"Solar Airplanes and Regenerative Fuel Cells"

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A solar electric aircraft with the potential to "fly forever" has captured NASA's interest, and the concept for such an aircraft was pursued under Aeronautics' Environmental Resarch Aircraft and Sensor Technology (ERAST) project. Feasibility of this aircraft happens to depend on the successful development of solar power technologies critical to NASA's Exploration Initiatives; hence, there was widespread interest throughout NASA to bring these technologies to a flight demonstration. The most critical is an energy storage system to sustain mission power during night periods. For the solar airplane, whose flight capability is already limited by the diffuse nature of solar flux and subject to latitude and time of year constraints, the feasibility of long endurance flight depends on a storage density figure of merit better than 400-600 watt-hr per kilogram. This figure of merit is beyond the capability of present day storage technologies (other than nuclear) but may be achievable in the hydrogen-oxygen regenerative fuel cell (RFC). This potential has led NASA to undertake the practical development of a hydrogen/oxygen regenerative fuel cell, initially as solar energy storage for a high altitude UAV science platform but eventually to serve as the primary power source for NASA's lunar base and other planet surface installations. Potentially the highest storage capacity and lowest weight of any non-nuclear device, a flight-weight RFC aboard a solar-electric aircraft that is flown continuously through several successive day-night cycles will provide the most convincing demonstration that this technology's widespread potential has been realized.

In 1998 NASA began development of a closed cycle hydrogen oxygen PEM RFC under the Aeronautics Environmental Research Aircraft and Sensor Technology (ERAST) project and continued its development, originally for a solar electric airplane flight, through FY2005 under the Low Emissions Alternative Power (LEAP) project. Construction of the closed loop system began in 2002 at the NASA Glenn Research Center in Cleveland, Ohio. System checkout was completed, and testing began, in July of 2003. The initial test sequences were done with only a fuel cell or electrolyzer in the test rig. Those tests were used to verify the test apparatus, procedures, and software. The first complete cycles of the fully closed loop, regenerative fuel cell system were successfully completed in the following September. Following some hardware upgrades to increase reactant recirculation flow, the test rig was operated at full power in December 2003 and again in January 2004. In March 2004 a newer generation of fuel cell and electrolyzer stacks was substituted for the original hardware and these stacks were successfully tested at full power under cyclic operation in June of 2004.

A multi-day closed cycle continuous run demonstration of a 12 hr / 12 hr charge / discharge cycle, consistent with a high altitude solar electric aircraft operating at tropical latitudes was carried out in the summer of 2005. This demonstration proved the following attributes:

1.) Fully closed cycle operation at rated power for extended time periods
2.) Operation under semi-autonomous control (automatic operation, with human operator oversight) through steady state operation, power level changes and mode transitions
3.) Fully automatic safety systems operation (no human intervention)

4.) Cyclic operation at full rated power
5.) Fully closed cycle operation at full power through repeated back-to-back contiguous charge / discharge cycles,
6.) Round trip efficiencies to 52 percent.

At the end of demonstration the system was still capable of repeating at least one more charge - discharge cycle. It was the first fully closed cycle regenerative fuel cell ever demonstrated (entire system is sealed: nothing enters or escapes the system other than electrical power and heat).

To the best of our knowledge, this is currently the only fully closed cycle hydrogen / oxygen regenerative fuel cell system in existence. Development expenditure for the RFC was $20M over eight years (total both Aero projects).

The RFC has demonstrated its potential as an energy storage device for aerospace solar power systems such as solar electric aircraft, lunar and planetary surface installations; any airless environment where minimum system weight is critical. Its development process continues on a path of risk reduction for the flight system NASA will eventually need for the manned lunar outpost.

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Solar Airplanes and Regenerative Fuel Cells

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WHAT WE WILL DISCUSS

Solar Electric Aircraft and the Energy Storage Requirements for Continuous Flight

The Hydrogen-Oxygen Regenerative Fuel Cell

- morphology
- technology
- favorable attributes

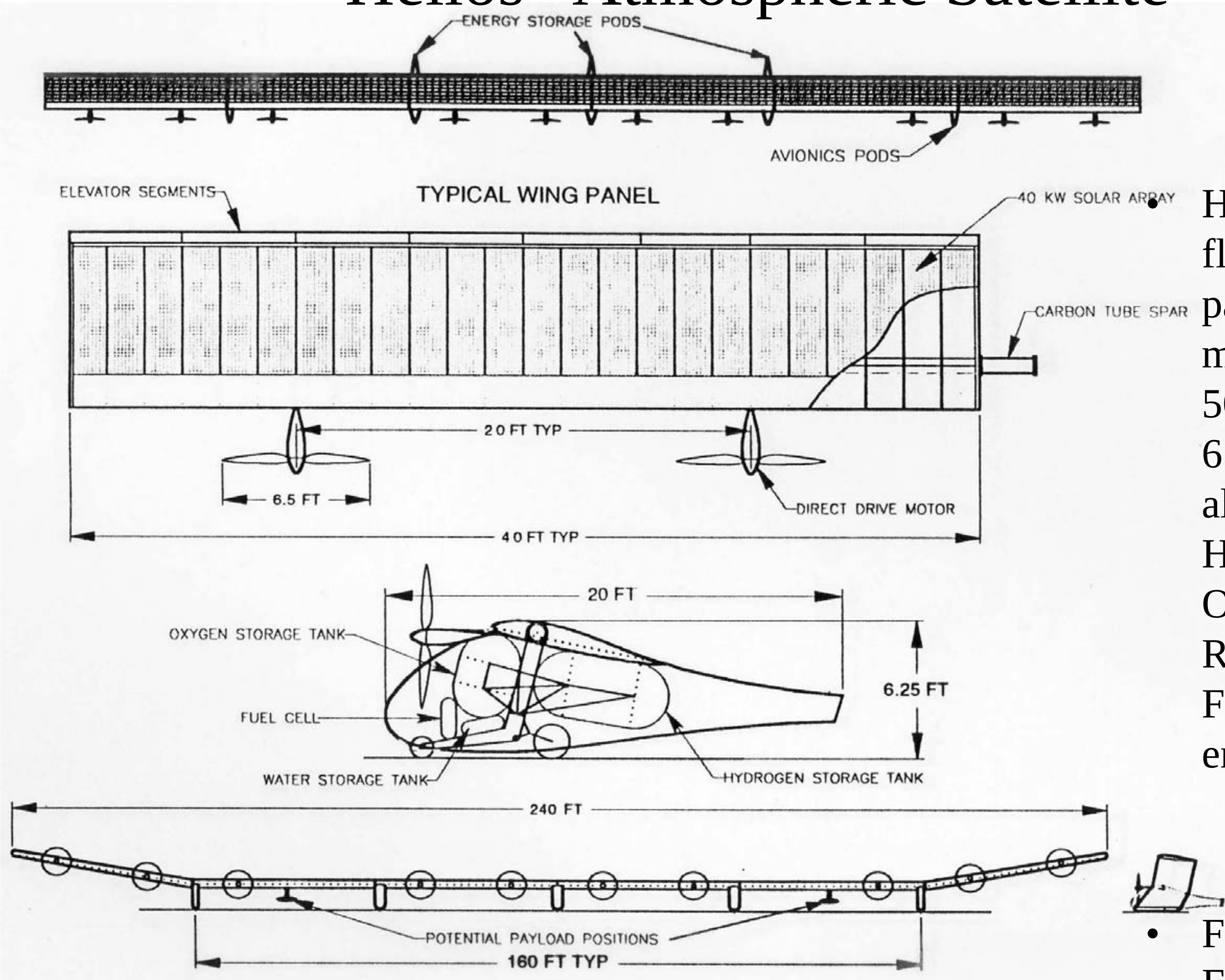
The H2-O2 Regenerative Fuel Cell @ NASA GRC

- developmental status
- future disposition

Solar Electric Aircraft and the Energy Storage Requirements for Continuous Flight

Solar Electric Aircraft

Helios “Atmospheric Satellite”

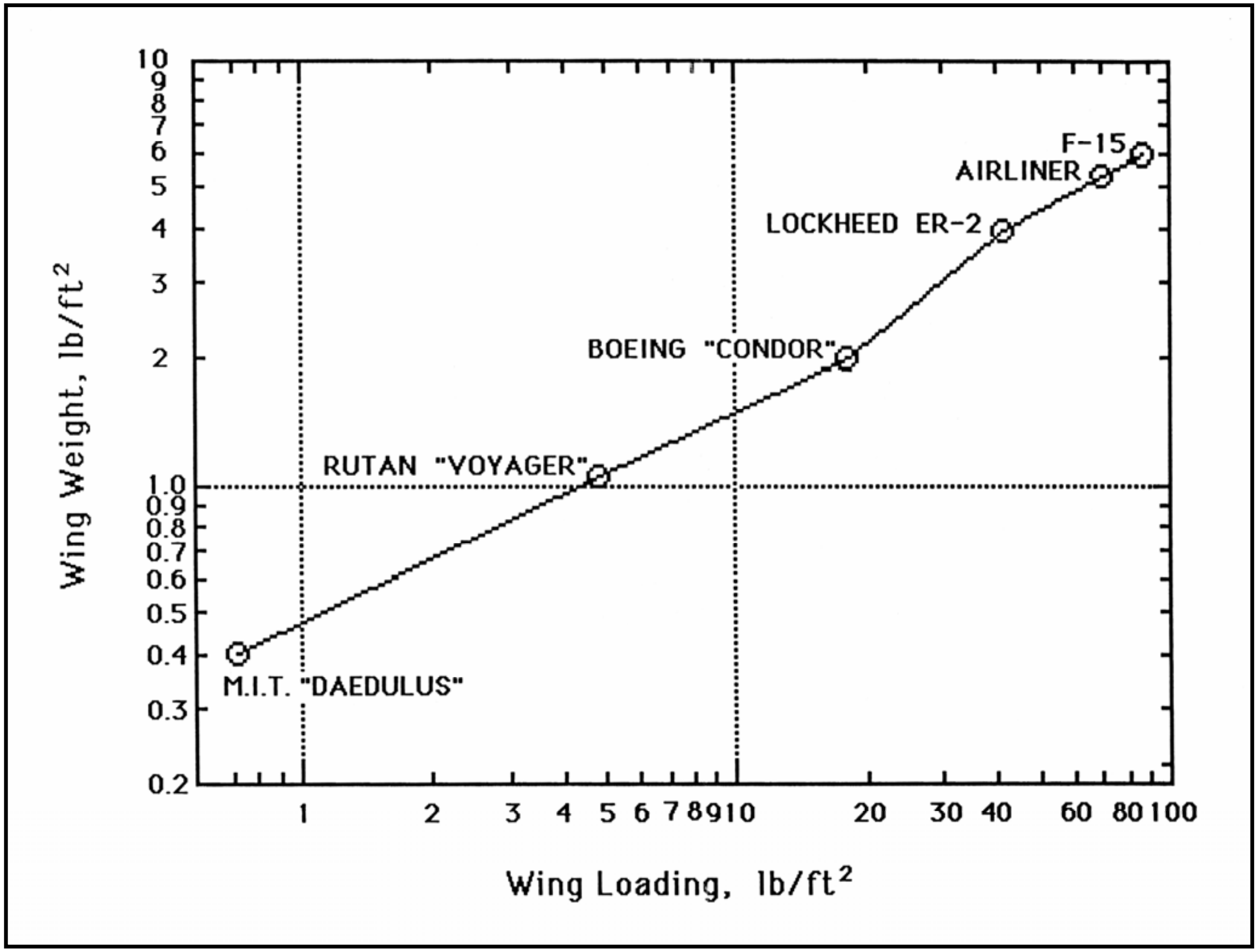


- Helios was to fly 200 pound payloads for > 3 months between 50,000 and 65,000 feet altitude using a Hydrogen-Oxygen Regenerative Fuel Cell for energy storage

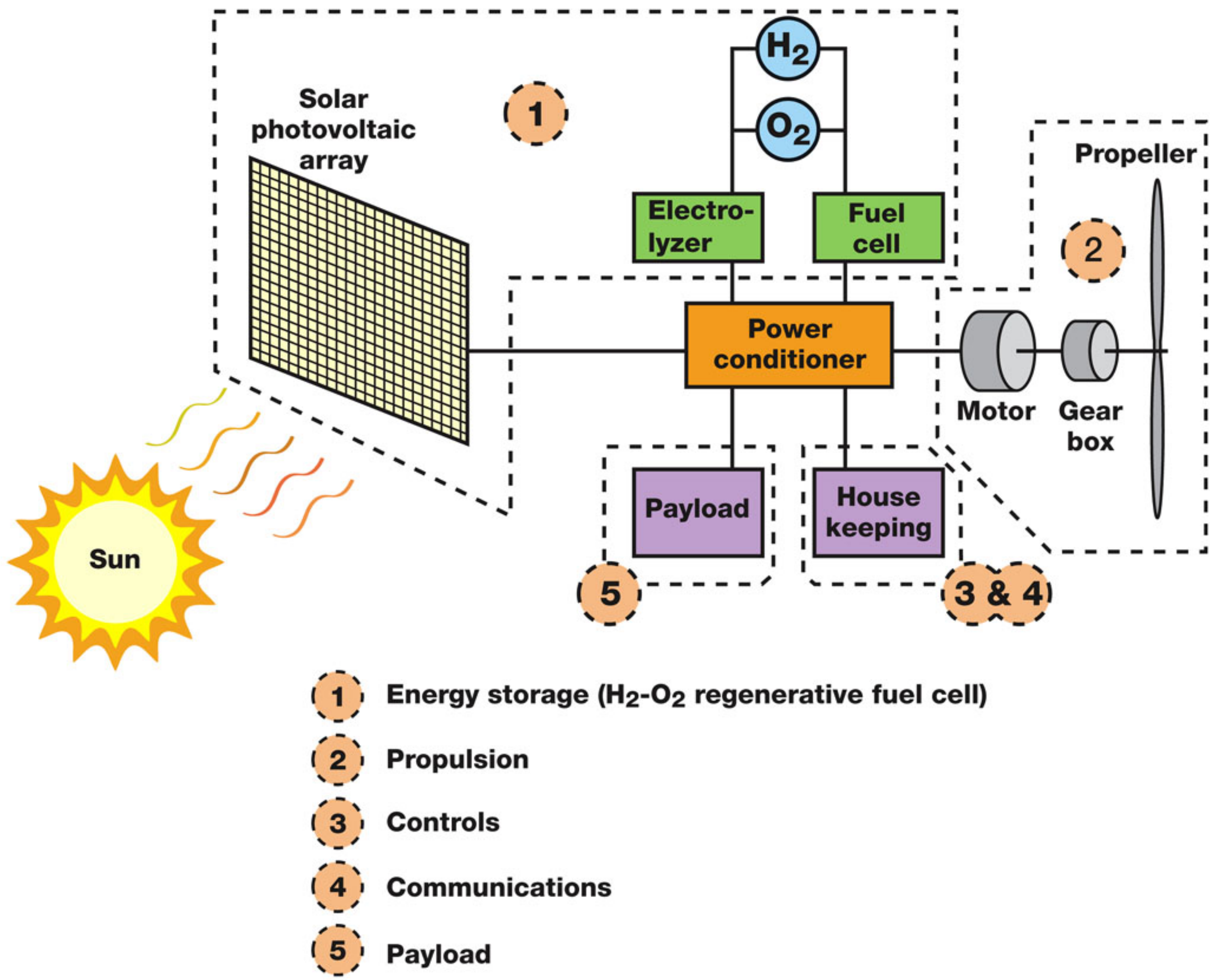
- First Helios Flight: Summer of 2003

4802
NASA
4800
AeroVironment Inc.
HELIOS
AeroVironment
ERAST
Pathfinder
FIRE TRUCK LANE

Aircraft structural weight versus wing loading



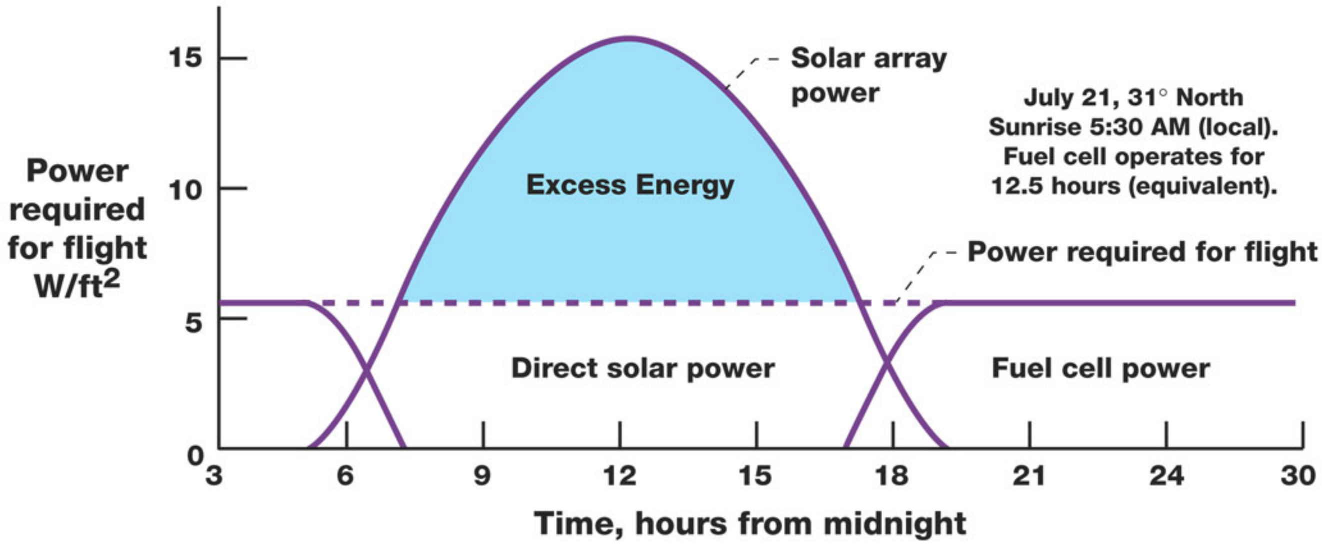
Solar Plane Power Train



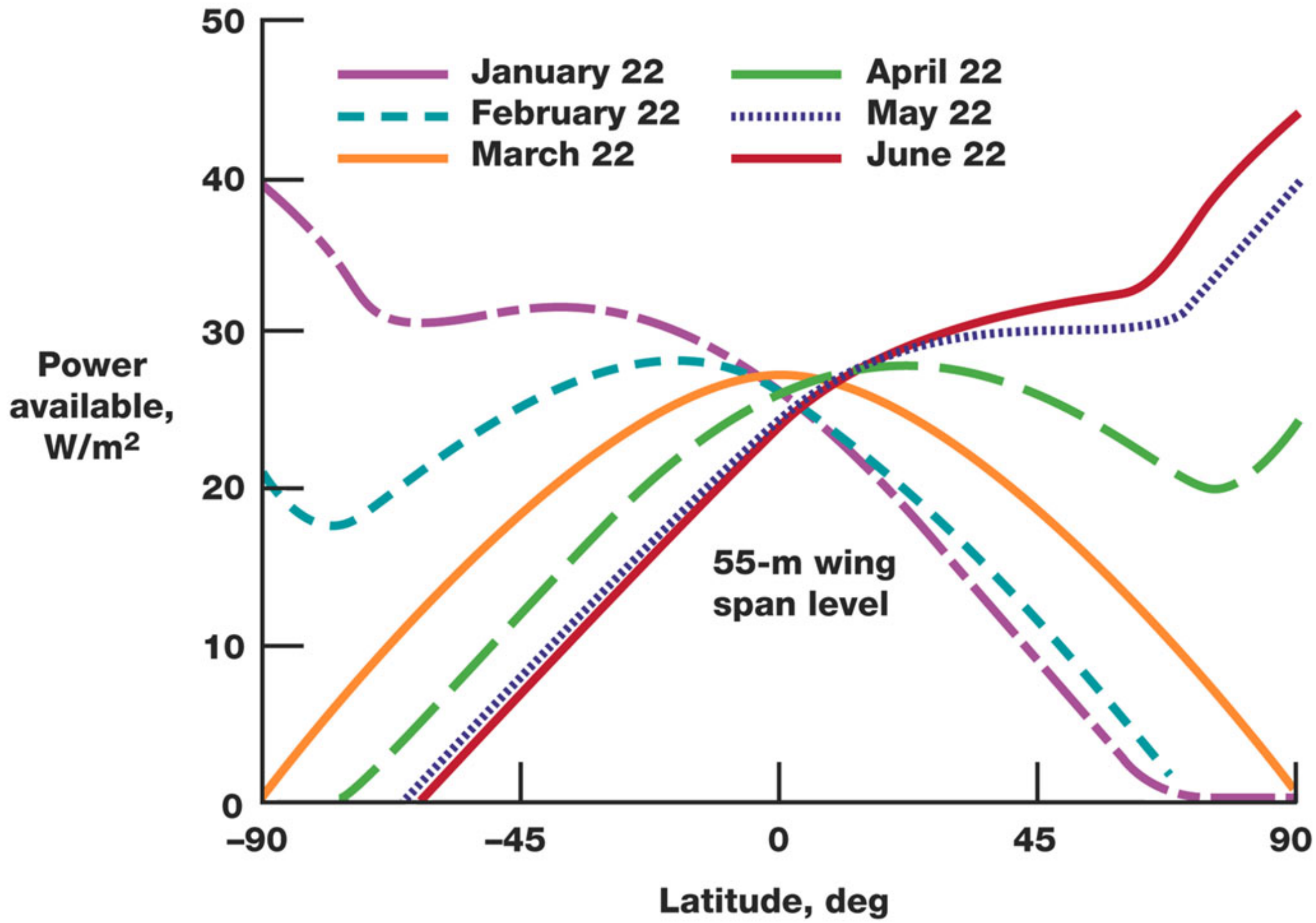
Energy Balance for Continuous Flight

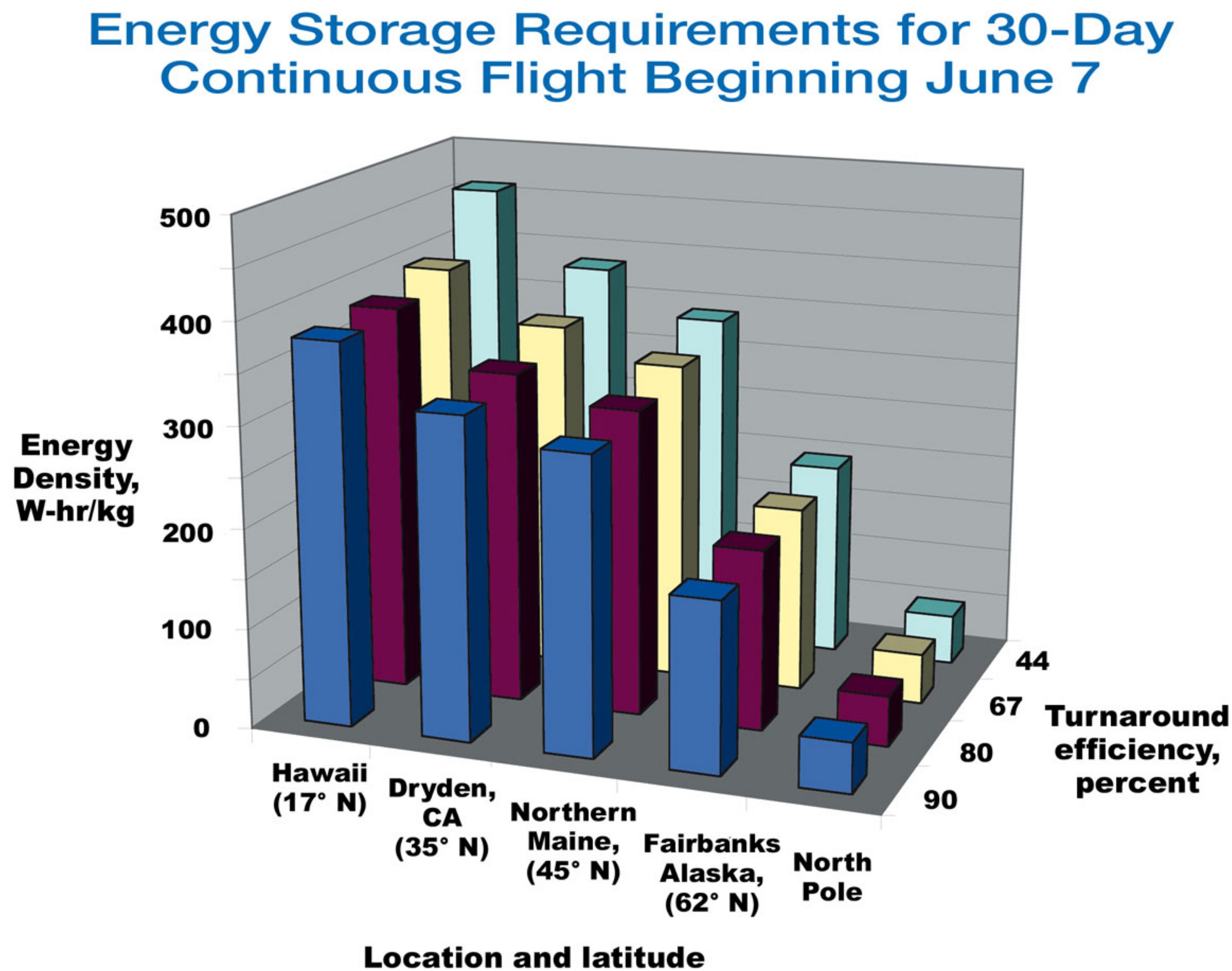
1) Energy capacity of fuel cell = Energy required to fly through night + Energy to run payload during night

2) Energy collected by solar array = Energy required to fly through day + Energy required to recharge fuel cells + Energy to run payload during day



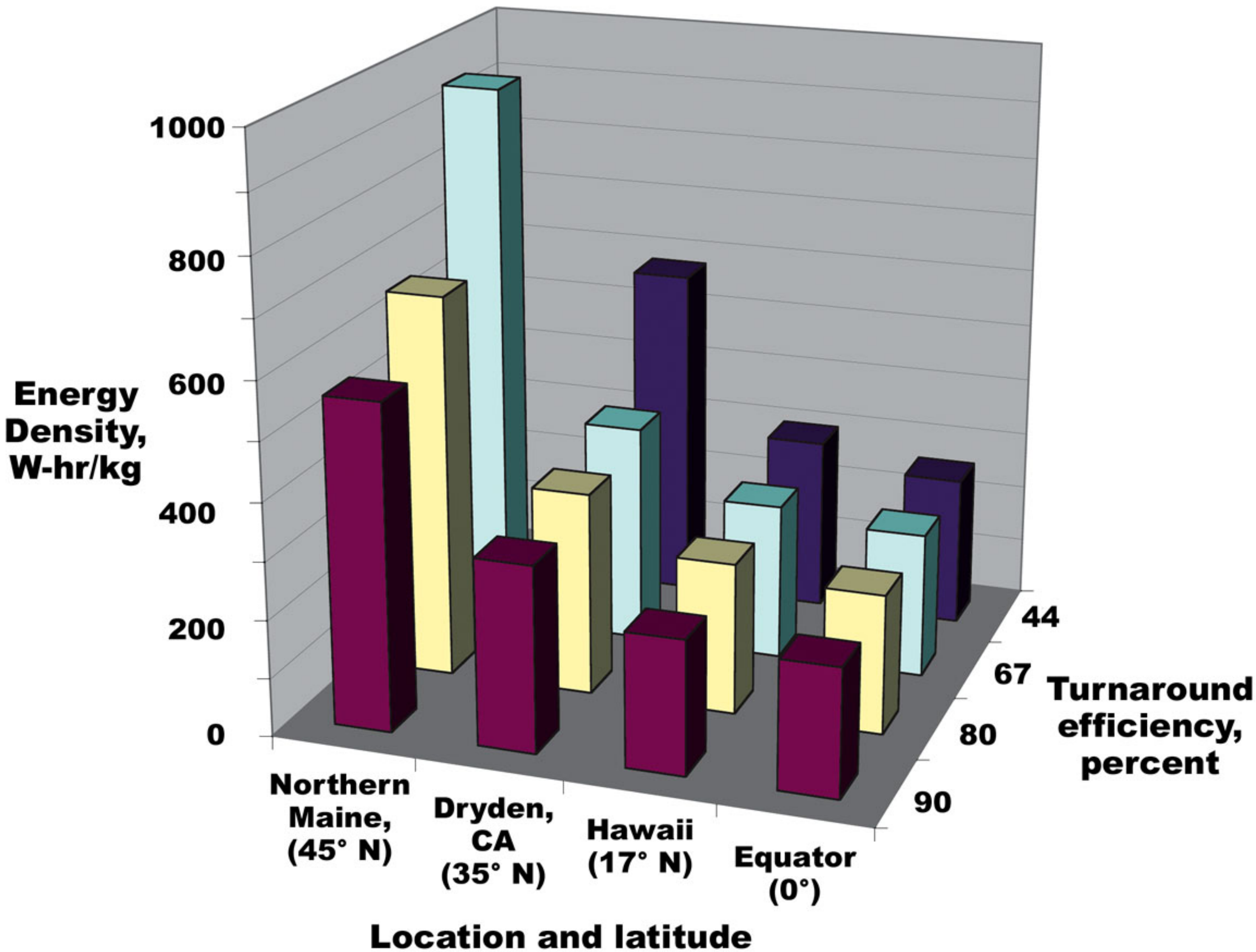
Solar Power Available Versus Earth Latitude From January to May



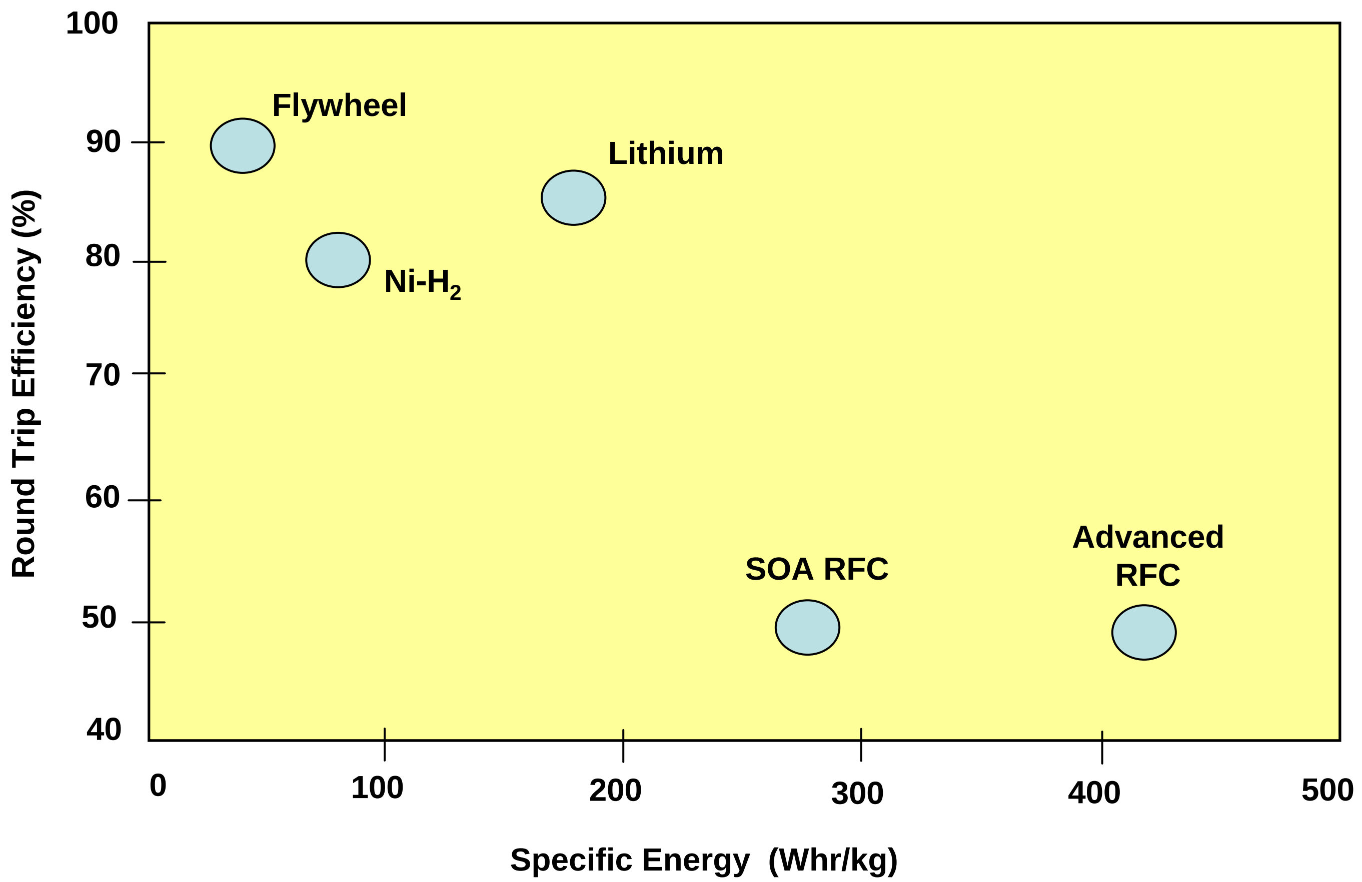


Energy Storage Requirements for 30-Day Continuous Flight Beginning June 7
500
400
300
200
100
0
Energy Density, W-hr/kg
Hawaii (17° N)
Dryden, CA (35° N)
Northern Maine, (45° N)
Fairbanks Alaska, (62° N)
North Pole
Location and latitude
44
67
80
90
Turnaround efficiency, percent

Energy Storage Requirement for Year Long Continuous Flight



Comparison of Energy Storage Devices
(12 hr/12 hr cycle)



The Hydrogen-Oxygen Regenerative Fuel Cell

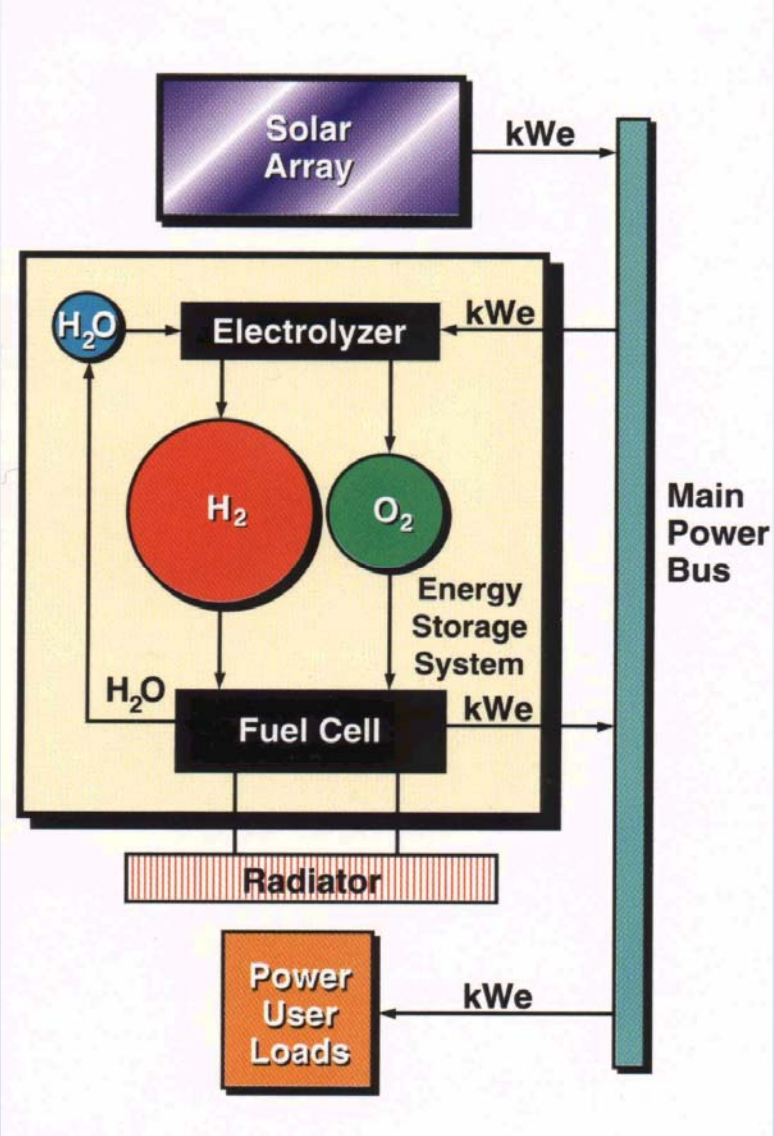
morphology

technology

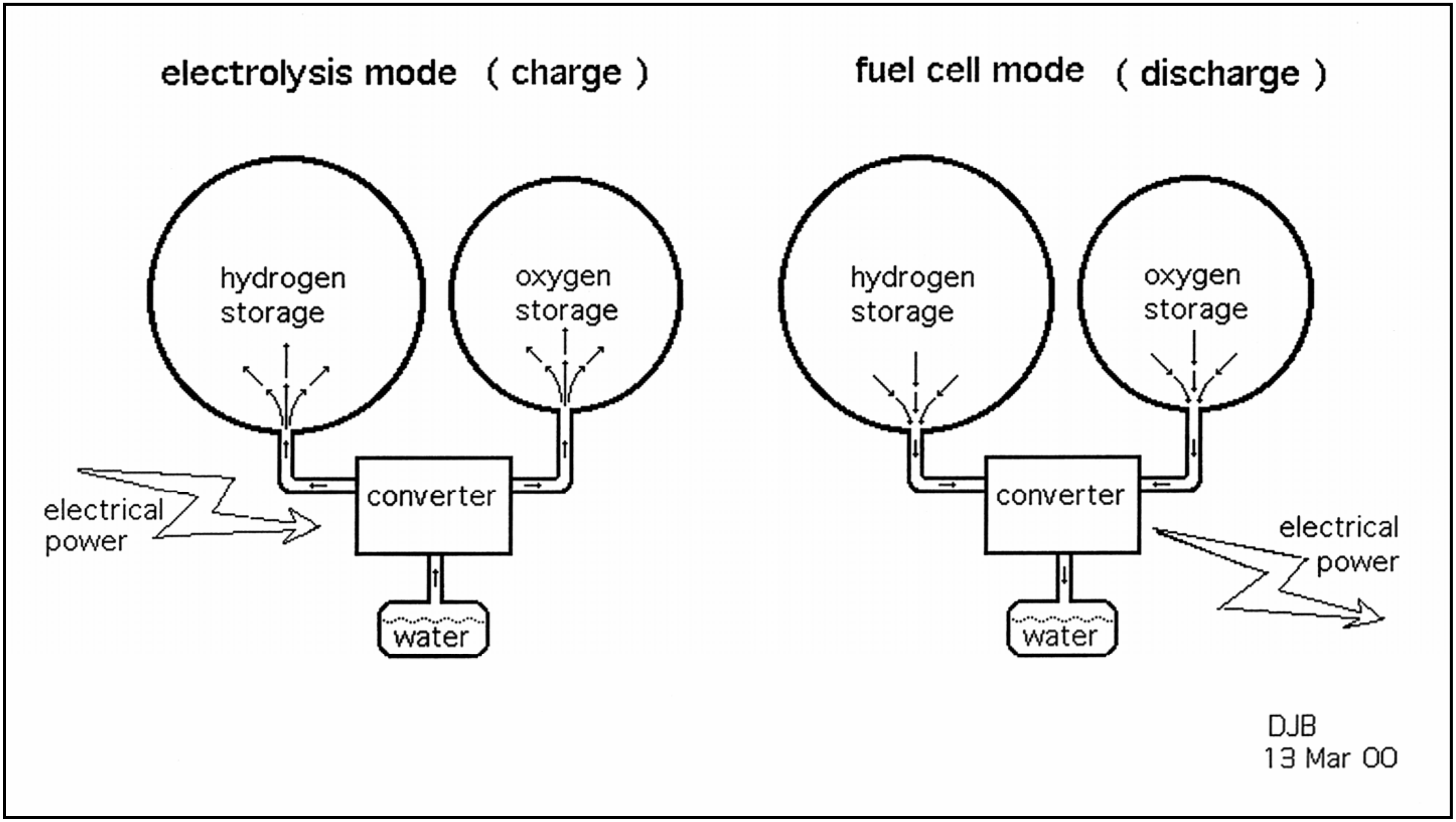
favorable attributes

Regenerative Fuel Cell System

- During the day a solar array captures the suns rays and converts them to electricity
- This electricity is used to run electrolyzer and the load
- The electrolyzer takes stored water and splits it into H_2 and O_2
- These gases are stored for later use
- When the sun goes down the fuel cell turns on
- The fuel cell uses the stored gases to make water and an electrical current which powers the load



Hydrogen – Oxygen Regenerative Fuel Cell



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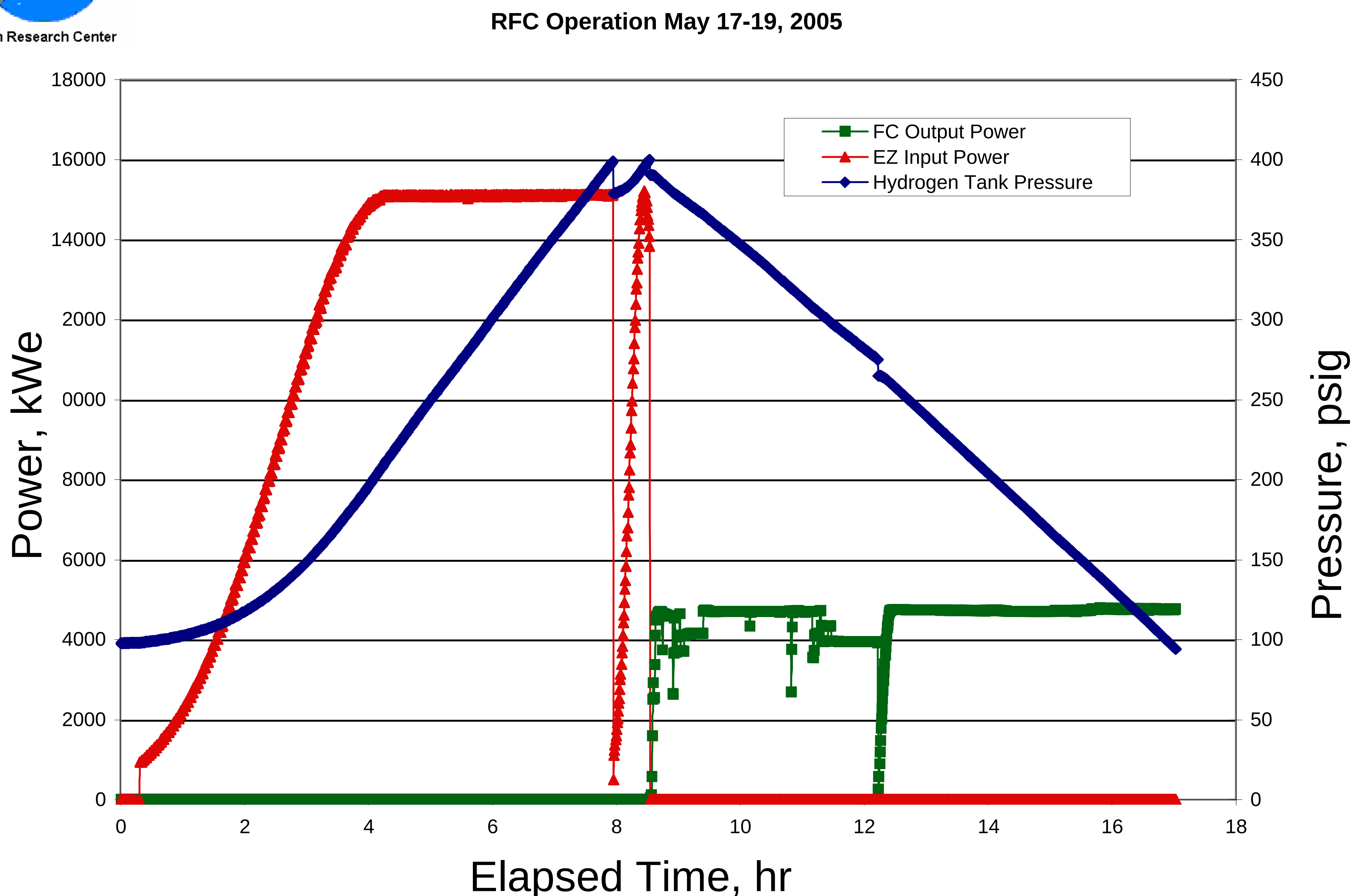

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Closed Cycle Regenerative Fuel Cell

Energy storage comparison

Mission Application	Sun / Shade cycle	Specific Energy, Delivered Whr per Kilogram of Storage	Remarks
Low earth orbit (space station)	0.9 hr / 0.6 hr	40 - 60 Whr/kg	Not competitive
Solar electric Aircraft	12 hr / 12 hr	300-600 Whr/kg	Highly competitive
Lunar base (@equator)	334 hr / 334 hr	1100 - 1200 Whr/kg	No competition

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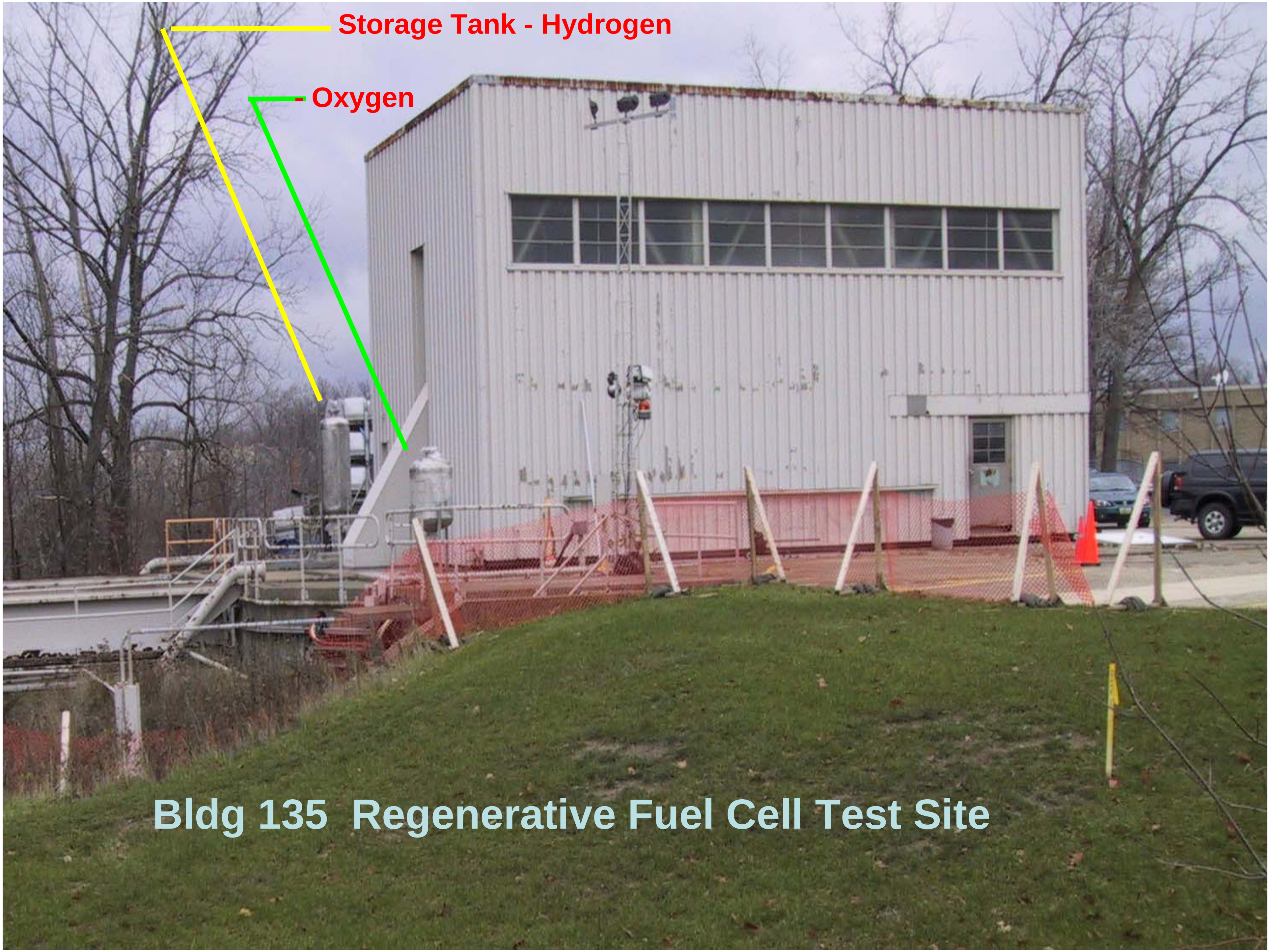
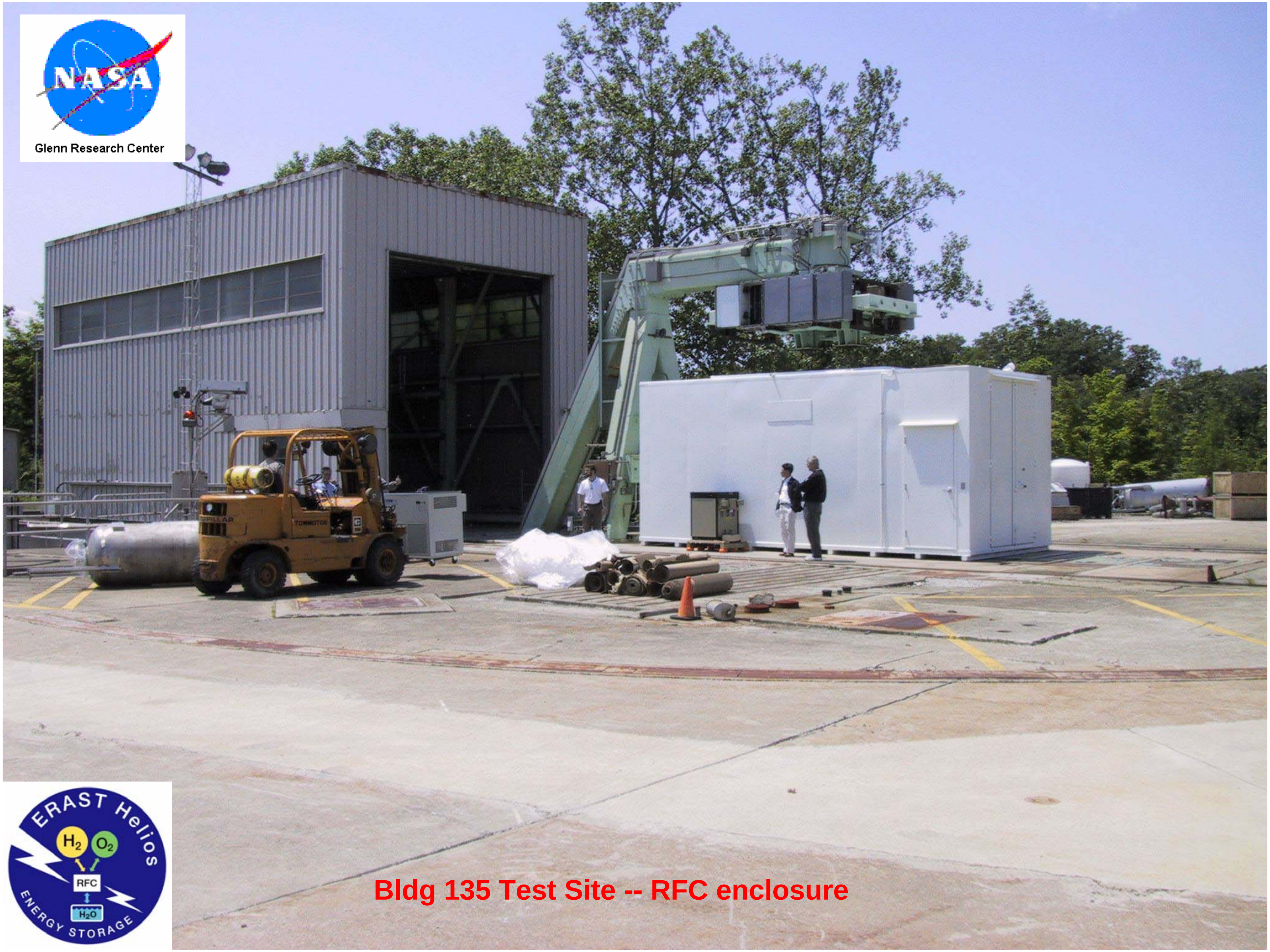
The H2-O2 Regenerative Fuel Cell @ NASA GRC

developmental status
future disposition

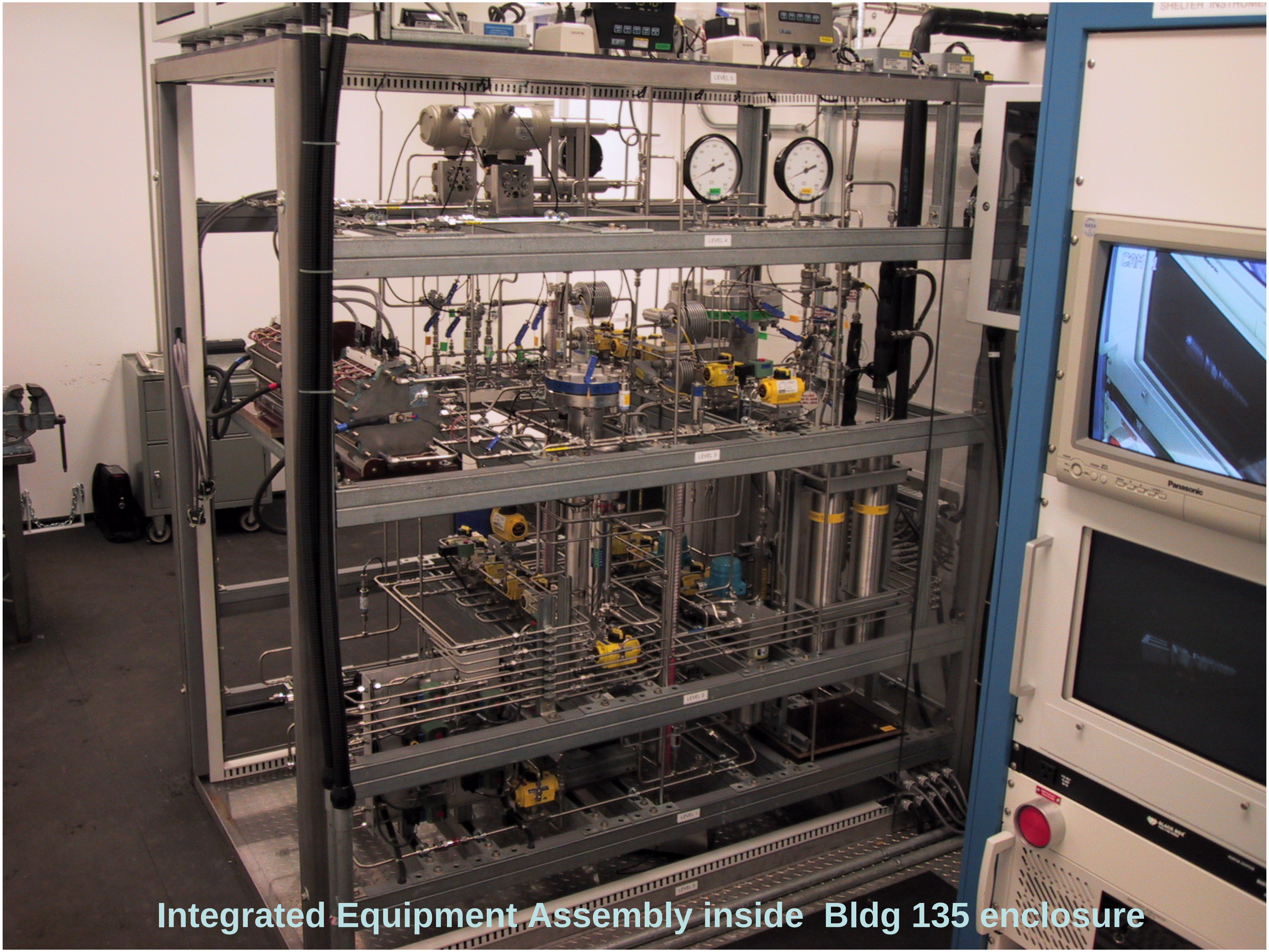
Closed Cycle H2-O2 Regenerative Fuel Cell

Built up at NASA GRC during FY 2002 - 2003
First closed loop demonstration Sep. 2003
Coordinated operation of fuel cell and electrolyser subsystems
as integrated electrical energy storage system
generate and store H2 and O2 reactant gasses
produce electrical power from stored H2 and O2
system is completely sealed: nothing goes in, nothing escapes
other than electrical power and waste heat
Closed loop operation at full power Jun 2004.
Further development testing July 2004-July 2005
Demonstrated 5 contiguous back to back charge-discharge cycles at full power without breakdown or degradations under semi autonomous control July 2005.
New reactant recirculation loop pumps, thermal control improvements made during FY2006, unattended operation demonstrated April 2006
Next step: build test hours, gain more operating experience.
Effort ends FY2008

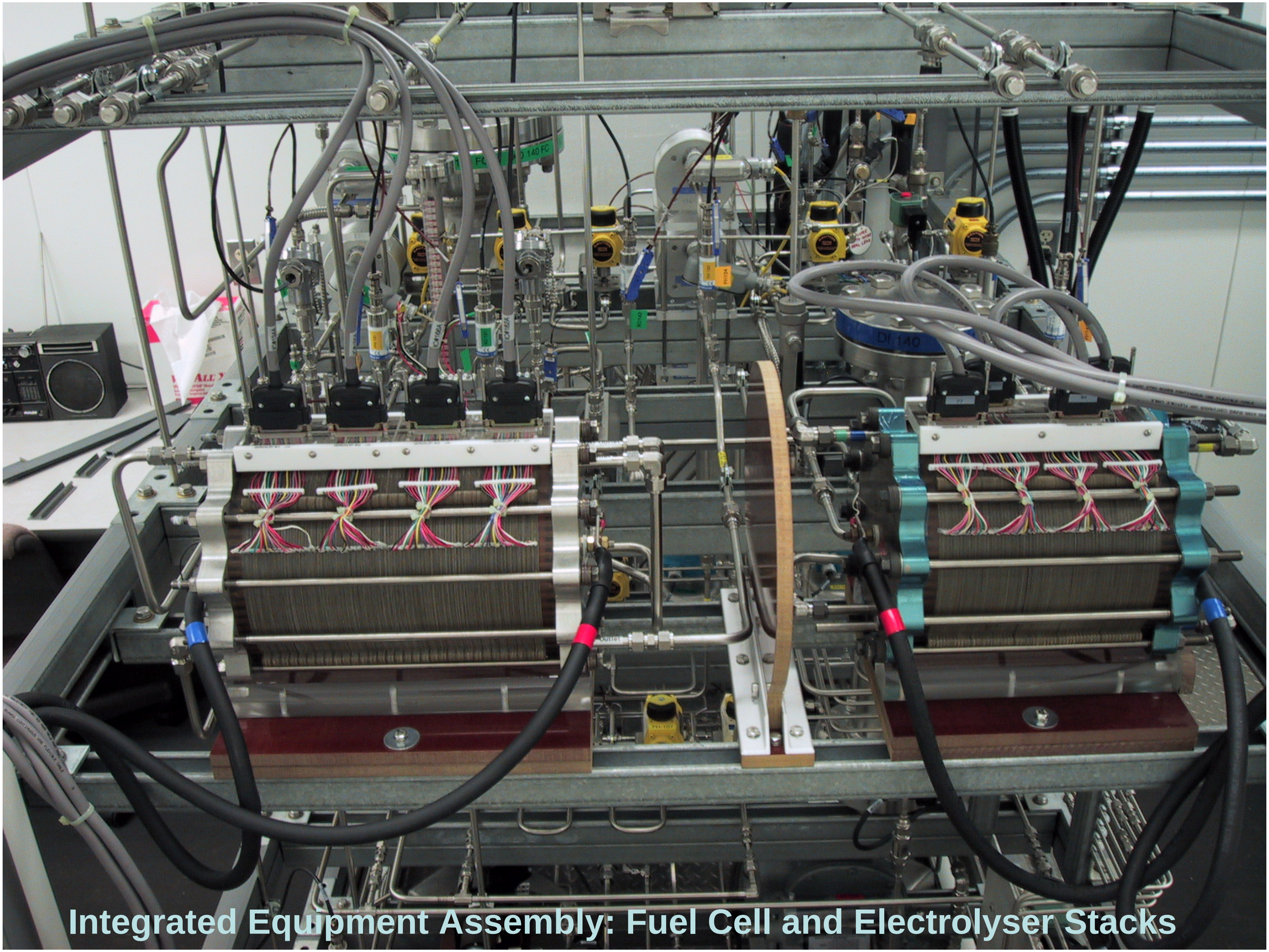

Storage Tank - Hydrogen
Oxygen
Bldg 135 Regenerative Fuel Cell Test Site



Bldg 135 Test Site -- RFC enclosure



Integrated Equipment Assembly inside Bldg 135 enclosure



Integrated Equipment Assembly: Fuel Cell and Electrolyser Stacks

CONTROL / MONITOR INSTRUMENTATION

Instrument data collection, most control actuation through National Instruments Field Point I / O modules

Ethernet Bus and multiport switching hubs accommodate Field Point I / O and RS232 / RS485 serial connections.

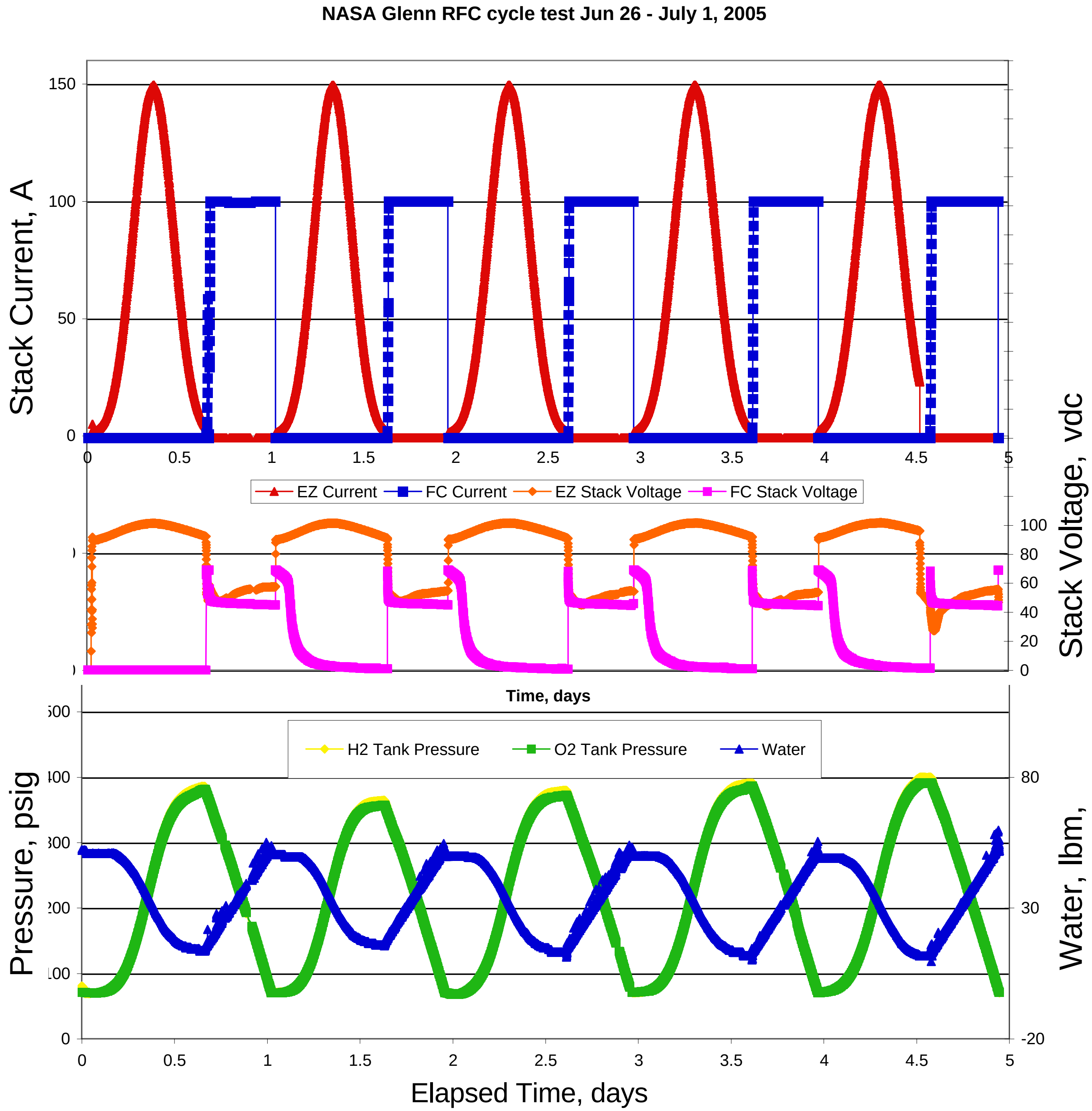
Fiber optic data link control room to test site

PC-based National Instruments <Lab View> controller
3 redundant controller PC's, master-slave hierarchy
"RFC Day Cycle" program

Critical safety functions hard-wired / relay logic


Mode Transition Control
Purge
Shutdown
EZ Mode

closed cycle energy storage system operations

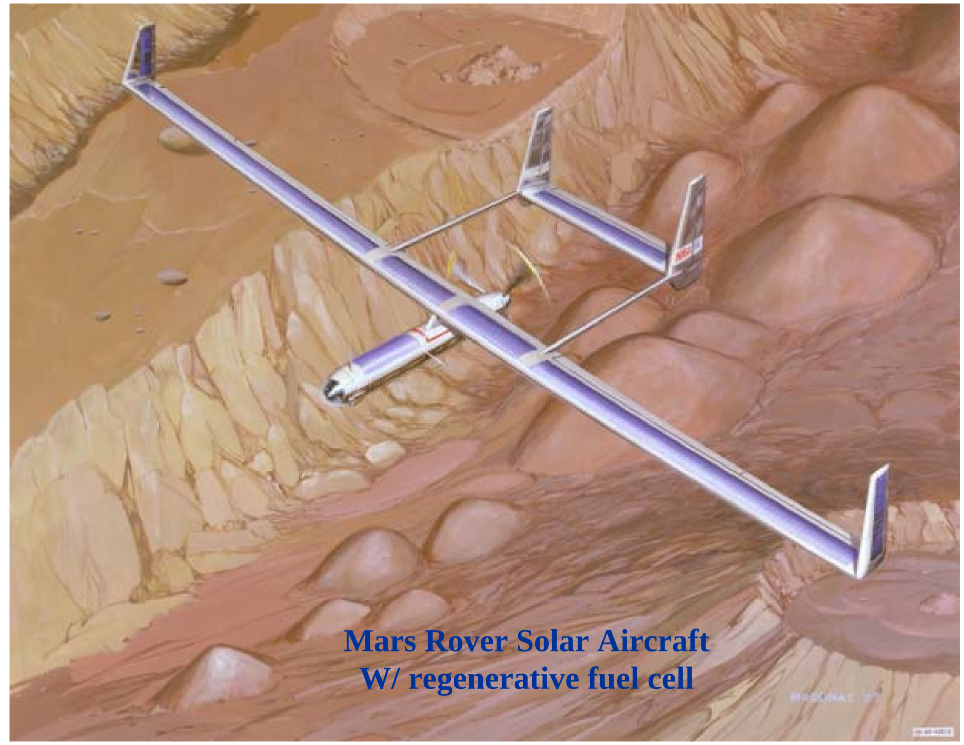


Summary

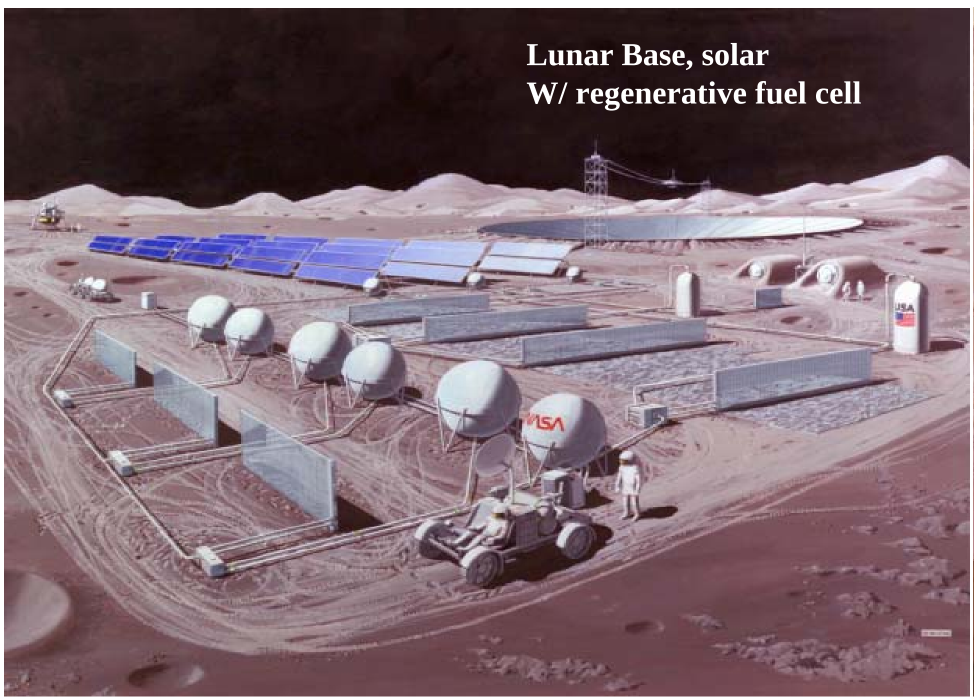
- **First Ever, Fully Closed Cycle Hydrogen-Oxygen Regenerative Fuel Cell**
- **Multiple Contiguous Day / Night Closed Loop Cycles completed at Full Power with SOA Hardware**
- **50 PCT RTE demonstrated**

Why we did it

- RFC enables future NASA missions
  - Lowest mass solar energy storage when day/night cycles > 4 hr
- Derived from modern air breathing PEM fuel cell commercial technology base -- hardware slightly different



Mars Rover Solar Aircraft
W/ regenerative fuel cell



Lunar Base, solar
W/ regenerative fuel cell

Mars Base Camp, solar
W/ regenerative fuel cell