Integrated ISRU for Human Exploration – Propellant Production for the Moon and Beyond

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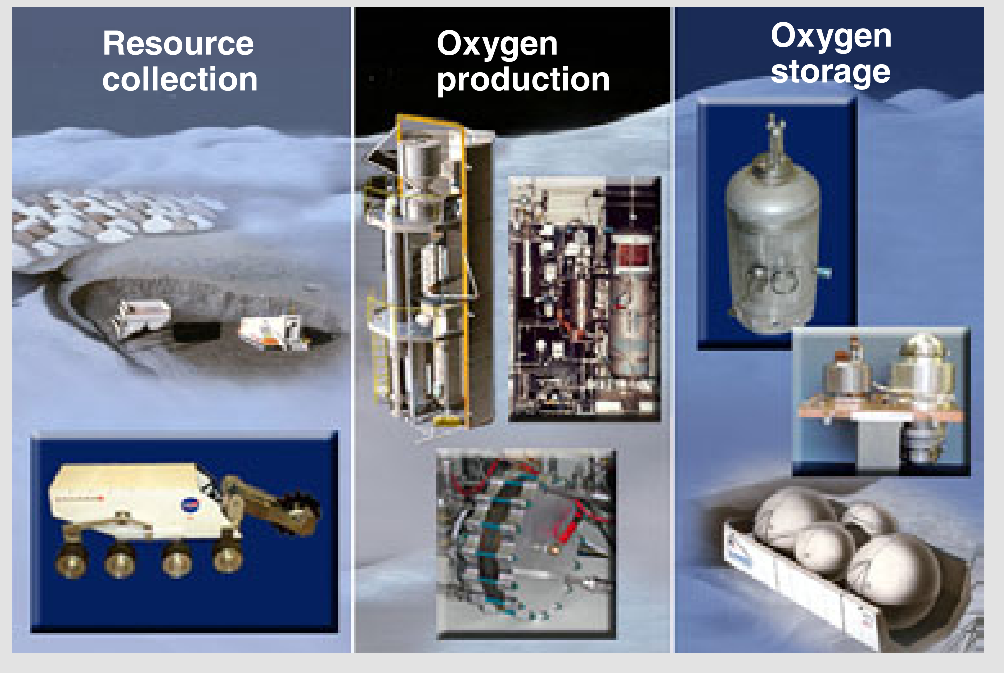
Overview

Precursor In-situ Lunar Oxygen Testbed - PILOT



- Target Mission: Initial Human exploration missions – Technology Testbed initially
- Provide Oxidant and breathing O2
- Implemented in a series of test bed missions that have residual value

Program Goals

- End to End System – Excavation to LOX Storage
- Provide a capability for oxygen production from lunar regolith – TRL 6
- Demonstrate production of oxygen at rates that support human life support
- Demonstrate critical hardware in relevant environments
- Provide mission designers a validated set of implementation criteria

Initial Production System Targets

- 4 kg LOX per 24 hours, minimum
  - 8 kg LOX per 24 hours target
- 400 kg system mass – Includes Excavators; power production; LOX storage
- Power <3 kWatt
- Operational life > 2 years
- Storage capacity - 300kg
- Production only during sunlit periods, hibernate during lunar night

Implementation Assumptions

- System will land on Lunar Mare
- Power system will be lightweight solar – 150 W/kg
  - Would correspond to 20 kg for 3 kW
  - Solar collectors for thermal power is under consideration

Initial Mass Allocations

400 kg Initial System Mass Allocation

- Power Generation – 50kg
- Regolith Excavator – 80kg
- Oxygen Production – 140kg
- LOX Storage – 100kg
- Margin – 20kg

Regolith Collection

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- Baseline Concept:
  - One excavator w/ dump bed
  - Bucket Wheel Excavator
  - Inverted Auger regolith transport
  - Beneficiation – Currently only planning to sieve larger rocks
- Trade study to be performed on other excavation methods

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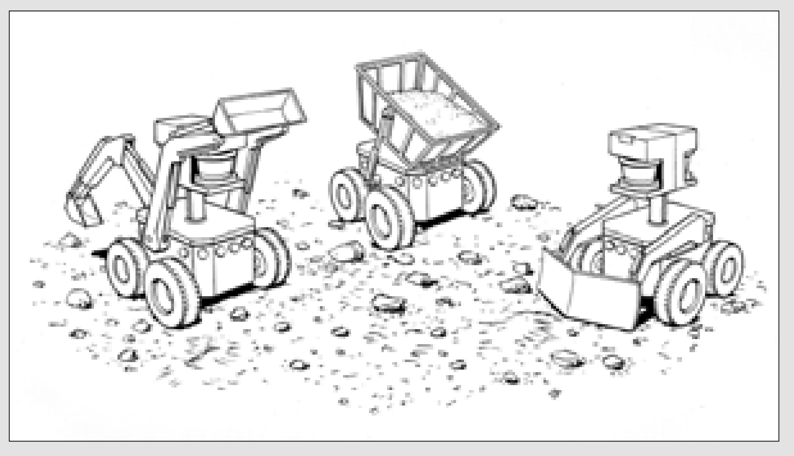

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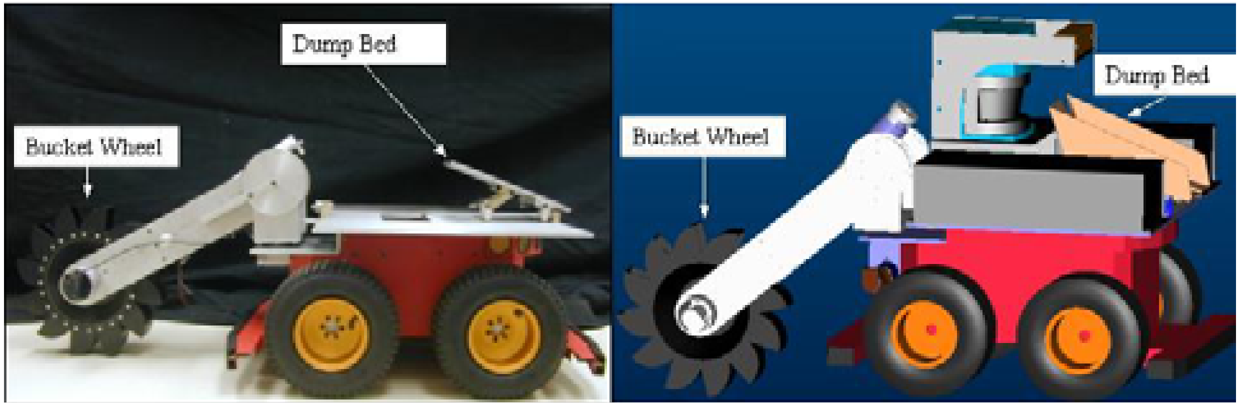
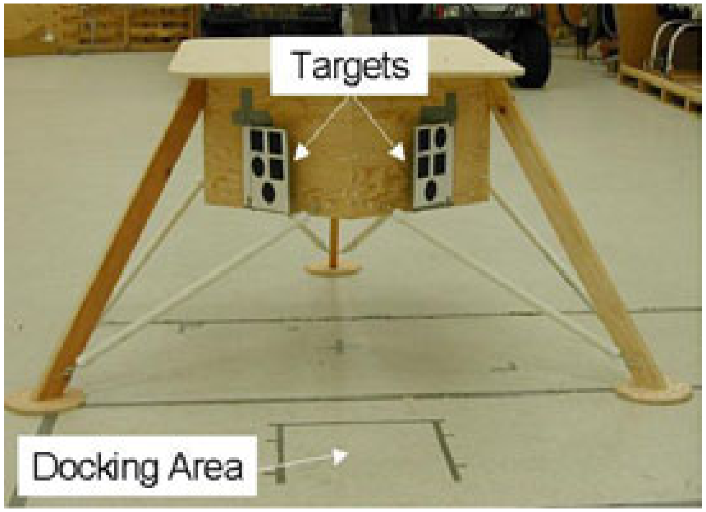
Regolith Excavator

- Bucket Wheel Baseline
- 50 kg per hour
  - Greatly exceeds reactor requirements
  - Idle time allows robot to haul and dispose of refuse
- Robotic Platform
  - Not a prime focus of this program
  - Will leverage ongoing activities
  - Use in-house lab robots
- Excavate in large area with lunar simulant



Task Planning

- Will leverage ongoing and existing body of knowledge
- Robot will use preset routes for excavation and disposal
  - Autonomously navigate from lander to disposal area
  - Autonomously navigate from disposal area to predetermined excavation area
- Leading to functional demonstration
  - Full scale mockup of Phoenix class lander with targets added
  - 10 meter distance to excavation area
  - Obstacle avoidance during traverse



Regolith Collection Challenges

- Bearings, lifetime, loads, complexity
- Dust mitigation
- Power consumption
- Power Source – While not a prime focus of this program, we need to know the energy required for operations
- Regolith properties – The handling of granular materials in reduced gravity is not well understood

Oxygen Production

- Three methods for initial investigation
  - Hydrogen Reduction
  - Carbothermal Reduction
  - Molten Salt Electrolysis
- Methods will be compared for effectiveness at end of first year leading to selection of preferred methods

Hydrogen Reduction

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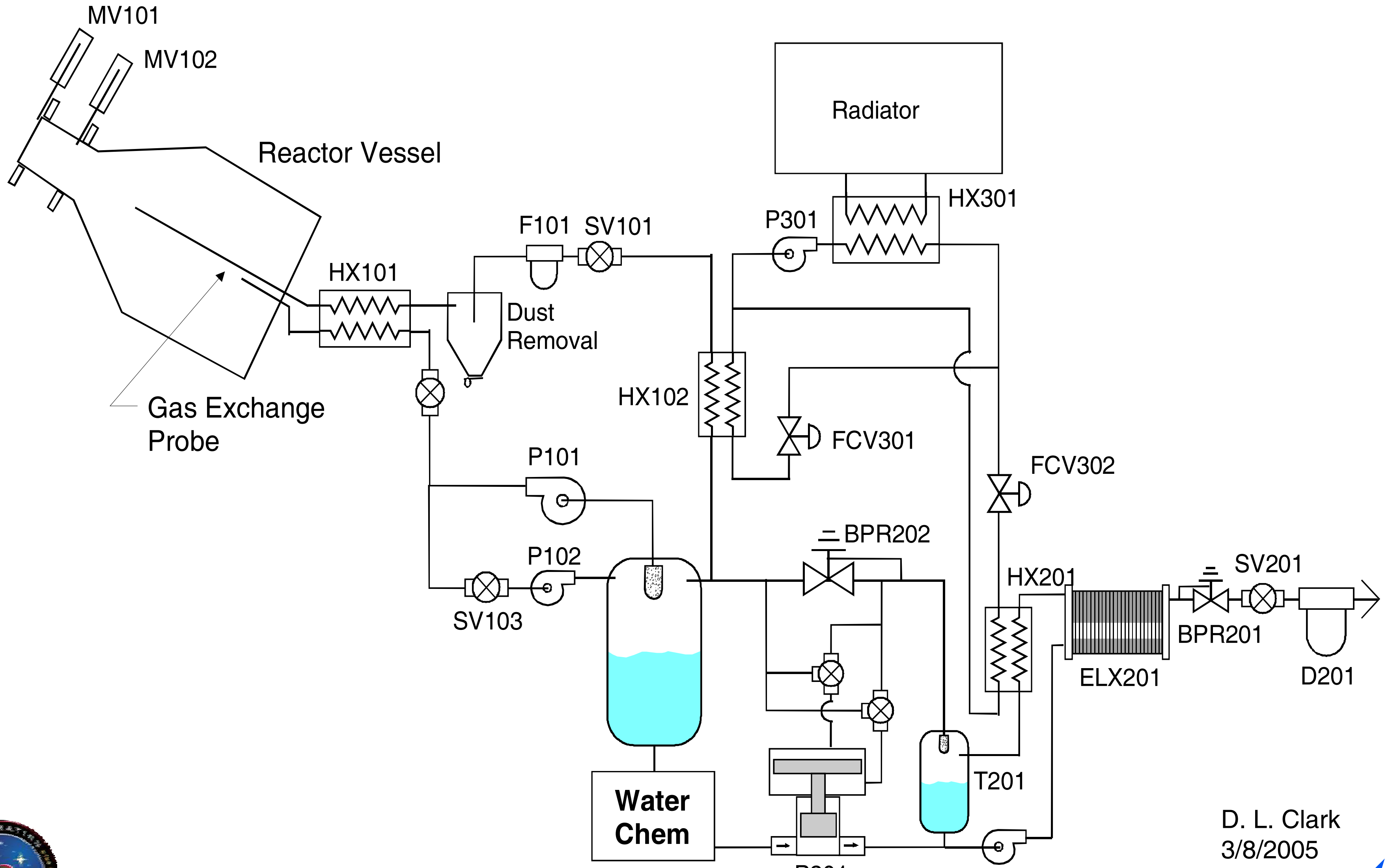

D. L. Clark
3/8/2005

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Hardware Implementation

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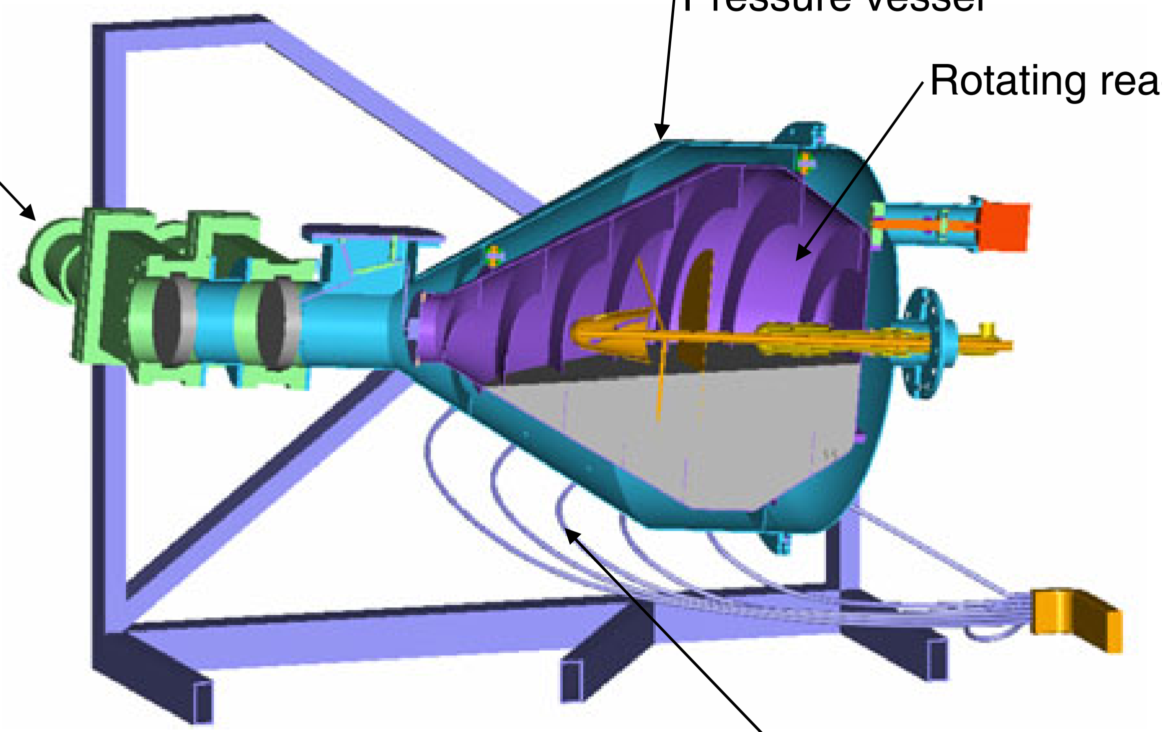
- Reactor Detail



Pressure vessel

Rotating reactor chamber (mixer)

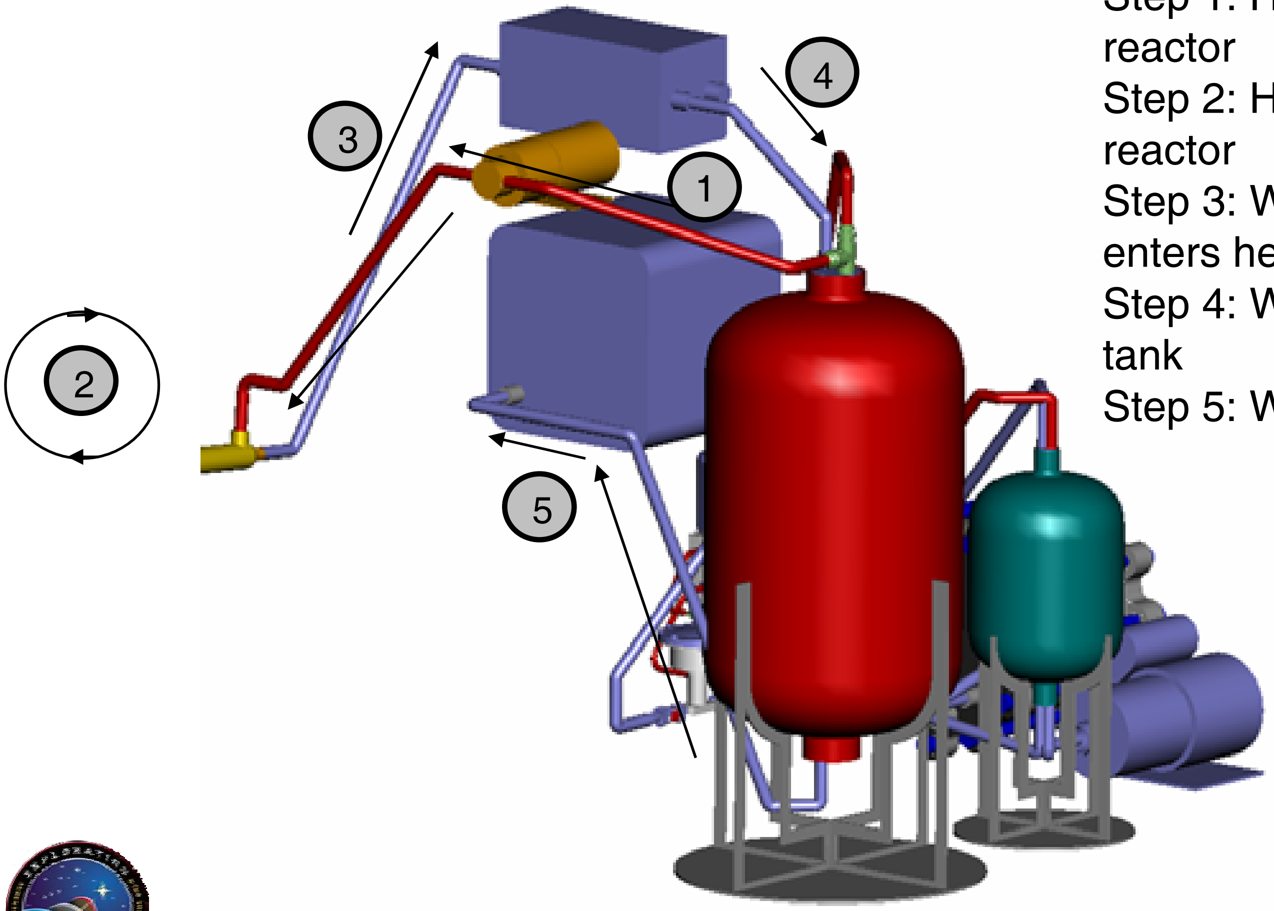
Gate valves
Seals
pressure
vessel

Solar concentrator fiber optic heaters

Concept of Operations

Precursor In-situ Lunar Oxygen Testbed - PILOT

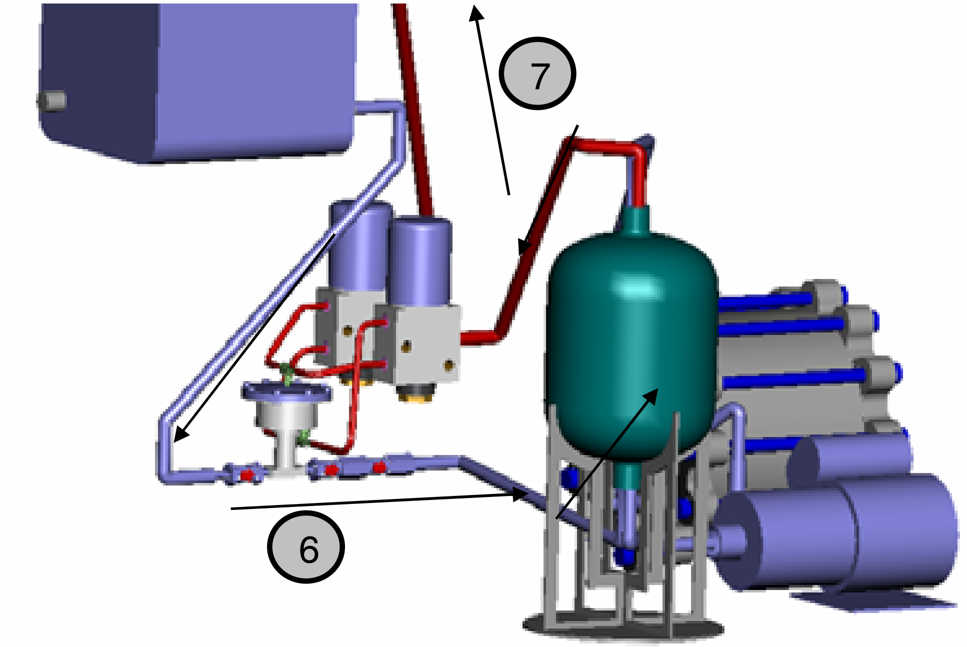
- Oxygen Production - Subsystems



Water vapor collection process:
Step 1: H2 gas from tank pumped into reactor
Step 2: Hydrogen reduction within reactor
Step 3: Water vapor leaves reactor, enters heat exchanger
Step 4: Water condenses in hydrogen tank
Step 5: Water enters treatment plant

Concept of Operations

- Oxygen Production - subsystems



Water vapor collection process:

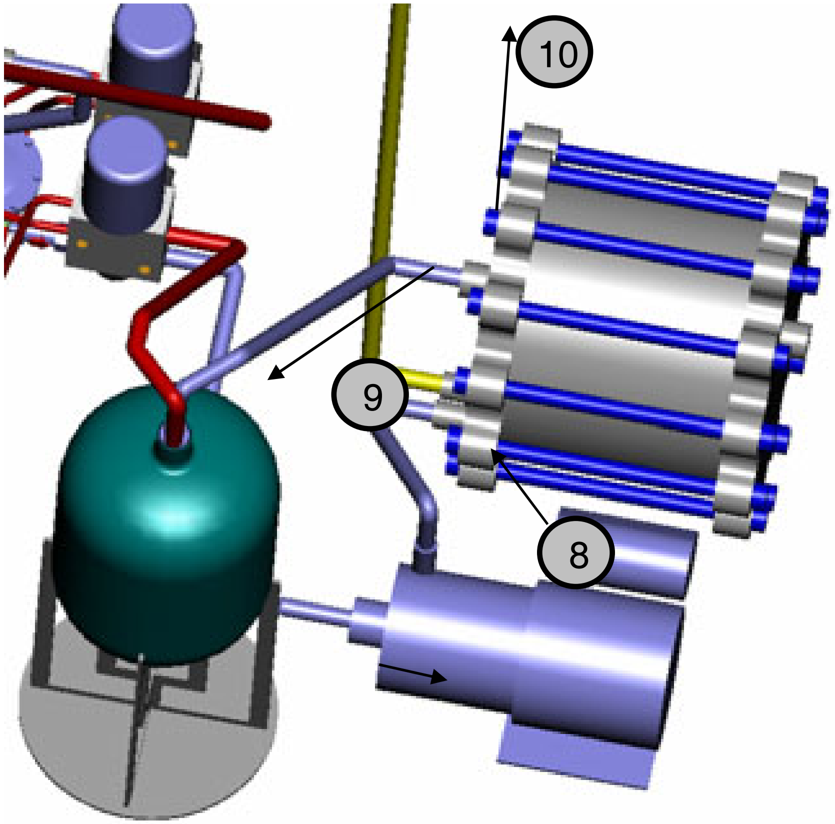
Step 6: treated water flows through pressure boost pump into electrolyzer circulation tank

Step 7: H2 gas driven through solenoids to run boost pump, vents to large Hydrogen tank

Concept of Operations

Precursor In-situ Lunar Oxygen Testbed - PILOT

- Oxygen Production - subsystems



Water processing:

Step 8: Water flows from circulation tank through circ pump into electrolyzer

Step 9: Water and H2 gas return to circ tank

Step 10: O2 gas flows to dryer and LOX tank

Hydrogen Reduction Challenges

- Regolith Handling
  - Storage, feed hoppers
  - Waste removal
- Thermal Control
  - Need high efficiency heat exchanger
- Beneficiation- Is there a way to improves yields by treating the raw regolith
- Hydrogen Recycle
- Water Handling and Purification
- Hydrogen Losses and makeup
  - Solar implanted hydrogen may leave us with net gain in hydrogen
- Removal of inert gases

Carbothermal Reduction Overview

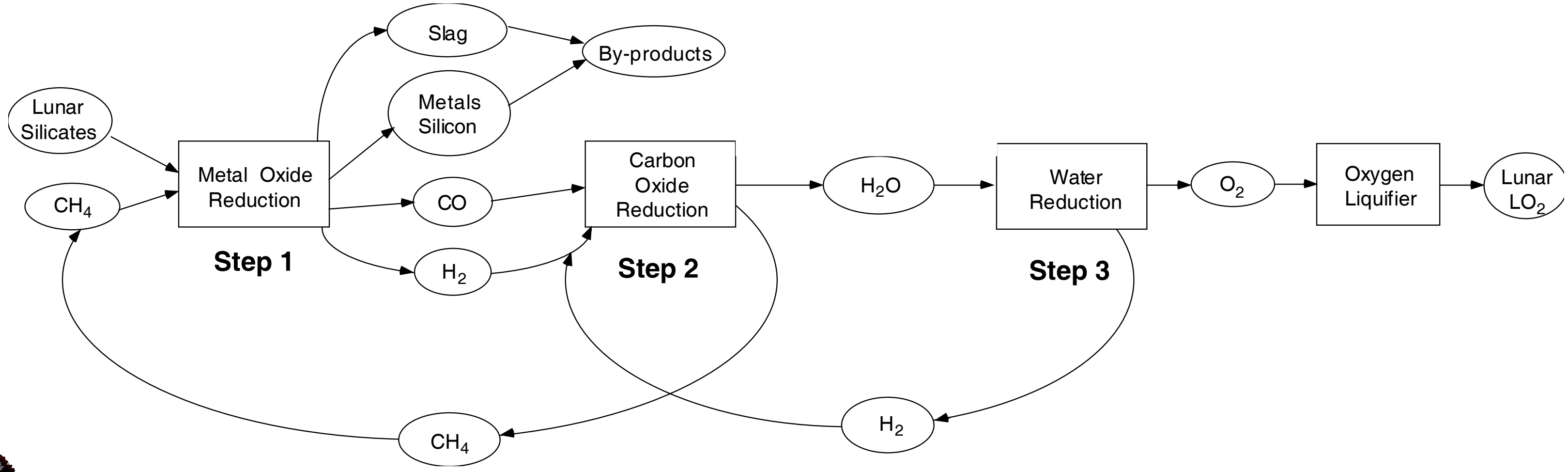
- The carbothermal reduction process extracts oxygen from lunar regolith through the carbon reduction of silicon, iron, and titanium oxides
- By reducing the silicon, iron, and titanium oxides, over 28% of the bulk mass of the JSC-1 lunar regolith simulant mass can potentially be extracted as oxygen
    - SiO_2 = 25.4mass%
    - FeO = 2.1mass%
    - Fe_2O_3 = 1.0mass%
    - $TiO_2 \rightarrow Ti_2O_3$ = 0.2mass%
- Processing is achieved through the use of methane gas, providing a simple way to produce oxygen by handling only gases and water, with minimal separation techniques necessary
- Thermal compatibility issues with regolith containers are solved by using the regolith as its own processing container
    - Lunar regolith has a very low thermal conductivity of 0.0172 – 0.0295 W/mK

Carbothermal Reduction Overview

- The baseline carbothermal reduction process has three basic steps
  - Step 1. Reduction of Metallic Oxides $MO_x + CH_4 \rightarrow CO + 2H_2 + M$

    (*processing temperature of >1625 C)*
  - Step 2. Methanation Process $CO + 3H_2 \rightarrow CH_4 + H_2O$

    (processing temperature of ~250 C)
  - Step 3. Water Electrolysis $2H_2O \rightarrow 2H_2 + O_2$
- Together, these processing steps can form a nearly closed-loop system



Carbothermal Reduction Hardware

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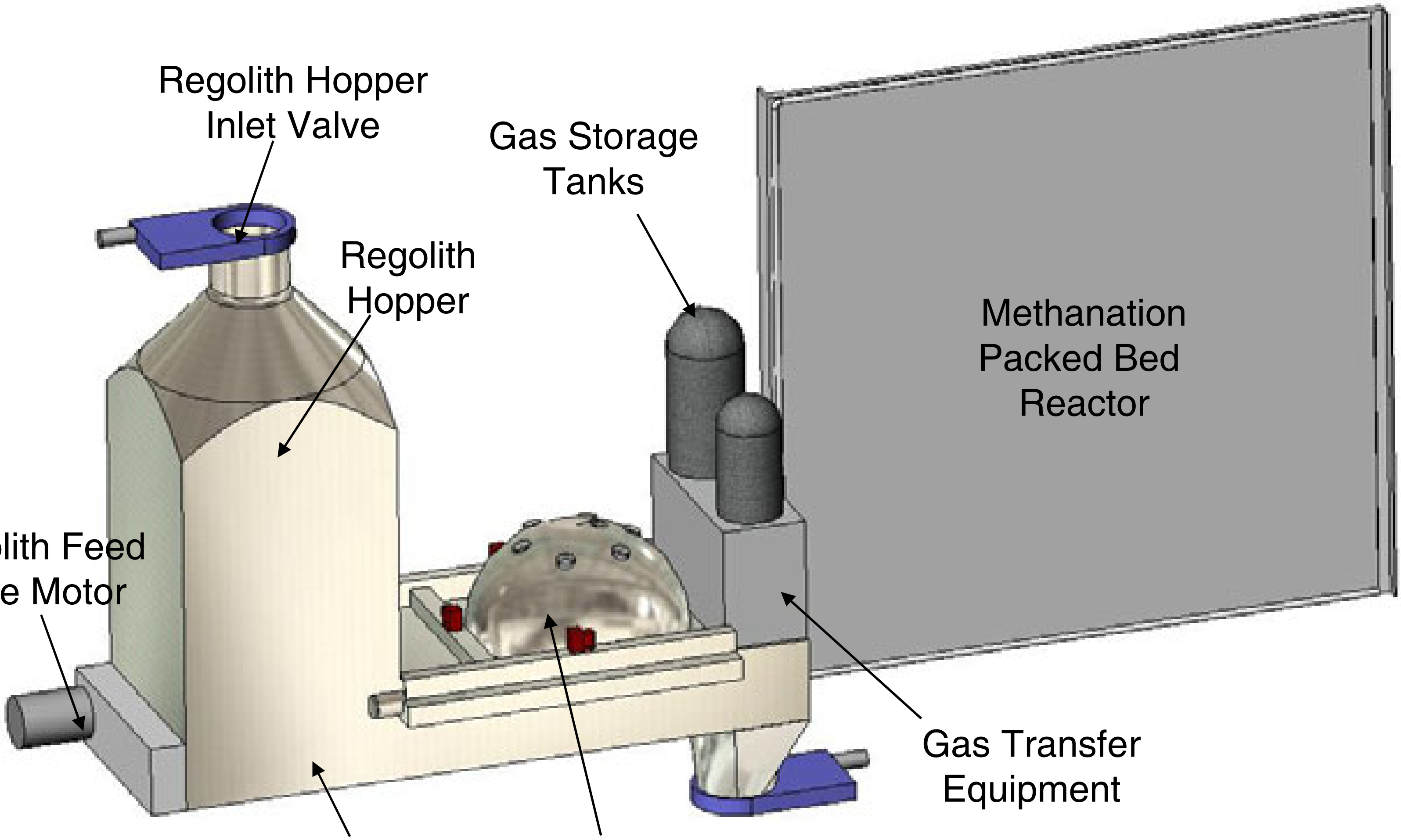

Regolith Hopper Inlet Valve

Gas Storage Tanks

Regolith Hopper

Methanation Packed Bed Reactor

Regolith Feed Drive Motor

Gas Transfer Equipment

Regolith Feed System

Carbothermal Reduction Reactor

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Carbothermal Reduction Challenges

- Material Heating
  - Current plans will use concentrated solar energy
- Product release
  - CO bubbles trapped in spent material
- Material Handling
- Material Disposal
- Thermal Control
- Methane losses and makeup

Molten Salt Reduction

- Electrochemical Reduction in conductive molten salt
- Use of lunar regolith as a solid (powder or pressed pellet) cathode in an inert molten halide with production of oxygen on an inert anode

– LiCl-KCl [60-40 mol. pct.]	375°C
– NaCl-KCl [50-50 mol. pct.]	650°C
– CaCl2	850°C

Subsystem Overview

The subsystem using molten salt extraction is being adopted using two fundamentally different schemes:

1. Use of lunar regolith as a solid (powder or pressed pellet) cathode in an inert molten halide with production of oxygen on an inert anode
    - Process Variables: salt constituents and temperature
    - System Variables: cathode container (powder or pellet), suspended pellet
2. Use of partial lunar regolith as dissolved species in an inert molten halide with production of oxygen on an inert anode
    - Process requirements: filtration of undissolved regolith

Hardware Implementation

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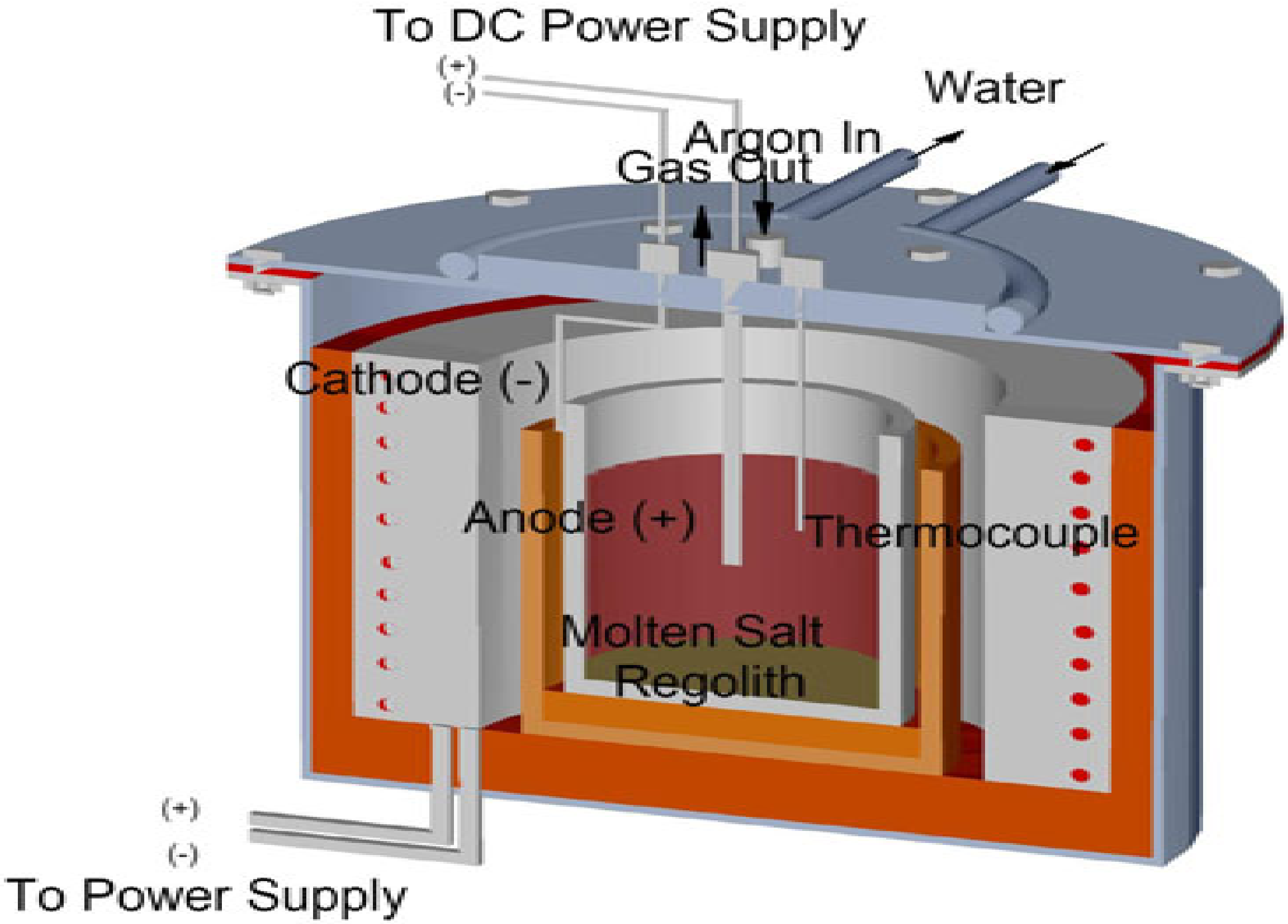
Test Reactor



Molten Salt Reduction Challenges

- Material Handling
- Salt recovery
  - Losses and makeup
- Oxygen recovery and purification
- Refuse disposal
- Thermal Control

Cryogenic Oxygen Storage

- Baseline design:
  - Pulse tube cryocooler liquefaction
  - 300 kg storage tank
  - Self pressurization for outflow

System Schematic

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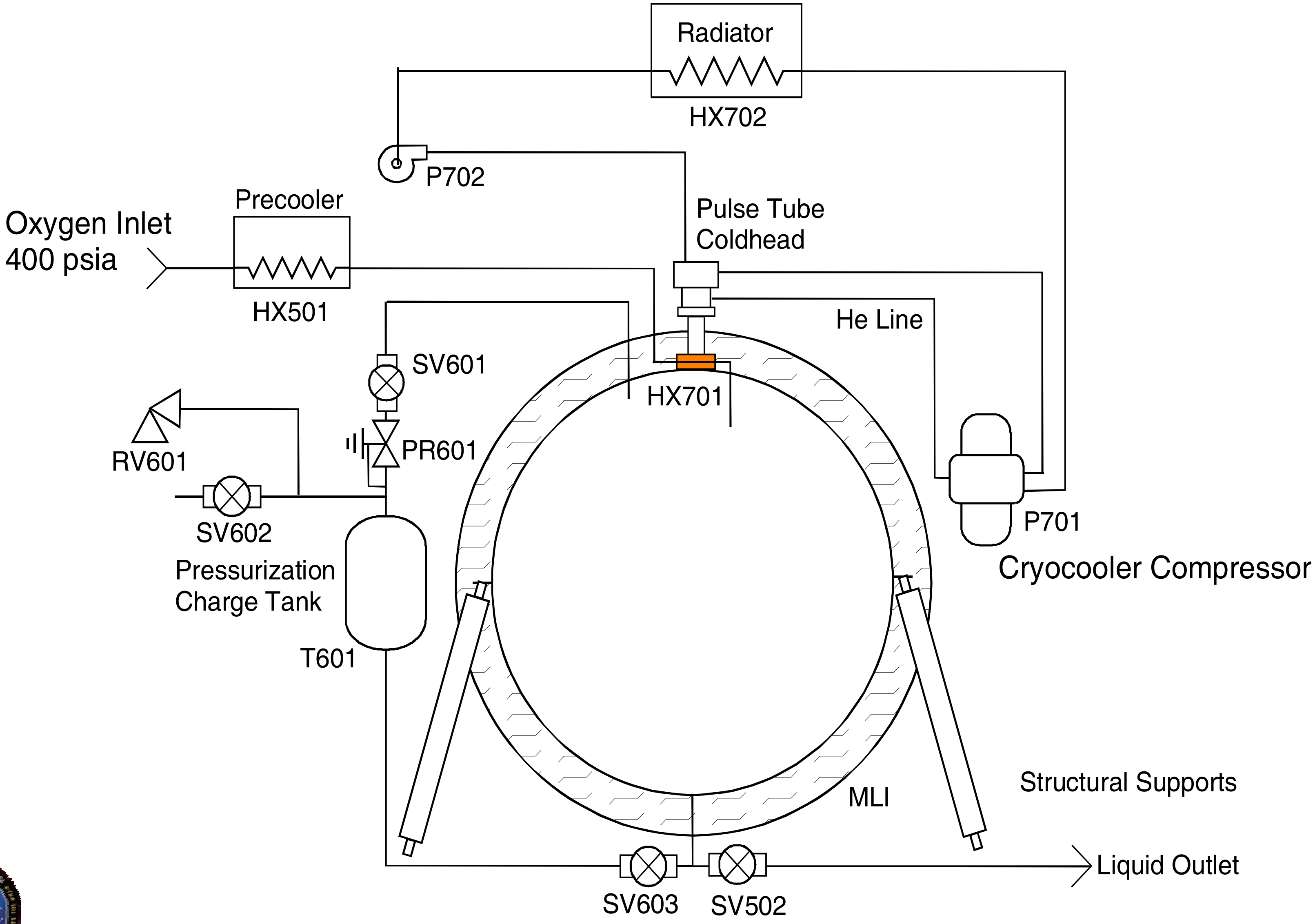

Hardware Implementation

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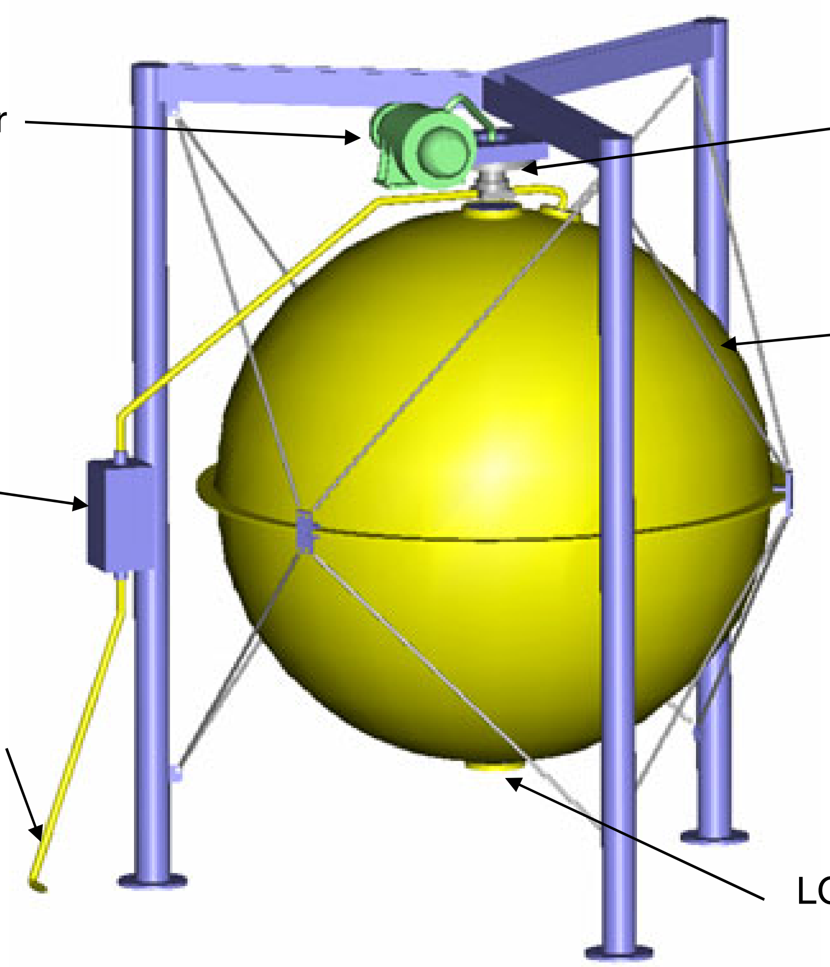


Cryocooler Compressor

Cold Head

LOx storage tank
(300kg capacity)

Dryer

GOx line from electrolyzer

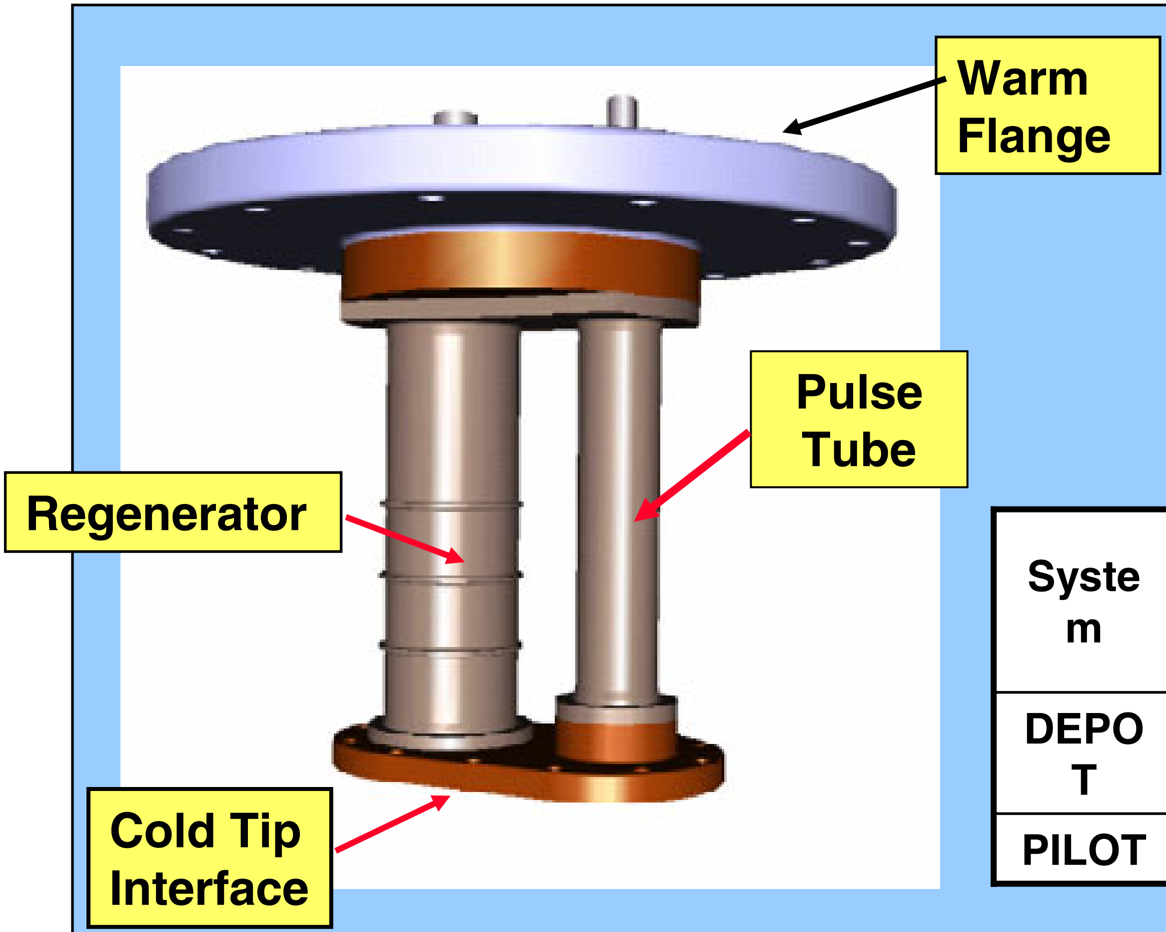
LOx outflow port

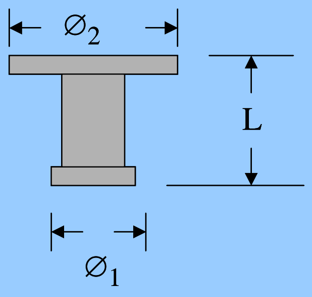
Pulse Tube Cold Head Characteristics

- The cold head has no moving parts
- Minimal vibration
- Eliminates motor or pneumatics for phase control with compressor
- No wear out or failure mechanisms (except working gas leakage)
- No tight tolerance components
- Simple, reliable and light weight
- Well proven, predictable design

PILOT Cryocooler Coldhead

- PILOT based on well established single stage Cold-head





System	Weight (Kg)	L (mm)	$\varnothing_1$ (mm)	$\varnothing_2$ (mm)
DEPOT	4	140	165	400
PILOT	1.4	110	80	140

Cryocooler Compressor

- Compressor is high reliability design without any wear out mechanisms (design life of 10 year is common)
- Utilizes linear (voice coil) type motor for piston drive
- Two motors drive pistons in opposition to provide pressure wave and minimize vibration (momentum cancellation)
- Clearance seals between piston and cylinder eliminate wear, produce negligible gas leakage
- Flexures operating below infinite stress levels provide piston alignment, allow compression/expansion stroke
- Advanced moving magnet motor utilized
- Result is light weight, reliable, efficient compressor

PILOT Cryocooler Compressors

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- PILOT compressors are baselined to utilized the M5 motors

M4 Compressors shown
(M5 similar in physical size)

- M5 MIDI: (PILOT Tank)
  - **Weight – 4.7 Kg**
  - **Physical size - L: 252mm × ∅:119mm**

- M5 MEGA: (DEPOT Tank)
  - **Weight - 16 Kg**
  - **Physical size - L: 410mm × ∅:165mm**

Baseline Cryocooler for PILOT

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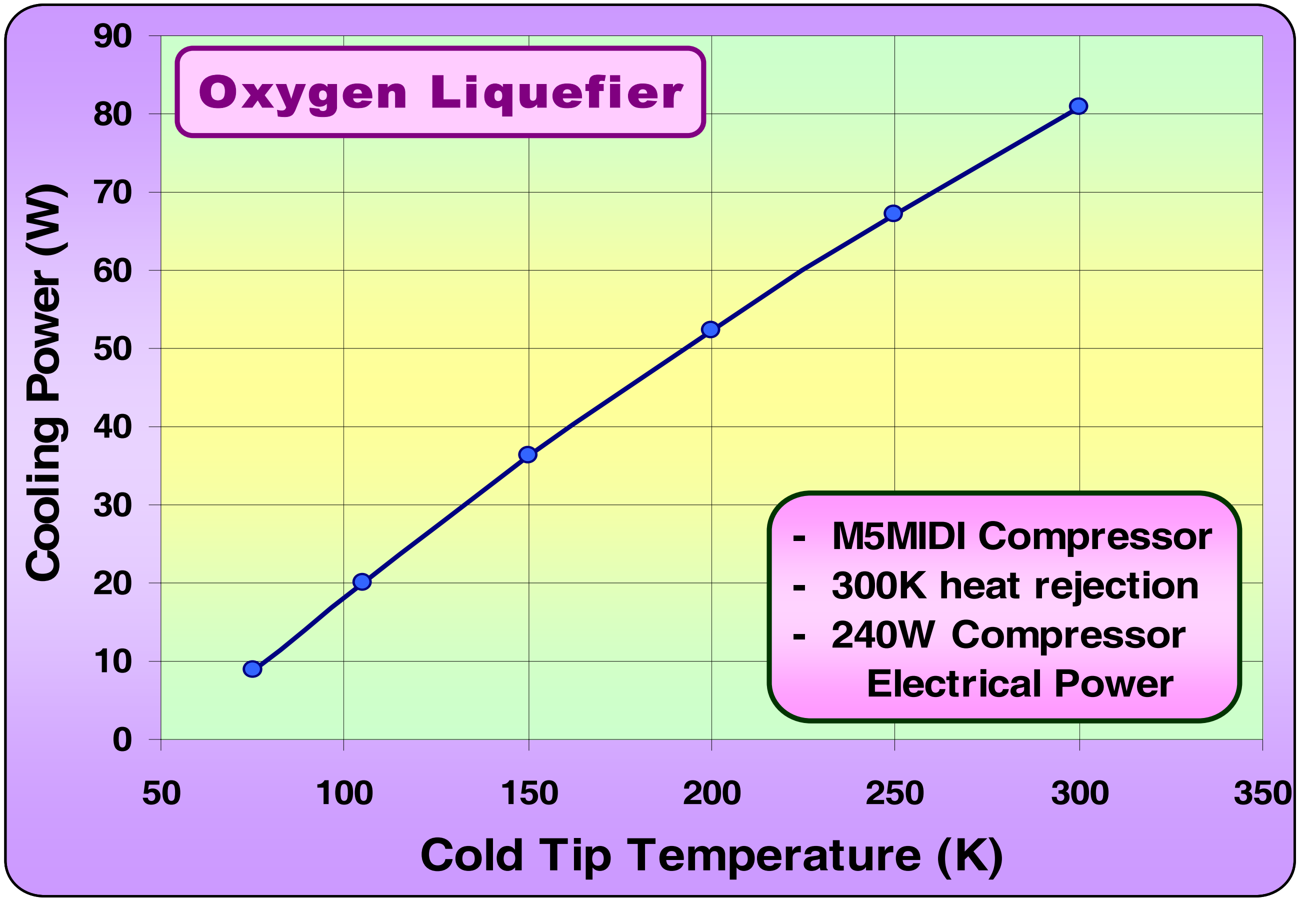
- Following plot shows cooling capacity up to ambient temperature



Assumptions:
- **M5MIDI Compressor**
- **300 mm separation between compressor and coldhead**

Cryogenic Oxygen Storage Challenges

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- Thermal control
  - Tank Insulation
  - Heat rejection
- Power draw
- System mass

Impact to Exploration Architecture

Precursor In-situ Lunar Oxygen Testbed - PILOT

For 1000 kg System Basis

- Reduce Landed Propellant Mass
  - 2.2 metric tonnes LOX produced enables option to
    - Deliver 2.2 tonnes additional cargo to lunar surface
    - Reduce earth launch mass by 15 tonnes
- Reduce Earth Launch Mass by 15 tonnes
  - Launch cost savings of $165 million @ $5 K/lb

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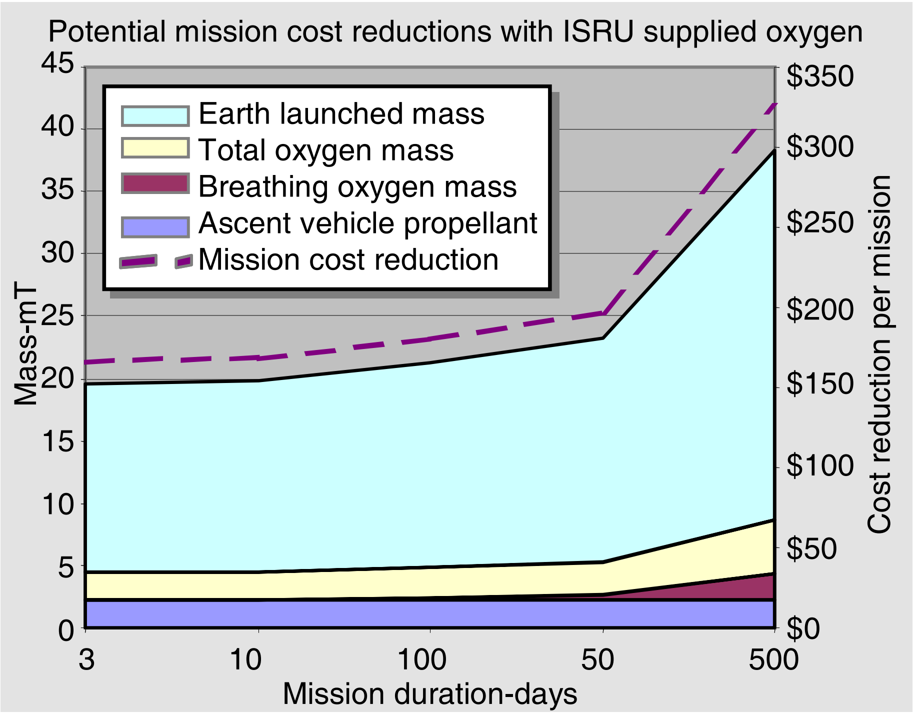

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