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FUELING FUTURE EXPLORATION

Demonstration of a Novel Electrochemical Hydrogen Refrigerator

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About Eta Space

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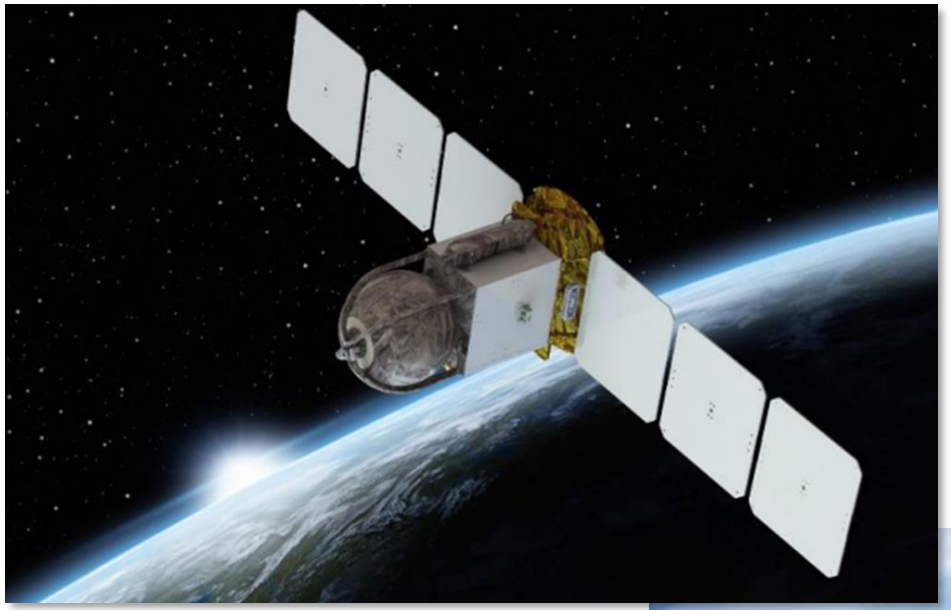
- Eta Space offers capabilities in cryogenic fluid management for the earth, orbit, and the moon. Leveraging our expertise and innovative technologies, we are developing the most efficient solutions for a greener Earth and more sustainable space for all
- Space
  - Orbital refueling
  - ISRU
- Energy
  - Cryogenic Production, Storage, and Transfer
  - Integrated Refrigeration and Storage
  - Zero Loss Hydrogen Refueling
  - Hydrogen Testing



LOXSAT

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- During its 9 month mission, LOXSAT will demonstrate storage, pressurization, and transfer of liquid oxygen in microgravity.

- LOXSAT is set to launch in 2025 and will serve as a technology demonstration for CFM techniques crucial to the development of a full scale cryogenic orbital fuel depot.

- Mission Objectives
  - Zero-boiloff storage
  - Pressure Control
  - No-loss tank to tank transfer

ISRU Propellant Production and Storage

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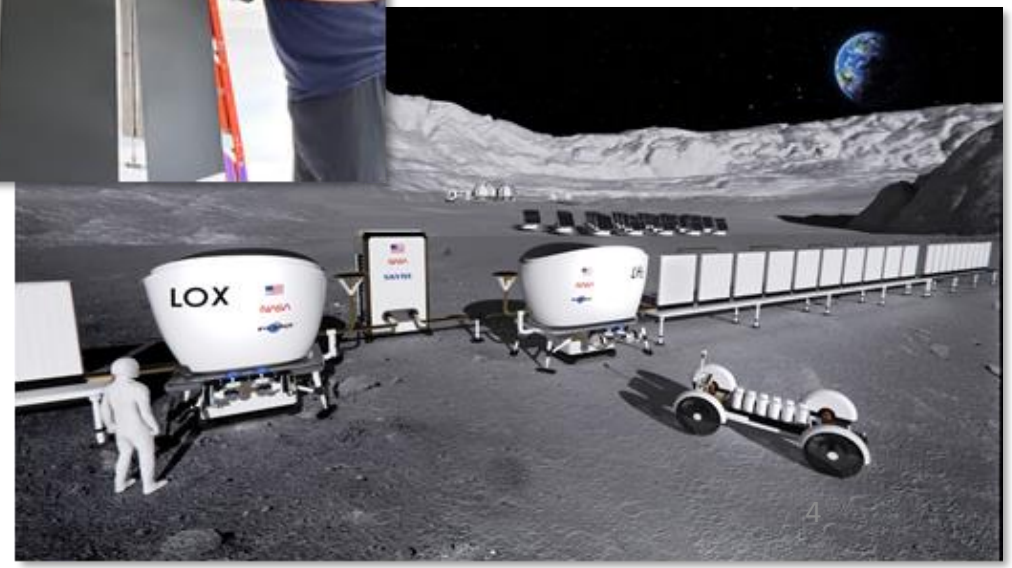
- Lunar Oxygen Station
  - Utilizes active thermal control methods to liquefy supplied low pressure oxygen collected from lunar regolith at a rate of 5 kg/day
  - Currently in preliminary design phase with testing planned
- Lunar Propellant Production Plant
  - Electrolysis stacks to supply hydrogen and oxygen for liquefaction
  - Oxygen liquefied using passive radiators and JT expansion at a rate of 5.93 kg/day
    - Scale system tested in simulated lunar environment at Eta Space
  - **Hydrogen fed into and electrochemical compressor and liquefied using the JT cycle at a rate of 0.74 kg/day**
    - **Integrated Refrigeration and Storage (IRAS)**



Integrated Refrigeration and Storage

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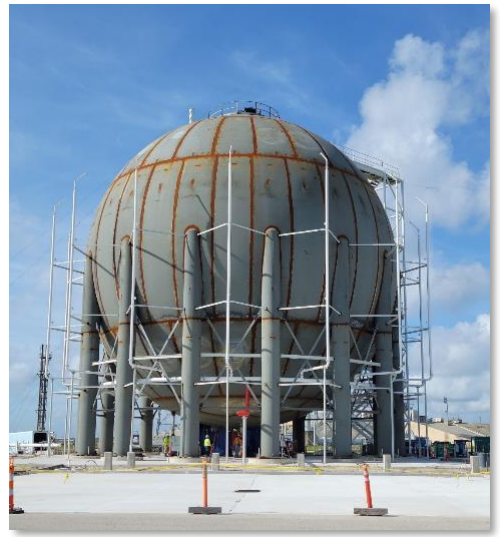
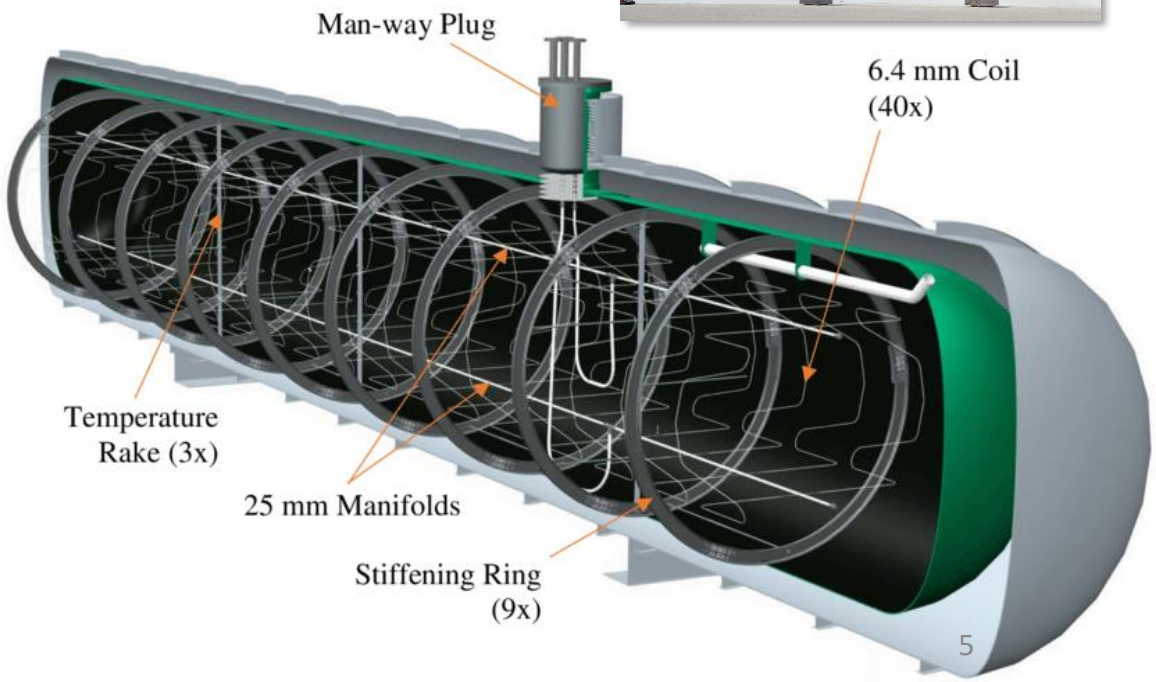
- Storage vessel with integrated heat exchanger coupled to a cryogenic refrigerator allowing for fluid state control within the vessel
- IRAS offers 4 capabilities over traditional storage vessels
  1. Liquefaction
  2. Zero Boil-Off Storage
  3. No Loss Transfer
  4. Densification
- GODU-LH2
  - Demonstrated all 4 IRAS capabilities within a 125 m^3 tank paired with 900W at 20K refrigerator

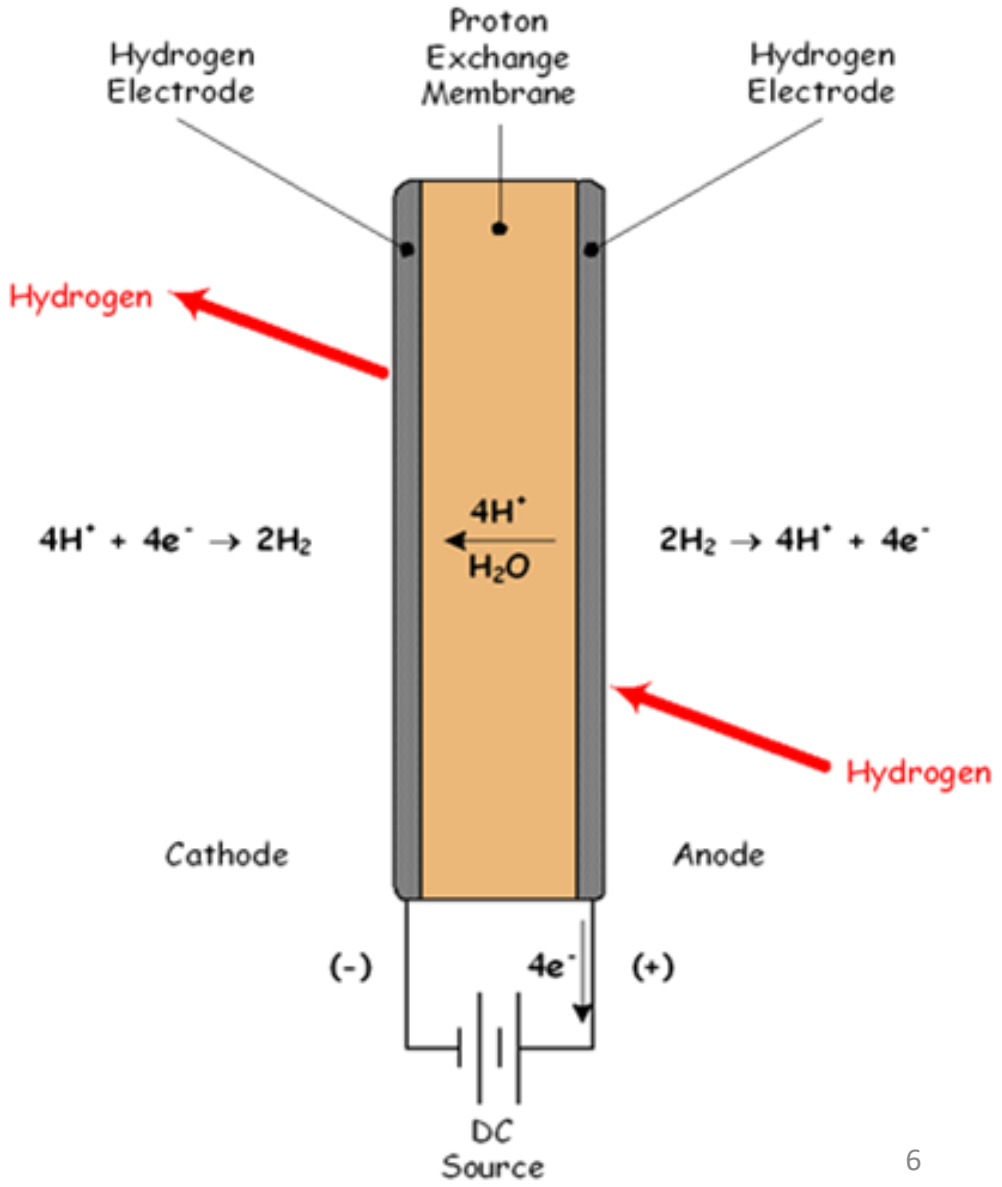




Electrochemical Compression

- Electrochemical hydrogen compressors (ECHCs) utilize a proton exchange membrane and electricity to compress hydrogen

- Advantages over mechanical compressors:
  - Simplicity
    - ECHCs have no moving parts
  - Efficiency
    - Performance is governed by the Nernst equation rather than the ideal gas law



Electrochemical Hydrogen Refrigerator

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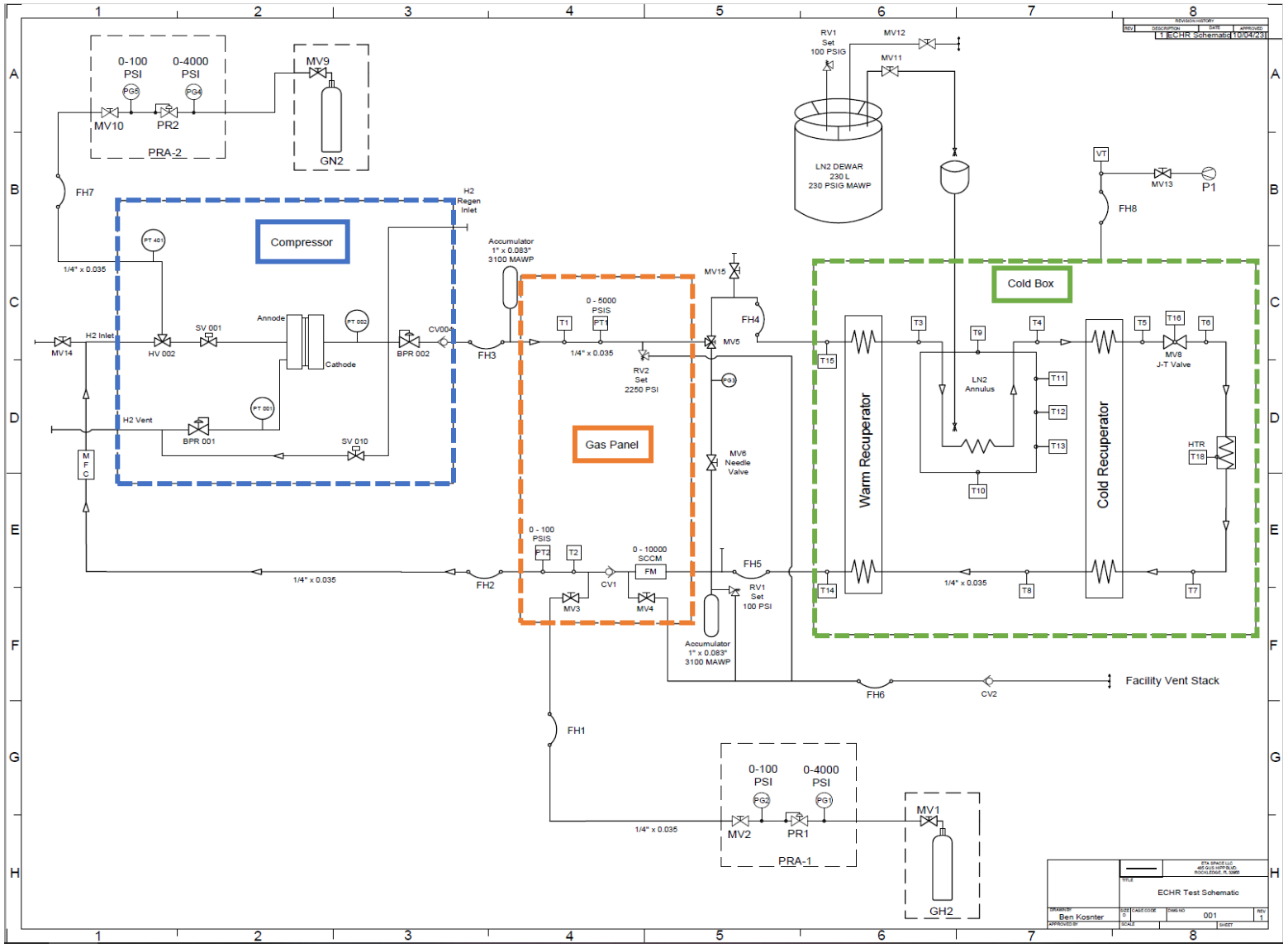
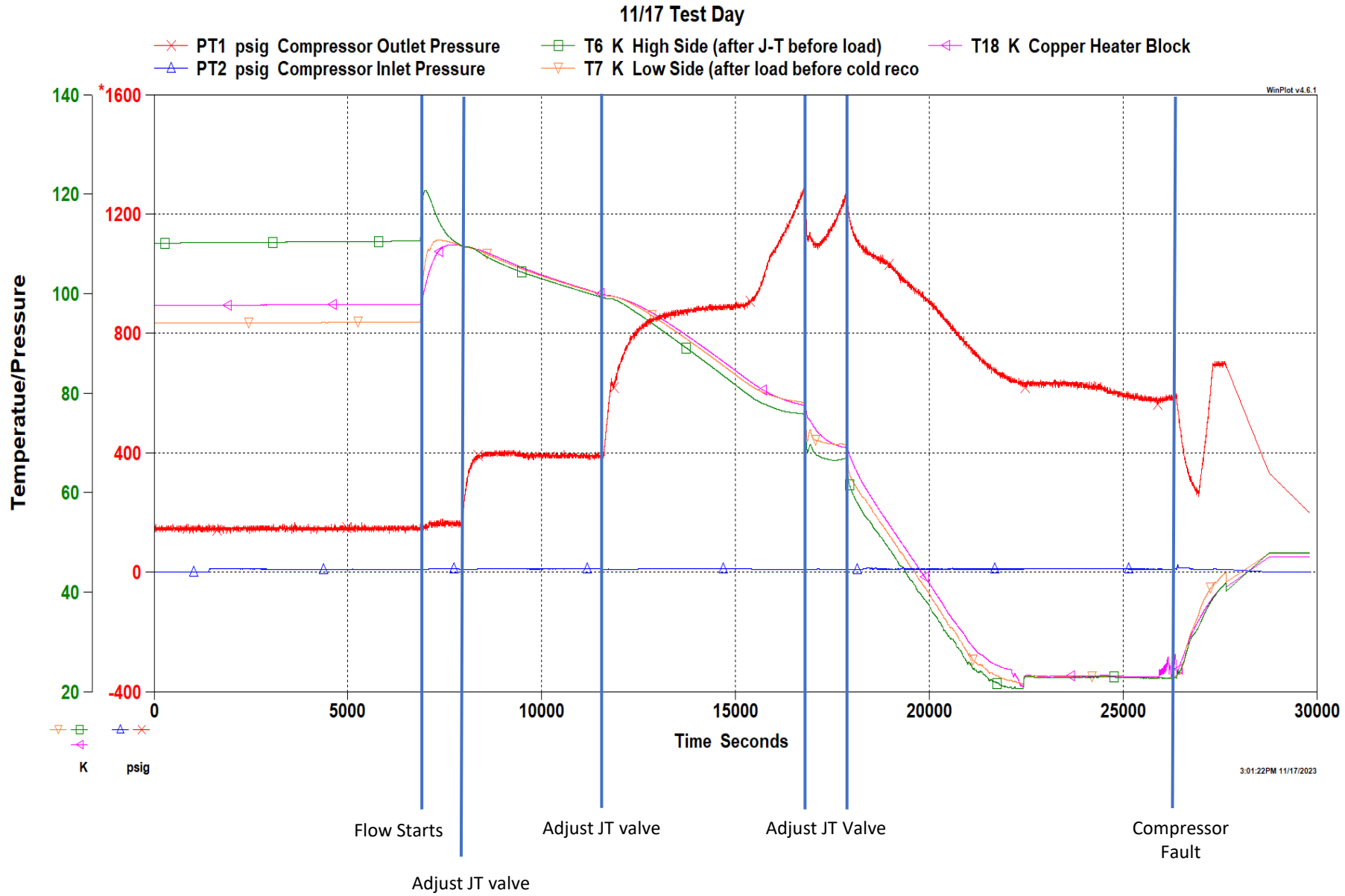
- Aims to utilize an ECHC in a JT cycle to achieve isothermal hydrogen refrigeration
- Also can be used in an open loop as a hydrogen liquefier
- Development started in 2018 through STMD funding and Eta Space was contracted with integration and testing of the system in 2022
- **Believed to be the first time that the liquid hydrogen temperature range has been accessed using an ECHC**



ECHR Background

- Consists of 3 main components
  - ECHC
    - Designed and manufactured by Skyre Inc.
    - Capable of producing 3000 psi hydrogen at a rate of 0.6 kg/day
  - Cold Box
    - Designed and built at the KSC Cryogenic Test Lab
    - LN2 precooler and cold wall
    - Hot and cold recuperators
    - Extended stem JT valve
  - Gas Management Panel
    - Pressure and flow instrumentation
    - System control valves
- Integrated and tested at Eta Space

Testing and Results



System Performance

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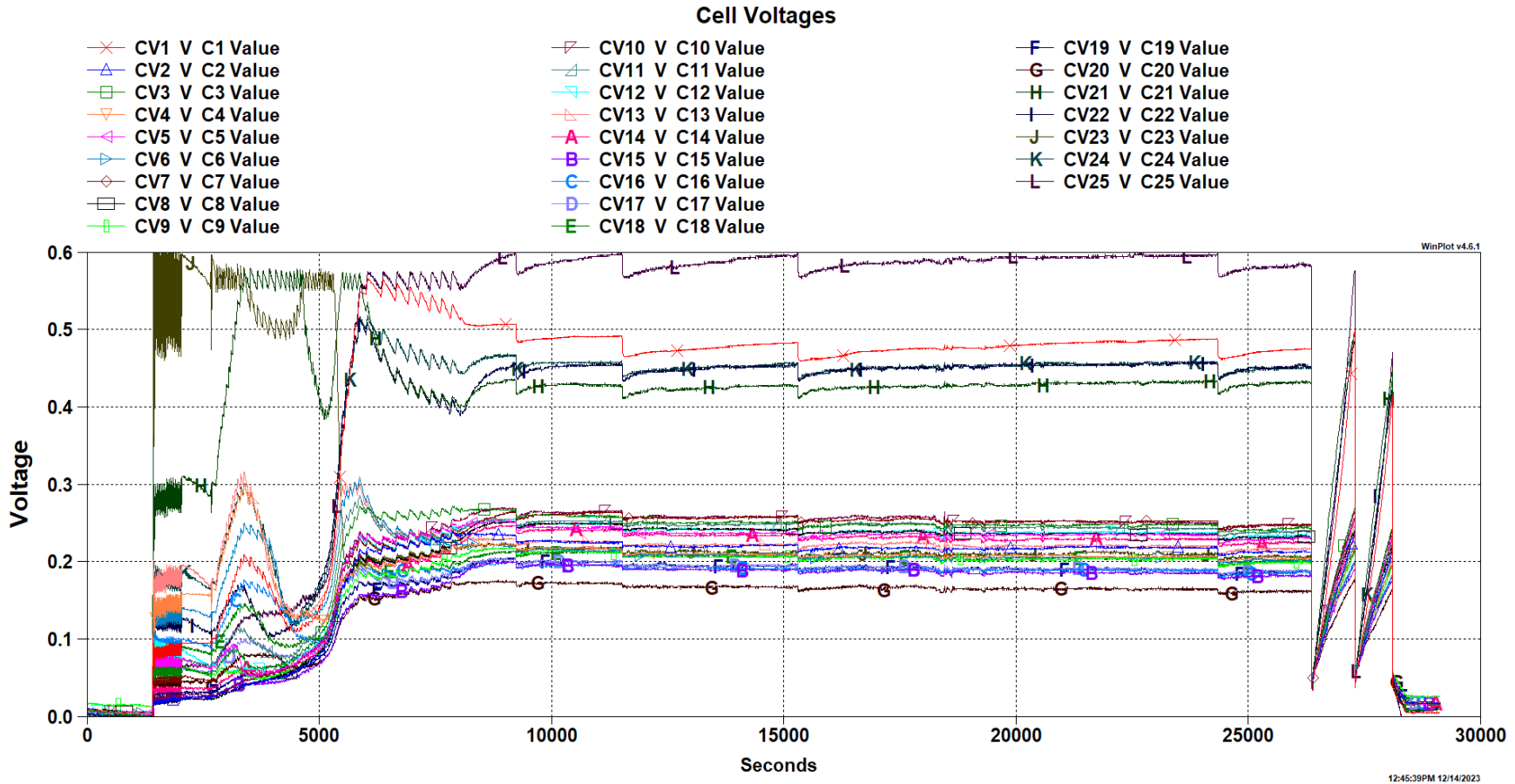
- System performance is estimated from the steady state period at which saturated hydrogen was flowing through the JT valve
- Future testing is planned to directly measure the liquefaction rate using a load heater

Selected Test Run

- Steady-state temp. of 22.8 K
- Supply pressure = 631 psig
- Low-side pressure = 10.8 psig
- Mass flow rate = 4.56 slpm
- Estimated Quality at JT Exit = 0.808
- Estimated Refrigeration Power = **0.57 W** (isothermal)
- Hydrogen Liquefaction Rate = **0.08 g/min**

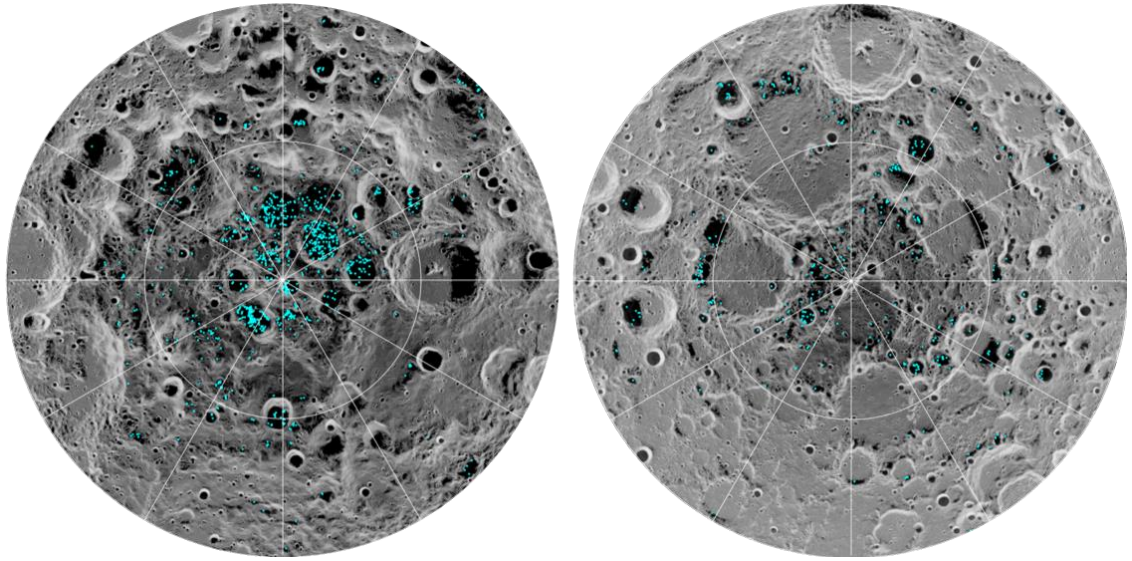
Challenges and Lessons Learned

- Compressor Faults
  - There is a learning curve associated with using these compressors in closed loop operation
- Contamination
  - Multiple tests were stopped due to blockages at the JT valve
  - These blockages are expected to be caused by excess water in the hydrogen product line freezing in the system



Applications

- In-Situ LH2 production
  - Design complete of system capable of producing 22 kg/month of liquid hydrogen using an ECHR
- Zero-boil-off storage
  - Using IRAS, ZBO is possible for indefinite storage of cryogen without loss
- Instrument/detector cooling
  - ECHRs are well suited for infrared detectors operating in the 20K range as there is no vibration produced by the compressor and superior reliability



Credit: NASA

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Eta Space's Path Forward

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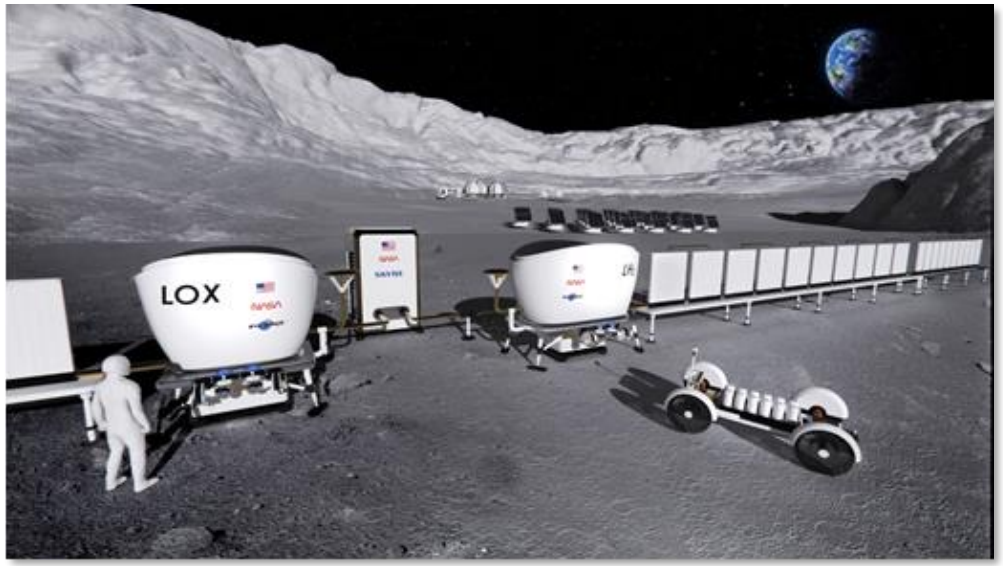
- In space storage and transfer of cryogenic fuels
  - LOXSAT launching in 2025 will demonstrate zero boil-off storage and no loss transfer of liquid oxygen in LEO
  - Eta Space is currently in the preliminary design phase of Cryo-Dock, a full scale cryogenic propellant depot that will be capable of fueling in orbit with zero product loss
- In-situ production of LOX and LH2 on the lunar surface
  - Continue advancing electrochemical hydrogen refrigeration technology for future use on the moon
  - Research into both active and passive means of liquefying hydrogen and oxygen in space



Conclusion / Acknowledgments

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- Eta Space successfully demonstrated the operation of an electrochemical hydrogen refrigerator
- Future applications for this technology are numerous and require further testing

- **Eta Space would like to acknowledge the NASA Space Technology Mission Directorate Center Innovation Fund (CIF) and KSC Independent Research and Technology Development (IR&TD) for their support and funding of the ECHR project**