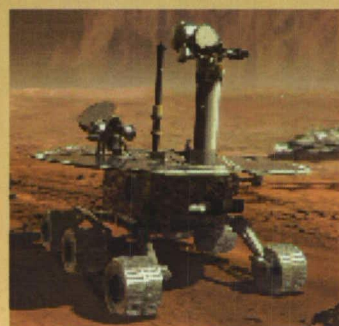
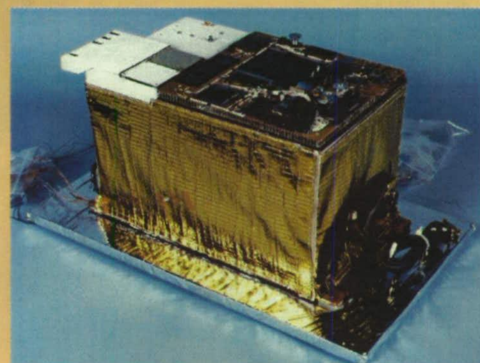
Mars ISRU Studies



- Focus has primarily been on Atmospheric processing.
  - Oxygen, Fuel, Water, Gas Acquisition & Separation
  - Dust may again be a problem
    - DART experiment was designed to study dust removal
    - Looking for flight opportunity on a future lander
- Chemical reactivity of soil needs to be understood.
  - Viking data showed strong soil reaction to warm temperatures and water.
  - Robotic program key to developing a better understanding.
- Sprit and Opportunity evidence for water







Mars ISRU Chemical Processes

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Carbon Dioxide (CO2)	95.5%
Nitrogen (N2)	2.7 %
Argon (Ar)	1.6%
Oxygen (O2)	0.15%
Water (H2O)	<0.03%

Primary Process Technologies
- Sabatier Reactor (SR)
- Zirconia Solid Oxide Electrolysis (ZE)
- Water Electrolysis (WE)
- Reverse Water Gas Shift (RWGS) Reactor
- Methanol Reactor (MR)

Consumable Option	Production Option*
O_2 Only	- **ZE** - RWGS & WE
O_2 & H_2O	- **RWGS & WE**
O_2/Methane (CH_4)	- **SR, WE, & ZE** - SR, RWGS, & ZE - SR & ZE
O_2/Methanol (CH_3OH)	- **ZE & MR** - RWGS, WE, & MR
O_2/Hydrogen (H_2)	- **WE**
O_2/Carbon Monoxide (CO)	- **ZE** - RWGS & WE

*Bold denotes preferred option at this time

Zirconia Solid Oxide Electrolysis (ZE)

$$2\,CO_2 \xrightarrow{900 - 1000\ C} 2\,CO + O_2 \qquad \Delta H = 283\ \text{kJ/mole}$$

Sabatier Catalytic Reactor (SR)

$$CO_2 + 4H_2 \xrightleftharpoons{200 - 300\ C} CH_4 + 2\,H_2O \qquad \Delta H = -165\ \text{kJ/mole}$$

Water Electrolysis (WE)

$$2\,H_2O \longrightarrow 2\,H_2 + O_2 \qquad \Delta H = 242\ \text{kJ/mole}$$

Reverse Water Gas Shift (RWGS)

$$2\,CO_2 + 2\,H_2 \xrightleftharpoons{400 - 650\ C} 2\,CO + 2\,H_2O \qquad \Delta H = 37.2\ \text{kJ/mole}$$

Methane Conversion to Hydrogen

$$CH_4 \xrightarrow{>900\ C} C_{(s)} + 2\,H_2 \qquad \Delta H = 75\ \text{kJ/mole}$$

$$C_{(s)} + CO_2 \xrightarrow{1000\ C} 2\,CO \qquad \Delta H = 172\ \text{kJ/mole}$$

$$CO_2 + CH_4 \xrightarrow{400 - 900\ C} 2\,CO + 2\,H_2 \qquad \Delta H = 247\ \text{kJ/mole}$$

Fuel Production from CO/CO_2 & H_2 (MR)

$$CO_2 \text{ or } CO + 2\,H_2 \longrightarrow CH_3OH,\ C_2H_4, \text{ or other Hydrocarbons}$$

Fuel Production from CO_2 & CH_4

$$CO_2 + 2\,CH_4 \longrightarrow C_2H_4 \text{ or other Hydrocarbons}$$

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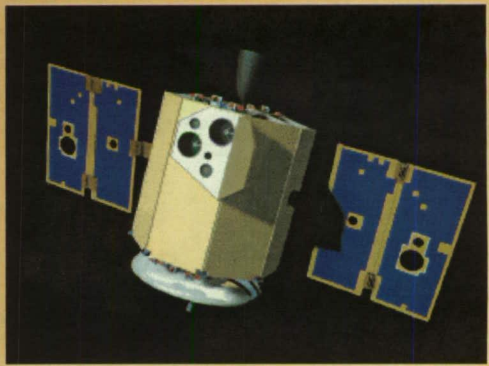
Lunar Ice?



- Lunar Prospector and Clementine detected elevated levels of Hydrogen at the Poles.
- One possible conclusion is that there is Water Ice in the permanently shaded areas of polar craters.
  - Hotly debated issue
  - "Ground-truth" is the best way to resolve the debate
- Lockheed Martin Astronautics and the Colorado School of Mines Technology Study.
  - Goal is to define the technologies needed for a small robotic system to explore Lunar "Cold Traps"
  - Part of the study will create an icy regolith simulant to characterize mechanical properties
- **Space Transportation Architectures and Refueling for Lunar and Interplanetary Travel and Exploration Report, Colorado School of Mines, KSC, Florida Institute of Technology, Northern Canadian Center for Advanced Technology, Global Aerospace Corp, and JSC**

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ISRU-Products

- Propulsion
  - Ascent vehicles
  - Extended Mobility Vehicles
    - Planes, Hoppers
- Energy Production and Storage
  - Fuel Cell Reactants
  - Solar Cell Production
- Raw Materials
  - Metals
  - Building Materials
  - Plastics

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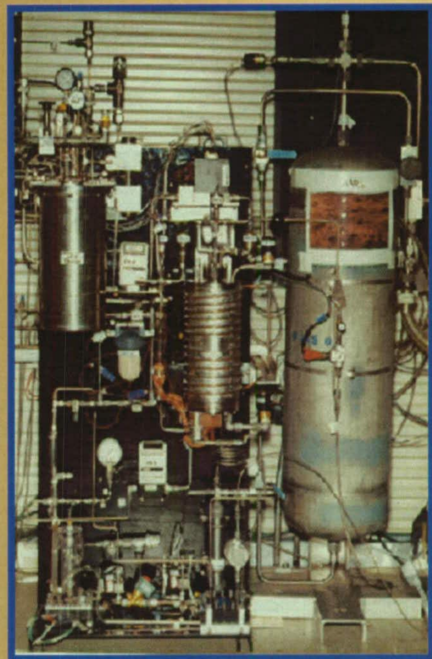
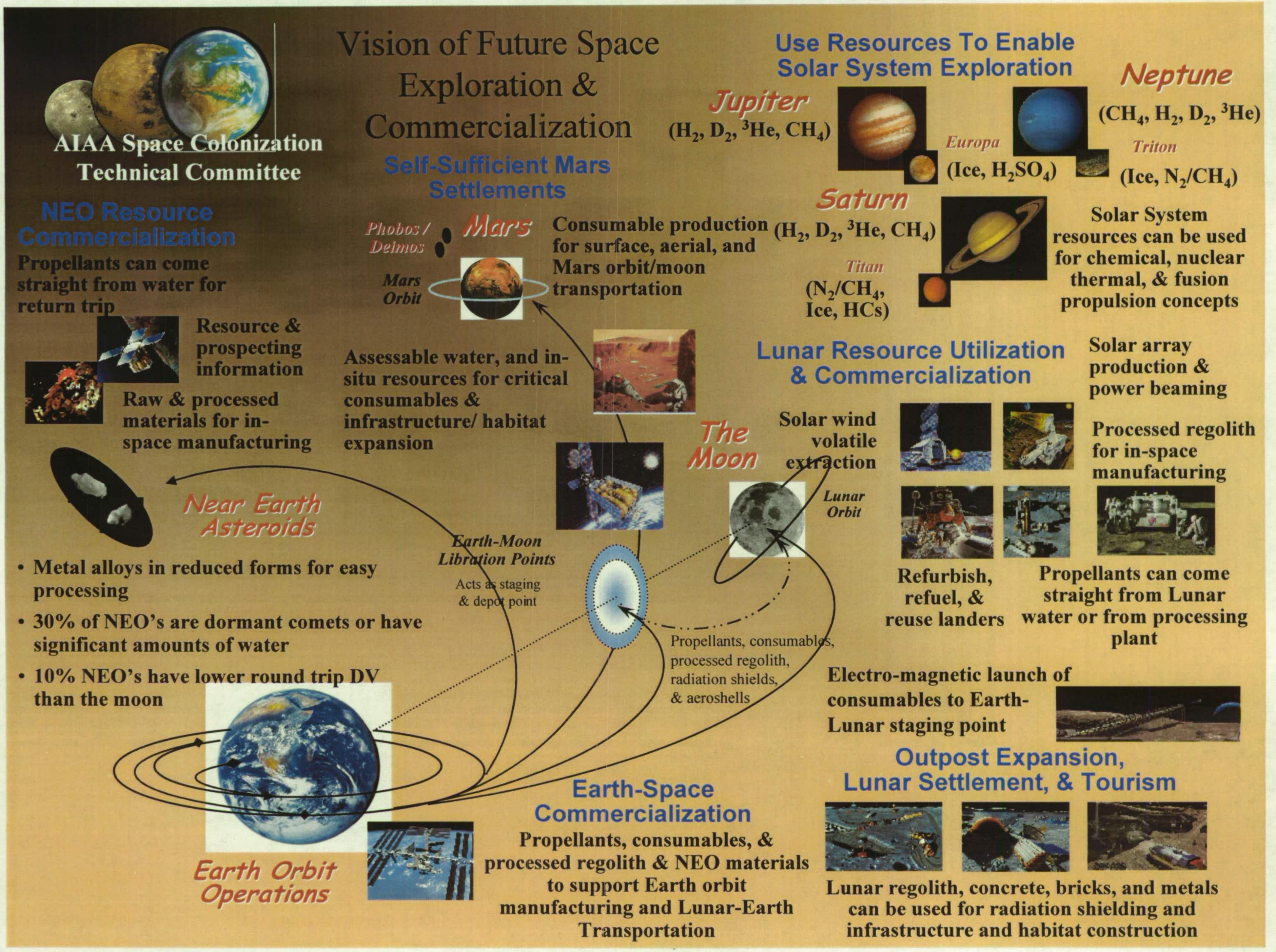
ISRU Processes

- Sabatier/Water Electrolysis (SWE)
  $CO_2 + 4H_2 \Rightarrow 2H_2O + CH_4 + \text{Energy}$
  $2H_2O + \text{Energy} \Rightarrow 2H_2 + O_2$
- Solid-Oxide Electrolysis
  $2CO_2 + \text{Energy} \Rightarrow O_2 + 2CO$
- Reverse-Water-Gas-Shift
  $CO_2 + H_2 + \text{Energy} \Rightarrow CO + H_2O$
- Carbothermal Process Produces Oxygen, Si, Fe from Lunar Regolith
- Higher Hydrocarbon Production





Vision of Future Space Exploration & Commercialization
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Use Resources To Enable Solar System Exploration
Jupiter
(H_2, D_2, ^3He, CH_4)
Europa
(Ice, H_2SO_4)
Neptune
(CH_4, H_2, D_2, ^3He)
Triton
(Ice, N_2/CH_4)
Saturn
(H_2, D_2, ^3He, CH_4)
Titan
(N_2/CH_4, Ice, HCs)
Solar System resources can be used for chemical, nuclear thermal, & fusion propulsion concepts
Self-Sufficient Mars Settlements
Phobos / Deimos
Mars
Mars Orbit
Consumable production for surface, aerial, and Mars orbit/moon transportation
Assessable water, and in-situ resources for critical consumables & infrastructure/ habitat expansion
NEO Resource Commercialization
Propellants can come straight from water for return trip
Resource & prospecting information
Raw & processed materials for in-space manufacturing
Near Earth Asteroids
• Metal alloys in reduced forms for easy processing
• 30% of NEO's are dormant comets or have significant amounts of water
• 10% NEO's have lower round trip DV than the moon
Lunar Resource Utilization & Commercialization
Solar array production & power beaming
Solar wind volatile extraction
The Moon
Lunar Orbit
Processed regolith for in-space manufacturing
Refurbish, refuel, & reuse landers
Propellants can come straight from Lunar water or from processing plant
Earth-Moon Libration Points
Acts as staging & depot point
Propellants, consumables, processed regolith, radiation shields, & aeroshells
Electro-magnetic launch of consumables to Earth-Lunar staging point
Outpost Expansion, Lunar Settlement, & Tourism
Lunar regolith, concrete, bricks, and metals can be used for radiation shielding and infrastructure and habitat construction
Earth-Space Commercialization
Propellants, consumables, & processed regolith & NEO materials to support Earth orbit manufacturing and Lunar-Earth Transportation
Earth Orbit Operations

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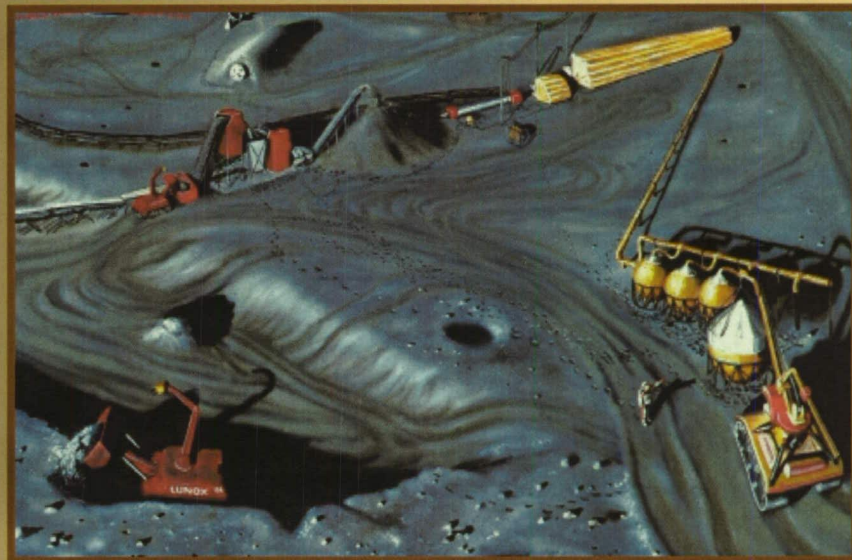
Lunar Missions

- **Products**
  - Water From Poles
    - Other Volatiles
  - Oxygen from Regolith
  - Metals and Silicates
  - Helium-3
- **Early Bases**
  - Water, Oxygen, Reactants
  - Propellants



Conceptual Lunar Mining Operation

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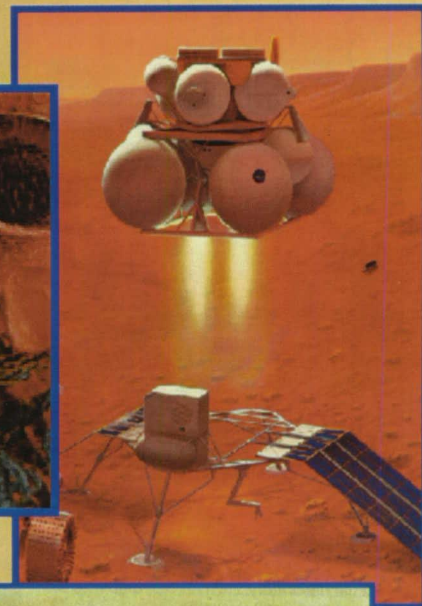
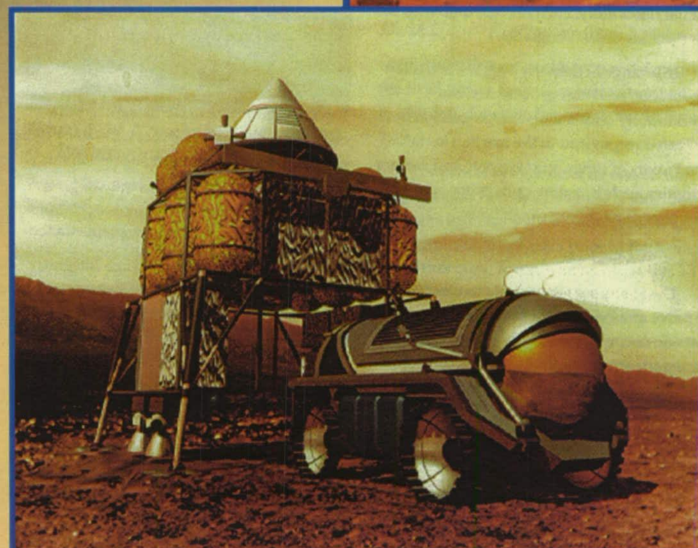
Mars Missions





Available Resources

- Carbon Dioxide from Martian Atmosphere
- Buffer Gasses; N_2, Ar
- Water from Regolith

Benefiting Missions

- Sample Return
- Extended Mobility Systems
- Depot-Based Missions

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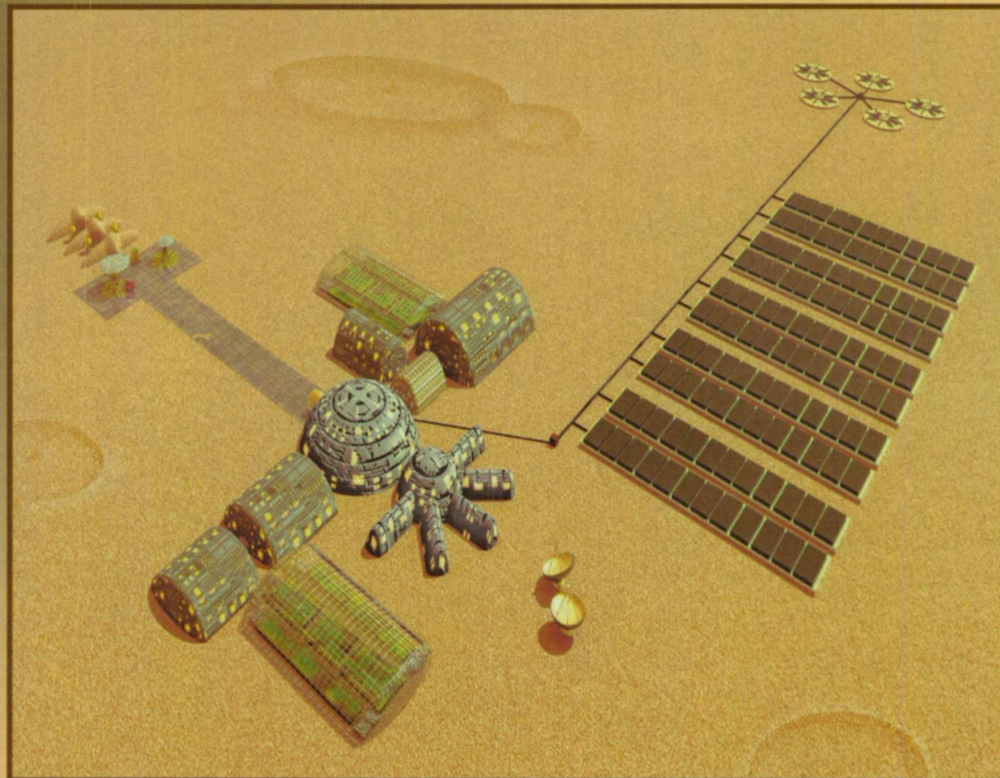
The Future

- Extended Human and Robotic Exploration
- Self-Sufficient Colonies
- True Space Economy



100-Person Mars Base Concept

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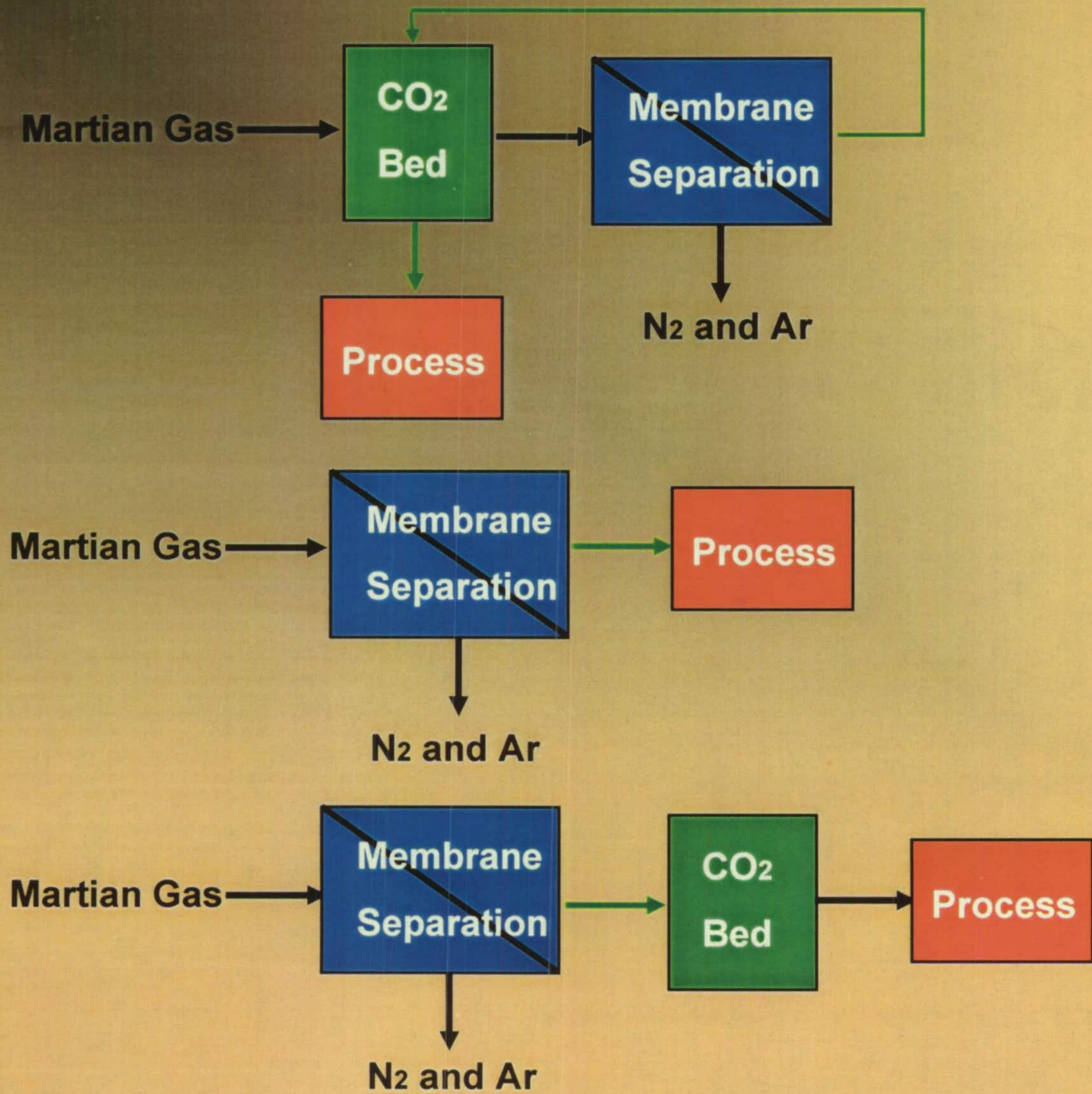
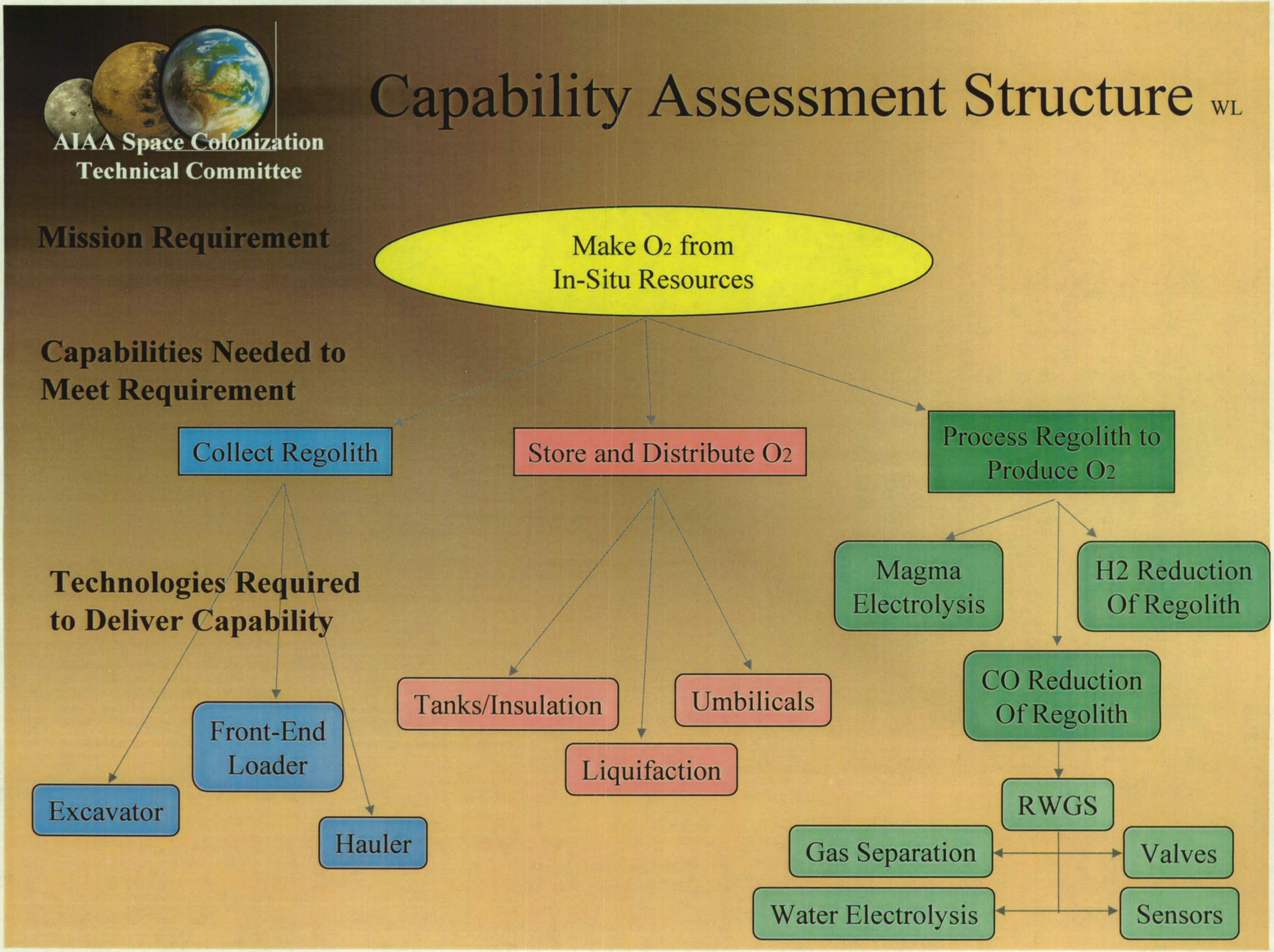
Source of Buffer Gases

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Capability Assessment Structure WL
Mission Requirement
Make O2 from
In-Situ Resources
Capabilities Needed to
Meet Requirement
Collect Regolith
Store and Distribute O2
Process Regolith to
Produce O2
Technologies Required
to Deliver Capability
Magma
Electrolysis
H2 Reduction
Of Regolith
CO Reduction
Of Regolith
Excavator
Front-End
Loader
Hauler
Tanks/Insulation
Liquifaction
Umbilicals
RWGS
Gas Separation
Valves
Water Electrolysis
Sensors

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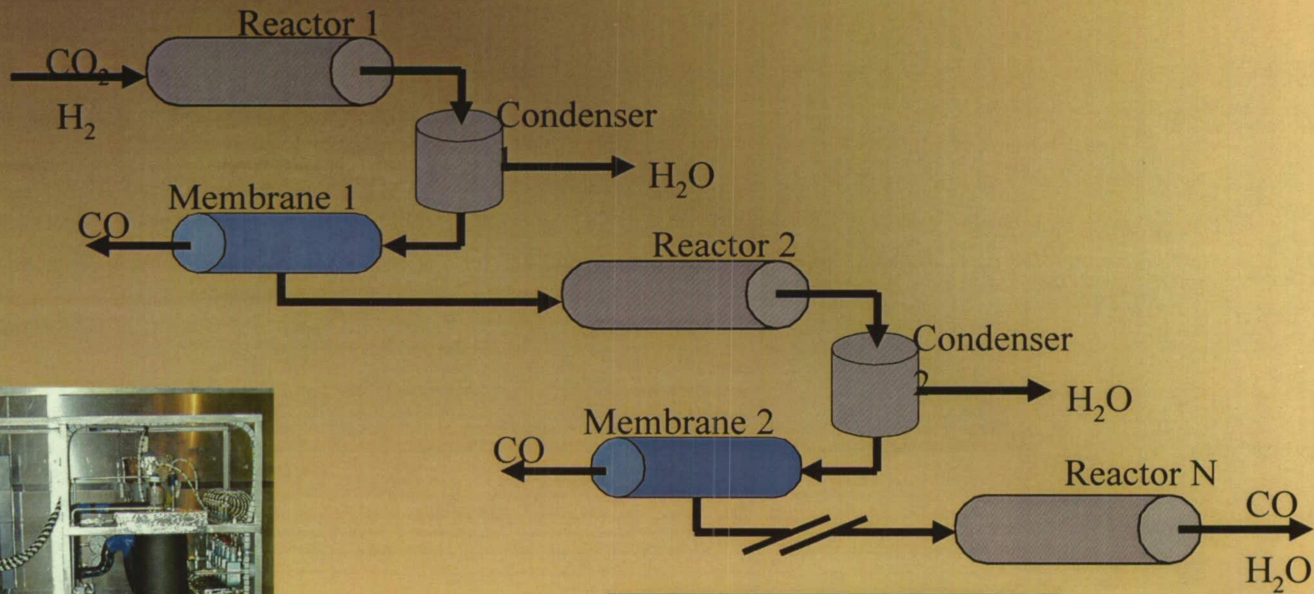
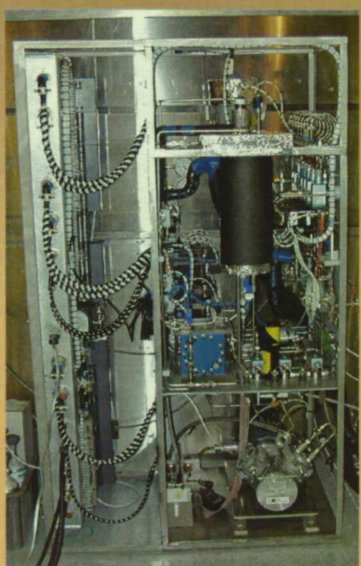
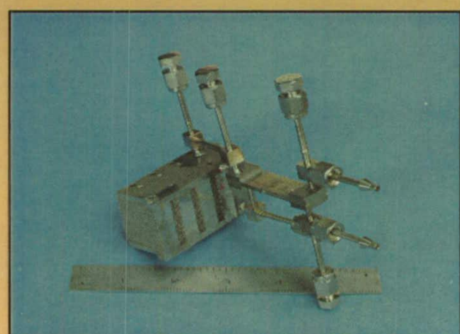
RWGS Oxygen Production JW

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

$$2\ H_2O - _{\text{Electrolysis}} \rightarrow 2\ H_2 + O_2$$







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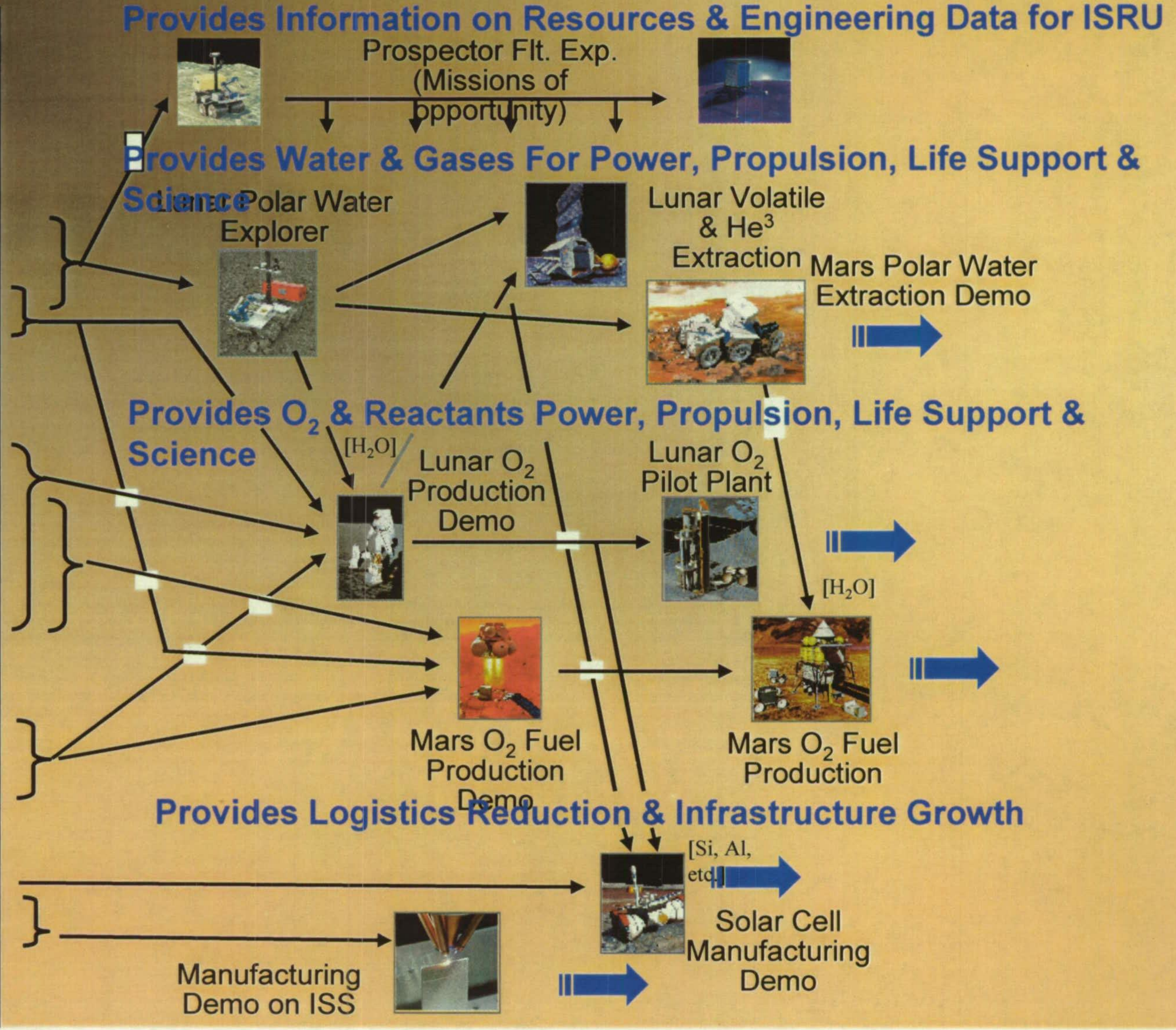
ISRU Research, Technology, & Mission Integration Roadmap JS

In-Situ Resource Excavation & Separation
- Regolith Excavation
- Thermal/Microwave Extraction
- H_2O Separation
- CO_2 & N_2 Separation

Resource Processing
- Carbothermal Regolith Processing
- CO/CO_2 Processing to Fuel
- H_2O Electrolysis
- Microchannel Chemical/Thermal Processing

Consumable Storage & Distribution
- Cryocoolers
- Light Weight Tanks
- Disconnects/pumps

In-Situ Manufacturing
- Solar cell production
- Metallic part fab
- Polymer part fab.



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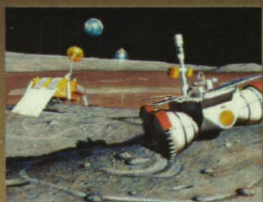
Surface Exploration Infrastructure Concept JS

- ☑ ***Power-rich environment enables new science***
- ☑ ***Modular hardware & common consumables for reduced logistics, and increased flexibility & safety***
- ☑ ***Initial ISRU plant on Lander or Habitat produces consumables for EVA and rover life support & power initially***
- ☑ ***Infrastructure is easily expandable from simple robotic lander and rover to full human presence***

Robotic Precursors & Tele-robotic Science

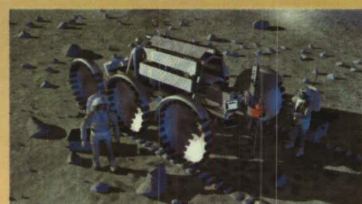


- Short trips from habitat or lander
- Lots of start/stops for science
- Lander or habitat resupplies Fuel Cell (FC) reactants when rover returns with samples

EVA Astronaut w/ Robotic Assistant

- Short trips (4 to 10 hrs)
- Rover carries equipment & supplies power
- Resupply EVA O_2 & FC reactants from Rover to extend EVA or emergency

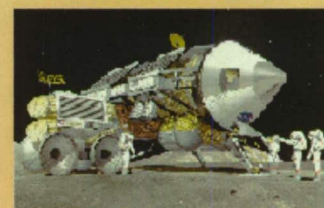
EVA Astronauts w/ Pressurized or Un-Pressurized Rovers



- Short trips from habitat
- 8 to 10 hrs
- Lots of start/stops for science
- Resupply EVA O_2 & FC reactants from Rover to extend EVA or emergency

- Long trips from habitat
- 1 to 5 days
- EVA's only for pre-screened science
- Rover stores EVA O_2 and power consumables – recharged before each EVA

Consumable Production



- Initial ISRU plant on Habitat Lander
  - Propellant tanks used for FC reactant & ELCSS backup storage
- Crew Lander reused with ISRU Propellant

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Flow for In-Situ Resource Utilization

Supporting Research & Tech → **Self-Sufficient Space Systems** → **System-Level Tech. Demos**

Supporting Research & Tech

Power/Thermal/Chemical Technology

- Vacuum Vapor Deposition
- CO_2 & N_2 Separation
- High Pressure H_2O Electrolysis
- CO_2 Electrolysis
- Hydrocarbon Reformers
- Microchannel Heat Exchangers
- Microchannel Reactors
- Microchannel H_2O Separators
- Hydrocarbon Fuel Processors

Self-Sufficient Space Systems

In-Situ Manufacturing

- Metallic Parts Mfg
- Polymer Parts Mfg
- Ceramic Parts Mfg
- Supporting Processes Systems
- Locally Integrated Sys. Components
- Locally Manufactured Energy Systems

Resource Excavation & Separation

- Regolith Excavation
- Material Transport
- Electro/Thermal Separation
- Atmosphere/Volatile Collection & Separation
- Physical/Mechanical Separation
- Electromagnetic / Electrostatic

Resource Processing and Refining

- Mineral & O_2 Extraction
- Water-CO_2 Processing
- Ceramic & Glass Production
- Concrete & Brick Production
- Hydrocarbon & Plastic Production
- In-Situ Bio Support
- In-Situ Bio Processing

Surface Construction

- Surface Prep (Materials Moving & Conditioning)
- Excavation & Tunneling
- Structure/Habitat Fabrication
- Launch & Landing Site Construction

Consumable Storage & Distribution

- ISRU Cryogenic Fluid Liquefaction, Storage, and Distribution
- Life Support & Gas Consumables Cache
- Processing Reagent and Non-Cryogenic Storage and Distribution
- Hazard Detection and Suppression
- Distribution Systems

System-Level Tech. Demos

Lunar/Planetary Exploration Demos

- ISS Manufacturing TFD (2012)
- Solar Array TFD (2015)
- Mars Drilling TFD (2012)
- Lunar Polar H_2O TFD (2013)
- Mars Regolith H_2O TFD (2019)
- Lunar O_2 Prod. TFD (2015)
- Mars ISPP TFD (2011)
- Mars ISPP Sample Return (2016)
- Lunar Construction TFD (2018)

January, 15 2004

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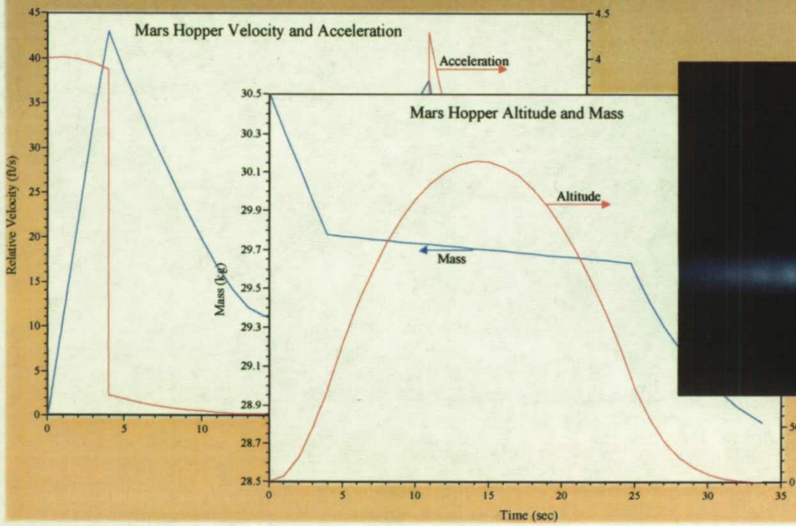
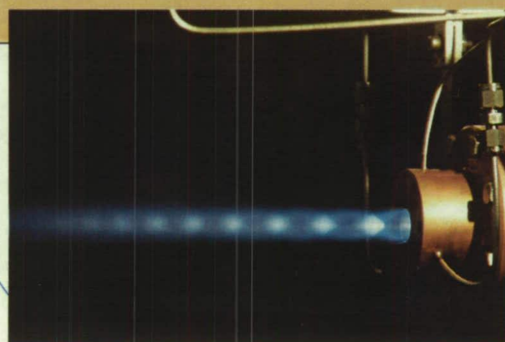
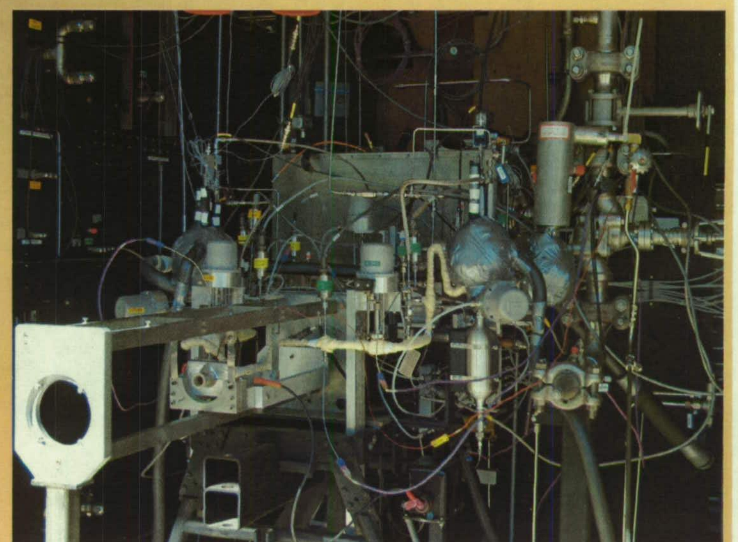
ISRU Mars Demonstration Concept

GRC

- Mars In-situ Propellant Rocket (MIPR)
  - Fly autonomously on Mars, manufacturing CO/O_2 from the atmosphere between each flight
  - Explores the Martian surface under rocket power, carrying a suite of science instruments over a range of hundreds of meters per hop
- Engine System: develop and demonstrate self-pressurization, natural engine throttle-down capability
- Power system: solar arrays and self-righting system
- Conceptual design analysis and trades: range and frequency of hops as function of dry weight, production plant, power







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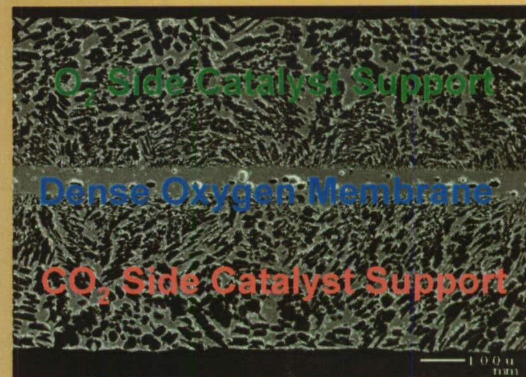
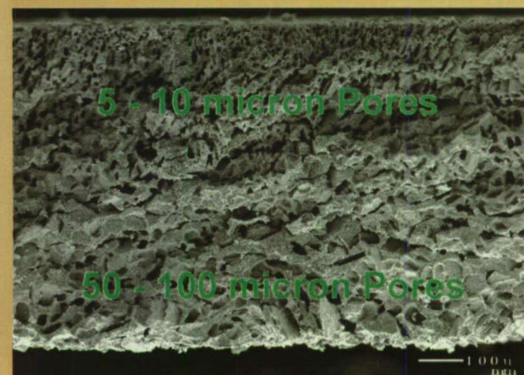
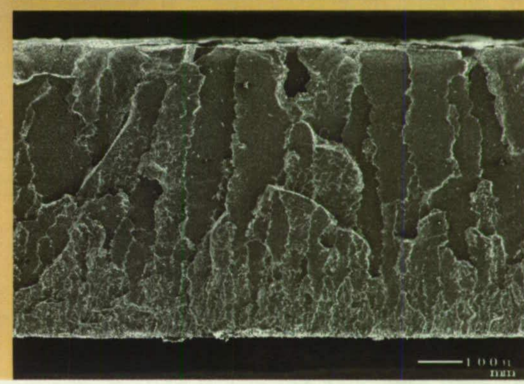
ISRU Production Technologies - Solid Oxide Fuel Cell Research (SOFC)

- Modified tape cast processing technique developed
  to fabricate SOFC with functionally graded and engineered pore structure
- Thin membrane allows for higher oxygen ion flux
- Porous support structures are impregnated with active electrocatalyst for CO_2 electrolysis and O_2 production
- Porous zirconia support allows wider range of electrocatalyst materials to be used
- Graded Pore Catalyst Support and Columnar Pore Catalyst Support fabricated with patent-pending NASA modified tape casting process. No pore formers or lamination required







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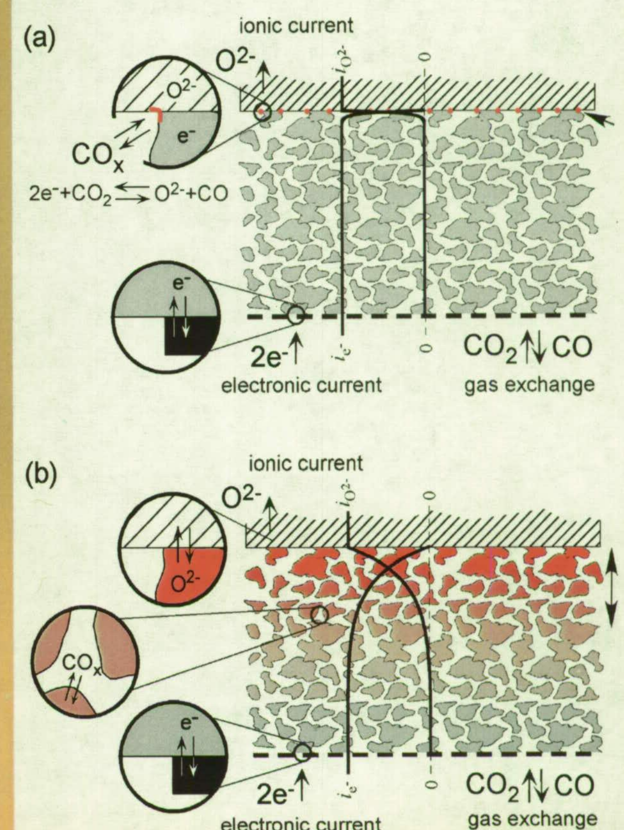
ISRU Production Technologies

- Increase life of SOFC electrodes by investigating and characterizing the performance and long-term degradation of electrode materials
- Use Mixed-Ionic-Electronic-Conductor to increase the three-phase boundary area

- Fuel Reforming (Aero program)
  - Chemistry is different but processes are similar
  - Need help defining/exploiting synergy here

Fig. 2. Active region for CO_2 reduction: a) porous platinum. b) a porous mixed-conductor.



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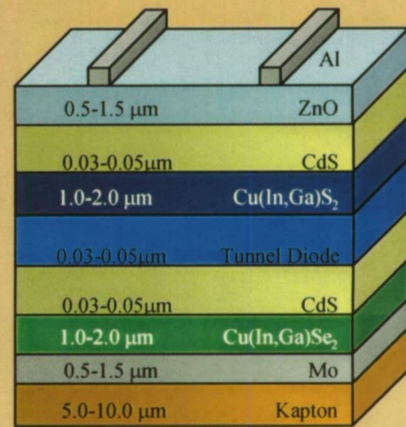
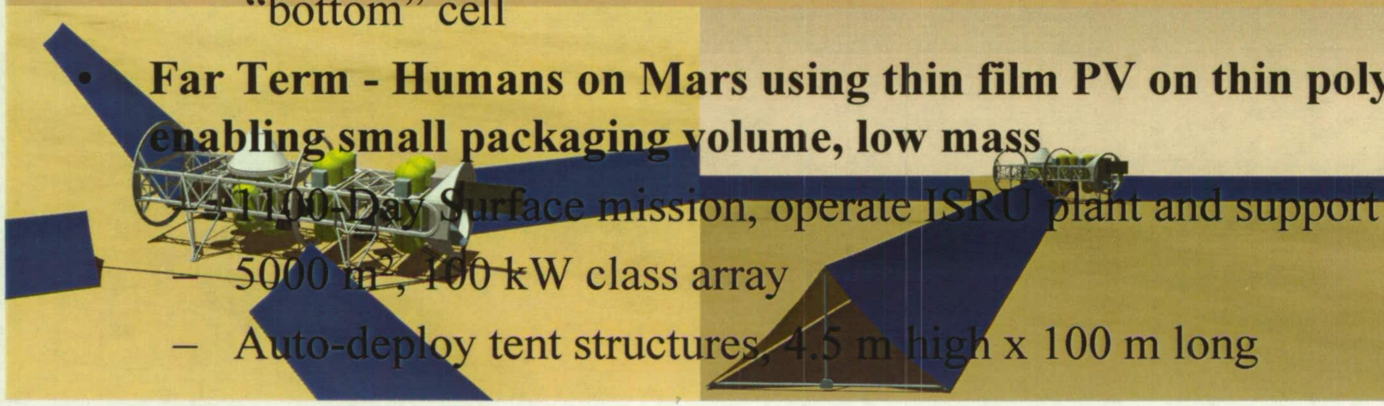
Space Power for ISRU - Solar



- **Chemical-based thin film deposition**
- **Ultra Lightweight Thin Film Solar Cell Arrays > 1 kW/kg**
  - Directly onto metallized space-qualified Kapton™ substrates
  - Low-temperature chemical Vapor Deposition
  - Electrochemical Deposition
  - Chemical Bath Deposition
- **GRC Milestones (Goal: 20% dual-junction CIS-based thin-film cell)**
  - Demonstrated 9% AMO $Cu(In,Ga)S_2$ thin-film "top" cell
  - Demonstrated 12% AMO $Cu(In,Ga)Se_2$ thin-film "bottom" cell
- **Far Term - Humans on Mars using thin film PV on thin polymer membrane enabling small packaging volume, low mass**
  - 1100-Day Surface mission, operate ISRU plant and support crew
  - 5000 m^2, 100 kW class array
  - Auto-deploy tent structures, 4.5 m high x 100 m long



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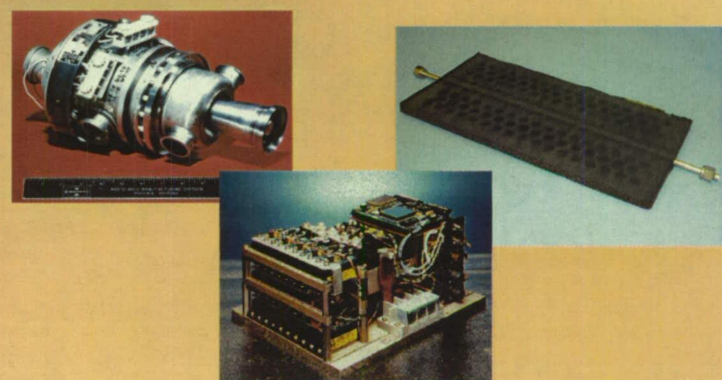
Space Power for ISRU - Nuclear

- Jupiter Icy-Moons Orbiter (JIMO)
  - Phase A studies investigating applications of JIMO class reactors for surface power applications in addition to Nuclear Electric Propulsion (NEP) missions
  - A range of reactor power is required depending on energy conversion selected (dynamic vs. static) and mission requirements
- GRC, as part of a larger agency team, is conducting architectural studies & systems analysis for reactor based power systems for both surface power and in-space NEP transportation systems
- GRC is responsible for system trades, systems analysis, architectural studies requirements development and supporting technology development for:
  - Reactor to energy conversion interface
  - Energy conversion systems
  - Heat rejection systems
  - High power management and distribution systems
  - Interface/requirements for power to ISRU



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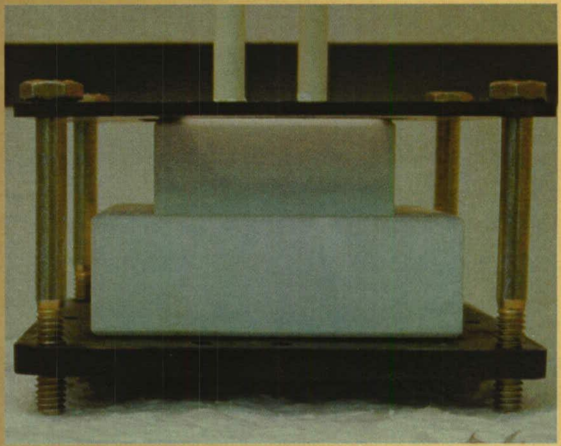
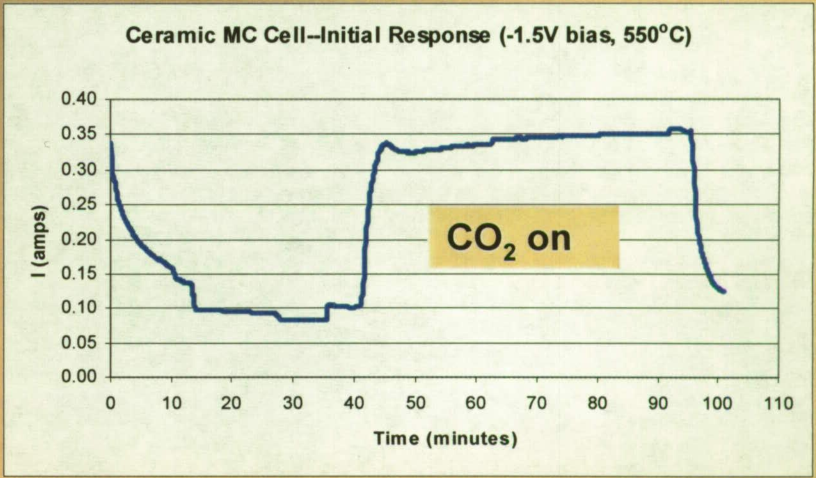
ISRU Technology Development Alternative Oxygen Production

- **Molten Carbonate Cell**
  - Lower Power and Temperature than Zirconia-based electrolysis.
- **Ionic Liquids (Low TRL)**
  - "Room Temperature" Liquid that will allow the electrolysis of dissolved Carbon Dioxide
  - Low temperature solution to the CO2 electrolysis problem.
  - Small lab demonstration completed, more work needed to synthesize a stable Ionic Liquid.



Molten Carbonate Test Cell



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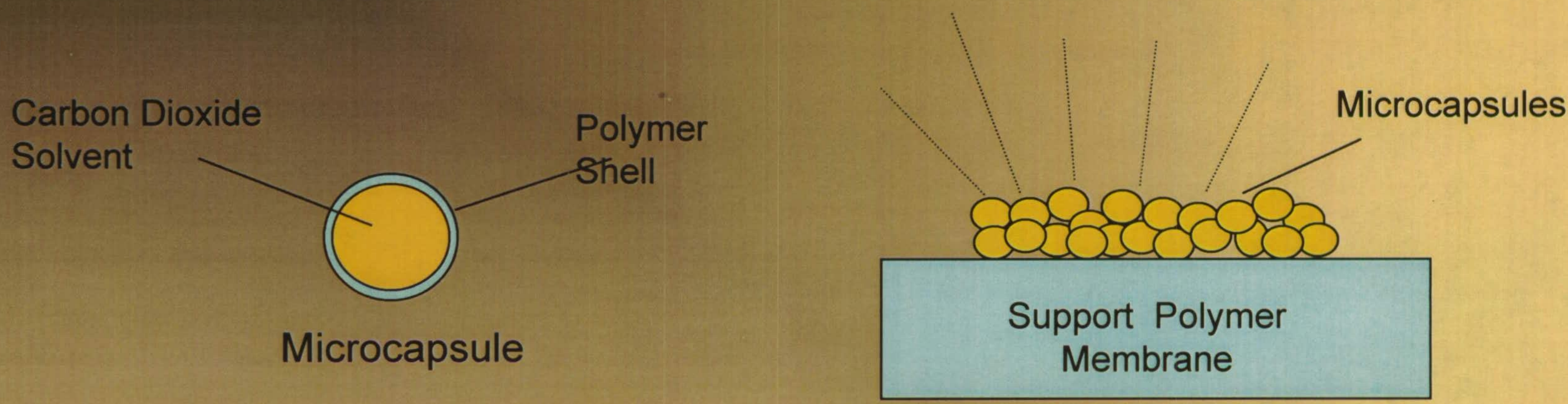
Gas Separation
Immobilized Liquid Membrane



- KSC Invention that will allow the creation of highly selective gas separation membranes.
- Early work suggests that a 10,000 to 1 selectivity of CO_2 vs. O_2 can be obtained.
- Diagram shows a microcapsule and a group of microcapsules on a porous membrane.
- Applications in Habitat and EVA air revitalization and ISRU process gas separation

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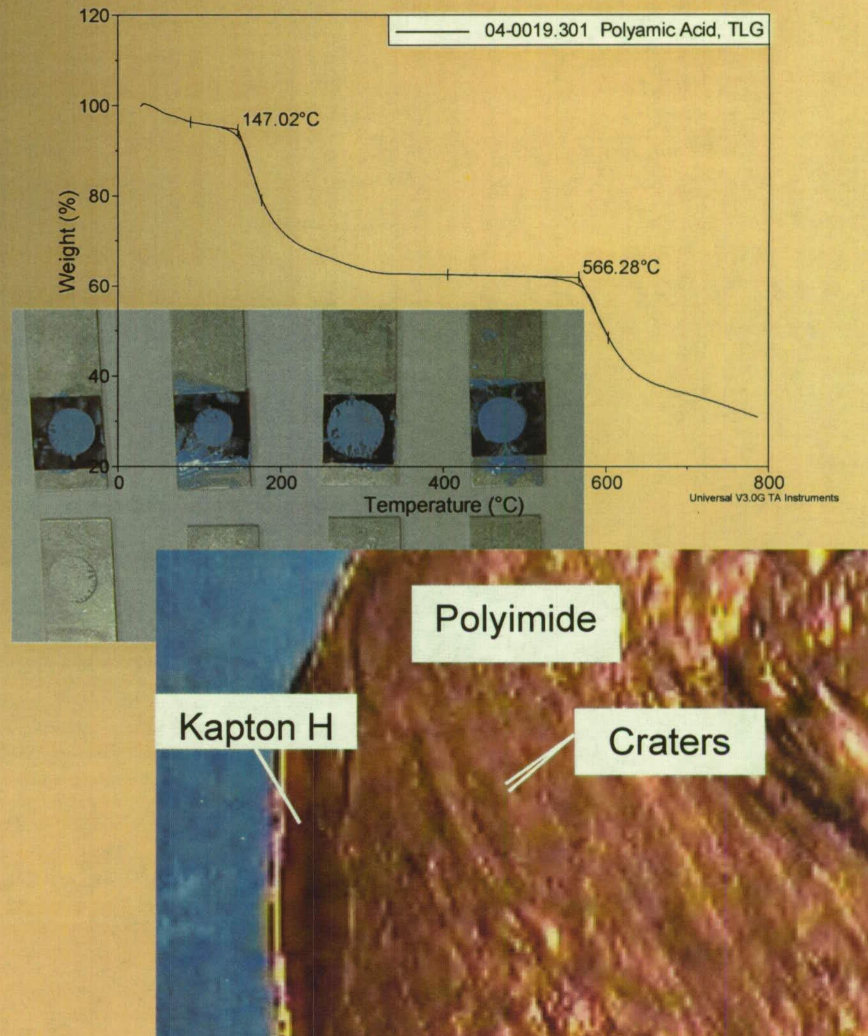
Self-Healing Wire Insulation

- Kapton wire breaks are common on all aerospace vehicles
- KSC has a development program underway in partnership with the FAA and US Air Force to develop Self-Healing Wire Insulation
- Leverages off of the work we've done in microencapsulation for Halon replacement and membrane separation.
- Early years of the program will yield an insulation repair kit where the tech will only have to apply the repair material over the breach and initiate cure manually.



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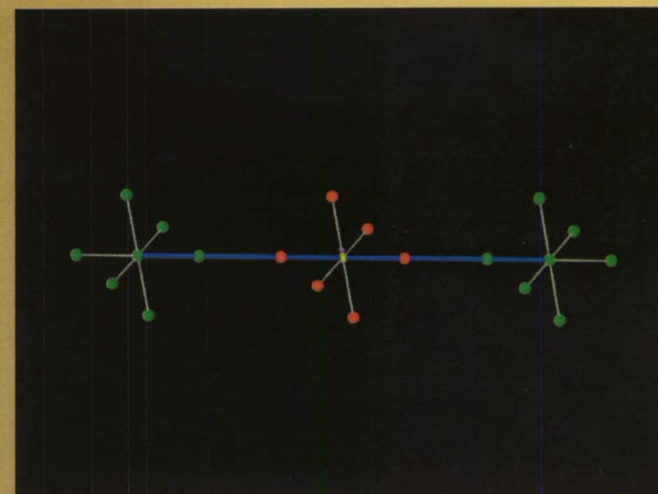
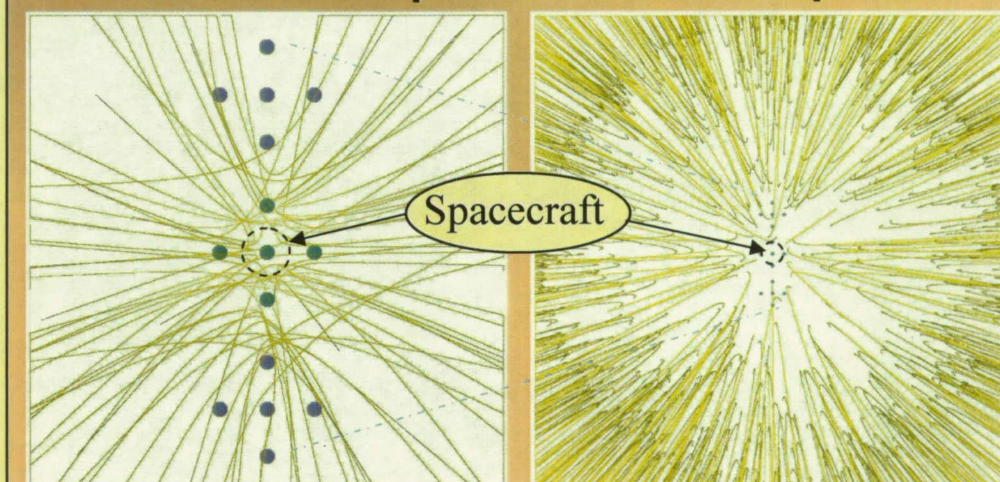
Electrostatic Radiation Shielding



- Proposed lightweight solution to the space radiation problem, self-inflating charged spheres create an electrostatic field that repels charged radiation.
- Eliminates the secondary radiation caused by passive shields.
- Reliable, achievable electrostatic generator technology used to charge the spheres.
- Current research is on momentum transfer and power requirements.
- To be published in 2004 IEEE Aerospace Conference Proceedings

Protons and ions repelled: **Electrons repelled:**



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Collapsible Cryogenic Storage Tanks

- Dedicated storage tank for in-situ produced propellants or consumables.
  - NOT a flight tank
- Very efficient packaging for launch
- Tested to date for LOX compatibility and temperatures

Tank Bladder

Demonstration of Completed Tank Expandability

Liquid Oxygen Transport/Sensor Research

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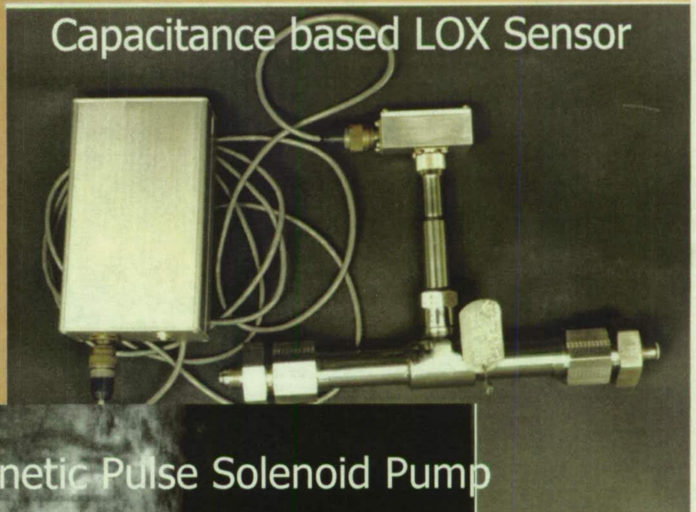
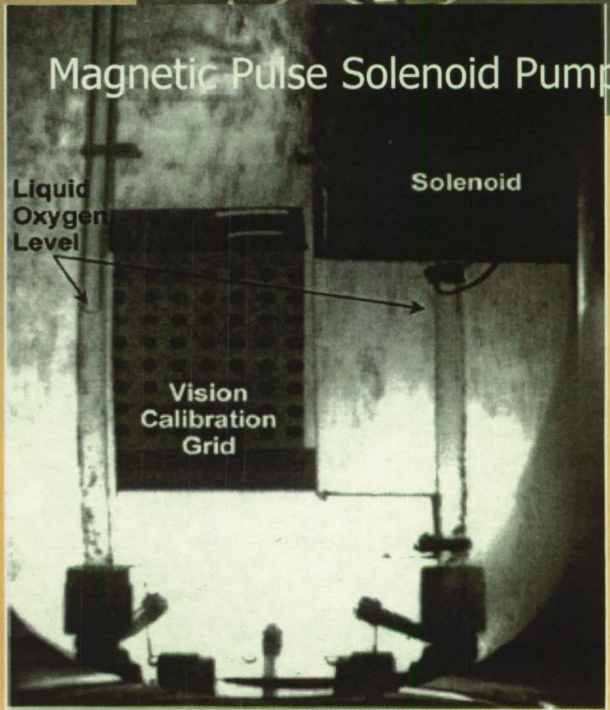
- Both capacitive and inductive liquid oxygen sensors have been demonstrated to measure density, total mass, and bubbles.
- Two non-mechanical methods for pumping LOX have been demonstrated using magnetic fields, a pulsed solenoid method and a thermal gradient approach.
- These devices allow LOX to be transported and monitored with no moving parts, just coils, plates, and electronics.
- Currently we are extending our capacitive sensor work to operate in the high pressure LOX tanks at SSFC.
- We have six publications and one patent in this area.





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SRU Sessions Moon & Mars

- Session E04. Space Resource Utilization on Mars
  - Spiral Development of a Deep Drill for Planetary Exploration Leveraging Terrestrial Mining
  - Effect of Temperature on Membrane Separation of Gases from the Martian Atmosphere
  - *In-Situ* Resource Utilization Robotic Precursor Missions for Human Exploration of Mars
  - Microchannel Reactors for ISRU Applications

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SRU Sessions Moon & Mars

- Session E07. Space Resource Utilization on the Moon
  - Solar Thermal Power System for Lunar ISRU Processes
  - Validation of the Bucket Wheel Excavator Design As a Primary Lunar Regolith Mining Mechanism
  - Carbon Reduction for Oxygen Production
  - Granular Materials and the Risk They Pose for Success on the Moon and Mars

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