IN-SITU RESOURCE UTILIZATION (ISRU) DEVELOPMENT PROGRAM

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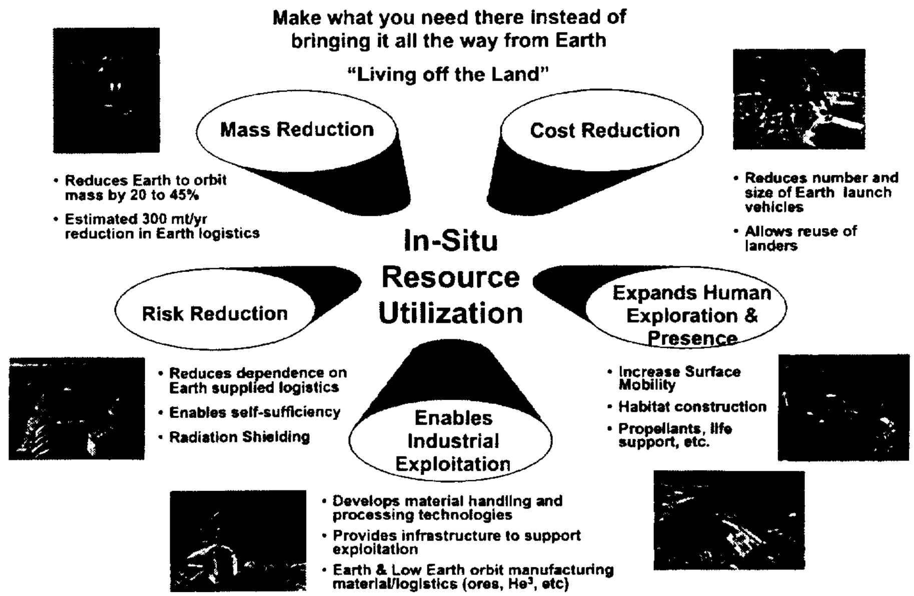
Why In-Situ Resource Utilization (ISRU)?



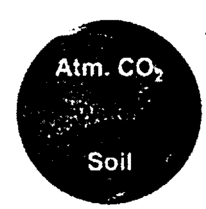
Resources and ISRU Products

Regolith
Oxygen (45%)
Silicon (21%)
Aluminum (13%)
Calcium (10%)
Iron (6%)
Magnesium (4%)
Other (1%)

Water
0.5 to 1% at poles?

Solar Wind
Hydrogen (50 - 100 ppm)
Helium (3 - 50 ppm)
He^3 (4 - 20 ppb)

Soil*
Silicon Dioxide (43.5%)
Iron Oxide (18.2%)
Sulfur Trioxide (7.3%)
Aluminum Oxide (7.3%)
Magnesium Oxide (6.0%)
Calcium Oxide (5.8%)
Other (11.9)
Water (?)
*Based on Viking Data



Atmosphere
Carbon Dioxide (95.5%)
Nitrogen (2.7%)
Argon (1.6%)
Oxygen (0.1%)
Water (parts per million)

Lunar Resources & Products

- Lunar regolith contains 45% oxygen by mass that can be used for propulsion, power generation, and crew breathing
- Lunar soil could be used for crew radiation protection
- H_2 and He (including He^3) from the solar wind are available at very low concentrations (parts per million) for fuel production and fusion reactors on Earth
- Aluminum, iron, and magnesium can be used in construction
- Silicon can be used to produce solar cells for power generation
- Ice in the lunar regolit can be used for life support or to make propellants for propulsion and power generation

Mars Resources & Products

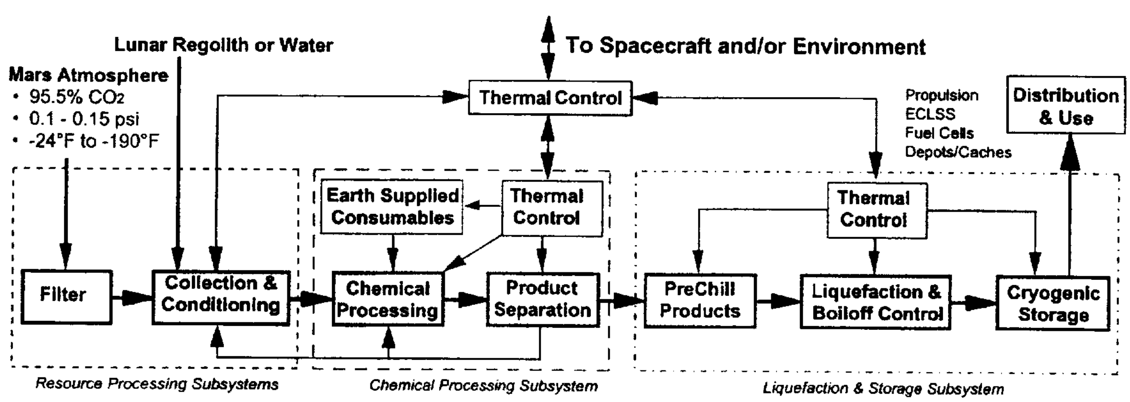
- The atmosphere contains >95% carbon dioxide that can be used to make oxygen and fuels
- Atmospheric nitrogen (N_2) and argon (Ar) can be used for life support, experiment carrier gases, inflating structures, purging dust from hardware, etc.
- Water in the atmosphere and in the soil (if available) could be extracted for use in life support, propulsion, and power generation
- Further information is required to determine how best to extract and use Mars soil based resources, especially water content

ISRU Term Definitions

- **In-Situ Resource Utilization (ISRU)**
  - Covers all aspects of using or processing local resources for the benefit of robotic and or human exploration. Examples:
    - > Using dirt/regolith for radiation shielding
    - > Making structures/habitats and solar cells from processed resources
    - > Making propellants or other consumables
- **In-Situ Consumables Production (ISCP)**
  - Is a subset of ISRU that covers all aspects of producing consumables from local resources
  - Consumable products/needs include:
    - > Propellant for ascent, hoppers, or Earth return
    - > Reagents for fuel cells
    - > O_2, H_2O, and N_2 for Environmental Control & Life Support System (ECLSS) backup
    - > Gases for purging or inflating habitats/structures
    - > Heat for spacecraft/habitat thermal control
- **In-Situ Propellant Production (ISPP)**
  - Is a subset of ISCP that covers all aspects of producing propellants from local resources for the benefit of robotic and or human exploration
  - ISPP requires the least amount of infrastructure to support and provides immediate benefits to mission plans

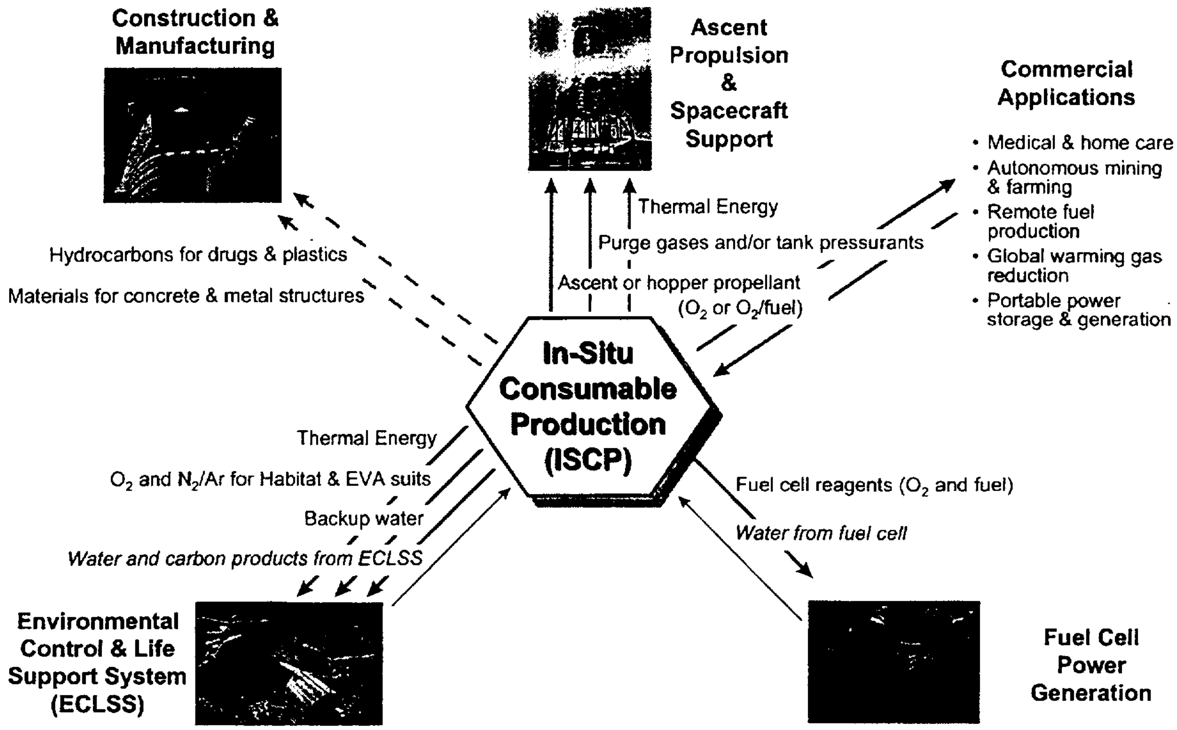
Note: Most work performed to date is specific to ISPP at this time

ISCP Process Diagram

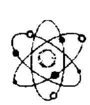


- *Resource Processing Subsystems*: Collects and prepares in-situ resources for use in process subsystem
  - Filtration, and collection & conditioning using adsorption beds or compressors for gas resources
  - Shoveling, mining, sorting, sifting, and grinding for solid resources
- *Chemical Processing Subsystems*: One or more chemical reactions and reactant/product separations to change the collected resource into usable products.
  - The Chemical Processing Subsystem defines the ISCP products, Earth consumable needs, and the system complexity and power characteristics for the ISCP plant
- *Liquefaction & Storage Subsystems*: Many in-situ products are gases. To efficiently store large quantities of these in-situ products, liquefaction and storage as a cryogenic liquid is required

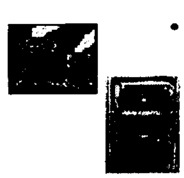
Possible Consumable Interaction



ISCP Development Challenges



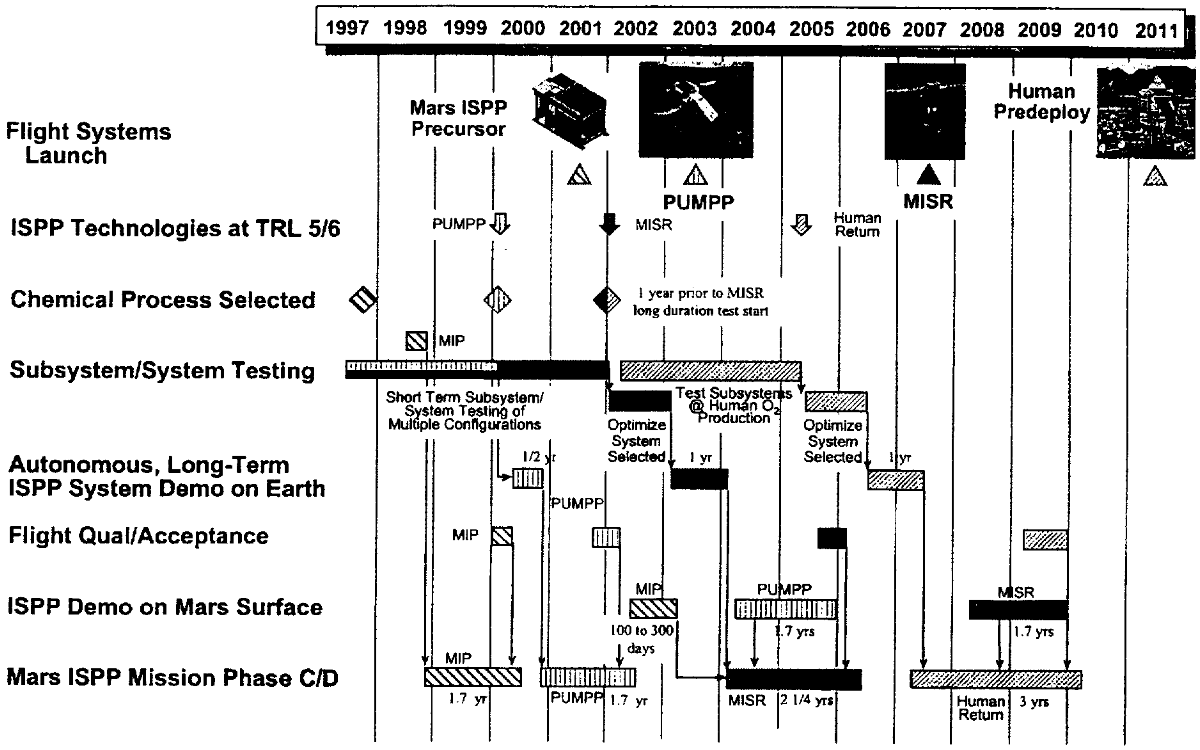
- **Chemical Process Development**
  - Chemica/separationl conversion efficiency
    - > Earth supplied consumable limitations
  - Thermal integration and management
  - Complexity
- **Operational Environment/Surviviability**
  - Autonomous control & failure recovery
    - > No crew for maintanance
    - > Non-continuous monitoring
  - Environmental compatibility [dust, temperature]
  - Long-life operation [months to years]



- **Support System Development**
  - Power
    - > Advanced solar cells or RTG's for robotic
    - > Nuclear power for human
  - Product liquefaction and cryogenic storage [months to years]
    - > Earth supplied Hydrogen

- **Cost**
  - Technology/system synergism between Moon and Mars
  - Technology/system synergism with other systems [ECLSS, fuel cells]
  - Commercial viability of technology

Top-Level Mars ISPP Development Plan

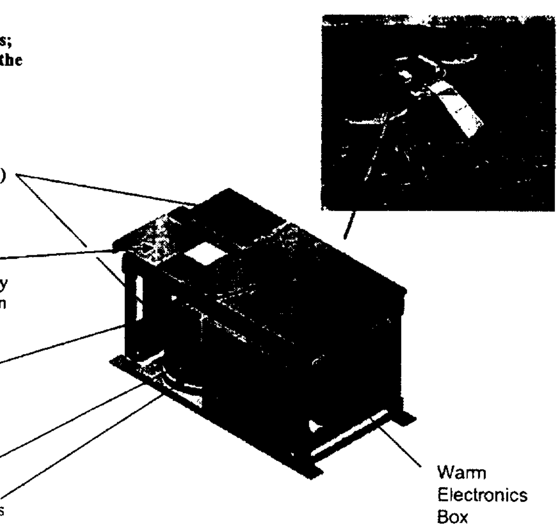


Mars ISPP Precursor (MIP) Flight Experiment

MIP will incorporate five experiments from three NASA institutions; Johnson Space Center (JSC), Lewis Research Center (LeRC), and the Jet Propulsion Laborator (JPL). JSC is also reponsible for integrating the experiments into the MIP flight demonstration unit

The five MIP experiments are:

- **MAAC - Mars Atmosphere Acquisition and Compression (JPL)** Demonstrate the ability to collect and compress Mars atmospheric carbon dioxde
- **MTERC - Mars Thermal Environment and Radiator Characterization (JPL)** Provide data to determine the effective sky temperature and the long term effect of the Mars environment on radiator performance
- **MATE - Mars solar Array Technology Experiment (LeRC)** Characterize advanced solar cell performance and obtain data on Mars surface environments that can impact future solar cell designs
- **DART - Dust Accumulation and Repulsion Test (LeRC)** Demonstrate techniques to mitigate dust accumulation on solar cells (tilting and electrostatic repulsion) and characterize dust properties and deposition rates
- **OGS - Oxygen Generator Subsystem (JSC)** Demonstrate the production of oxygen from Mars atmospheric gases in the Mars environment



MIP Design Characteristics

- **Mission Design Life = 300 Mars days (sols)**
- **Mass = 7.5 kg**
- **Dimensions = 40 cm L x 24 cm W x 25cm H**
- **Average Power; Day = 15 Watts*, Night = 3 Watts**

* When producing oxygen; 9 Watts average without oxygen production

Mars ISCP Technology Development Coordination

	Gov't/Industry	SBIR/ACRP	Univ.Partners & Grants
Resource Collection & Conditioning	• MIP CO_2 adsorption pump experiment (JPL) • MISR scale CO_2 adsorption pump (LMA/JPL) • Low-power CO_2 adsorption pump (ARC)	• Φ I water vapor adsorption pump (Adroit Sys)	• GSRP - water vapor adworption material (Univ. of Washington/JSC/JPL)
Chemical Processing	Sabatier/Water Electrolysis (SWE) • SWE breadboard (LMA/JSC) • Methane conversion (JPL) • CO tolerant H_2 separation (JPL) • Methane pyrolysis (HS/LMA) Zirconia CO_2 Electrolysis (ZCE) • ZCE cell stack (AS/JPL) • Methanol/HC production breadbaord (JSC) Support Hardware • COT sensor, separator, and pump evaluation (JSC) • Autonomous control & failure recovery (JSC/ARC/KSC)	Zirconia CO_2 Electrolysis (ZCE) • Φ II - O_2 extraction/separation (Nanomaterials Research) • Φ I - O_2 generation from Mars CO_2 (NexTech Materials) Reverse Water Gas Shift (RWGS) • ACRP - RWGS & ethylene breadboard (Boulder Center Science & Policy) • Φ II - RWGS & methanol breadboard (Pioneering Astronautics) • Φ I - Hydrocarbon fuel reactors (Pioneering Astronautics)	Zirconia CO_2 Electrolysis (ZCE) • Radio Frequency CO_2 dissociation (Old Dominion/JSC) • ZCE cell stack development (Univ. of Arizona/HS/JSC)
Product Liquefaction & Storage	NASA Cryogenic Working Group • Pulse-tube cryocooler (NIST/JSC) • Cryogenic storage architecture (JSC)	• Φ I - Pulse tube cryocooler (Mesoscopic Devices)	• H_2 transport to Mars study (Utah State Univ/JSC/JPL)

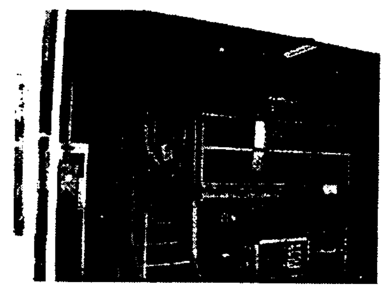
Mars ISRU System Technology (MIST) Objectives

- Characterize technology and subsystem performance for mission modeling and technology funding planning
  - Advance multiple ISRU process options to same TRL for design flexibility
  - Verify performance/benefits/risks associated with different process options
- Raise individual subsystem/component TRL by:
  - Providing low-cost testing for industry/university partnerships
  - Funding key technology development efforts
  - Work w/ industry, universities, and other government organizations to focus ISRU development and testing
- Reduce risk/concerns for sample return and human missions utilizing ISRU
  - Development and demonstration of autonomous control and failure recovery hardware, operations, and logic
  - System level testing to understand subsystem interaction
  - System level testing to optimize processes
  - Long term testing to verify component/system operation robustness
- Demonstrate environmental suitability of ISRU components/processes/systems
  - Mars pressure, temperature, and atmospheric composition
  - Continuous versus day/night production cycles
  - Loads & vibration
  - Life cycles and contamination sensitivity

MIST Facility Overview

- Building 353
  - Ambient test cells for subsystem and system testing
  - 20 ft dia chamber for Full Mars environment testing
    - > Atmosphere (CO_2, N_2, or Mars mixture), pressure, & temperature
    - > Designed for hazardous operation testing (explosion and fire hazards)
    - > Solar flux & dust conditions
  - Office area for hardware providers while at JSC

- Building 356
  - 5 ft dia. chamber for Partial Mars environment testing
    - > Atmosphere, pressure, & temperature
      - » -300 to +300F
      - » Vacuum to 10^{-6} torr
      - » Atmosphere at 6.5 torr & 100% CO_2 or N_2, or Mars mixture
    - > Night sky temperature simulation
  - Facility will be used for Mars ISPP Precursor development, qualification, and flight unit testing



Stage 1 Proof-of-Concept Demonstration Schedule