National Aeronautics and
Space Administration

Solar Arrays With Storage (SAWS) Mars Surface Power System Design and Trade Studies for future NASA Missions

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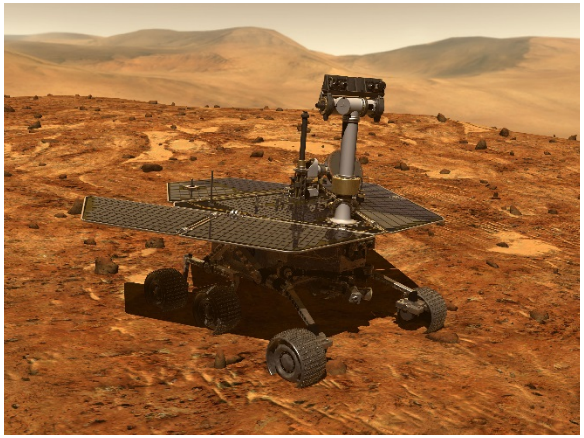
Motivation

Problem: NASA plans to send humans to Mars in the next 20+ years. Human exploration of Mars requires at least 10s of kilowatts of electrical power. Continuous power is needed, potentially lower at night but no option for "standby modes"

Concept Study Goal: Develop a credible solar array/energy storage system alternative to nuclear for Mars surface electrical power

- **40 kW class architecture / 10 kW class "modules"**
- **Can be delivered and deployed on the 1st robotic mission and remain functional for multiple crew missions**
- **For this concept, the system would be integrated into the lander and have autonomous deployment and operation**



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SAWS Study Overview

One Year Seedling Study funded by NASA Space Technology Mission Directorate (STMD), Game-Changing Development (GCD) Program

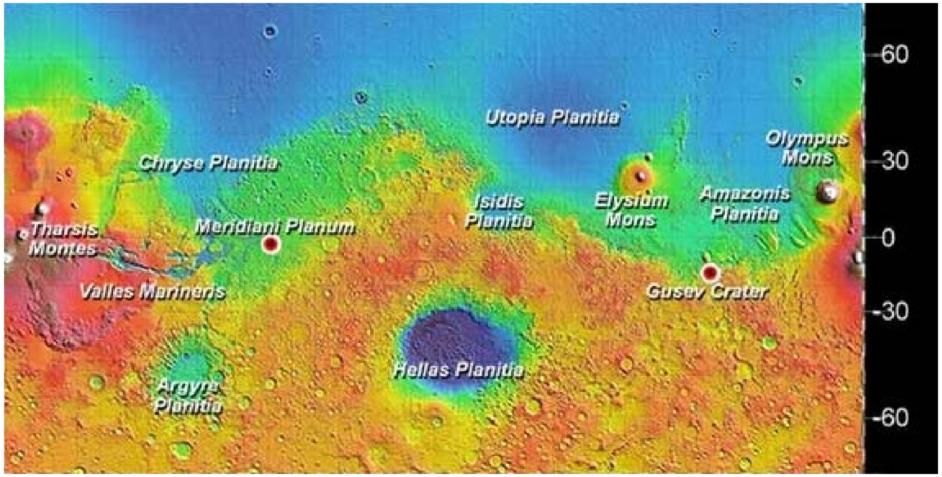
NASA is pursuing multiple Mars surface power technology options with primary goal to provide flexibility, robustness, and high reliability

Technical Approach

- **Establish SAWS Ground Rules, Assumptions, and Mission Guidelines**
- **Develop solar array and energy storage concept**
- **Identify performance benefits and limitations of the concept through varied mission parameters**
- **Identify technology gaps for further development**

Environmental Considerations

- **Light: Diffuse and variable throughout the day and during dust storms**
- **Global Dust Storms: Range up to 120 days with peak optical depth of 5 (~30% flux of OD 1). Historically, occur during Southern Summer ~ 1 in 3 years**
- **Wind Speeds: Viking landers measured typical wind speeds of 2-7 m/sec and wind gusts up to only 26 m/sec at an elevation of 1.6 m. Windy sites may be more beneficial (clearing dust off arrays) but loading on arrays likely higher**
- **Elevation: Higher sites slightly better than lower sites**
- **Latitude: Very high sites experience winter with dust storms so solar very challenged**
  - Sun Distance: Northern hemisphere is better – Mars distance from sun less during northern winter (when days are shorter)
  - Global Dust storms occur during southern summer (northern winter): dust storms happen in worst case winter conditions in northern hemisphere



Mission Constraints

Solar array must deploy autonomously from the lander. No ground robotic assistance.
No lander azimuth control
Solar array deployment and system operation in Mars 0.38 g gravity under low winds
Must survive daily temperature change of ~120 C (approx. -100 C to +20 C near equator) over a lifetime > 10 years
Minimum 1,000 m^2 deployed solar array area per lander
Solar array extensible to 1,500+ m^2 per lander for higher latitudes and dustier skies
Array mass goal < 1.5 kg/m^2 inclusive of all mechanical
Array packaging goal < 10 m^3, which is ~30 kW/m^3 at 1 AU
Array deployable on terrain with up to 0.5-m rocks, 15 deg slopes, and potentially hidden hazards
Max solar array deployment time of 8 hours
Solar arrays must survive 120 days of 40 m/sec wind gusts and 100 m/sec peak winds (dust devil), equivalent to ~30 mpg Earth winds
Solar arrays should have ability to tilt/feather for winds and dust removal
RFC nominal output power of 10 kW on 120 Vdc power bus on each lander
RFC operational life of ~12 years (>46,000 hrs electrolysis, >60,000 hrs fuel cell)
RFC charge/discharge of >74,000 cycles at 12.3 hr periods (landing site dependent)
RFC mass of <2,000 kg per lander

Solar Array Concept Selection

Previously Proposed Concepts

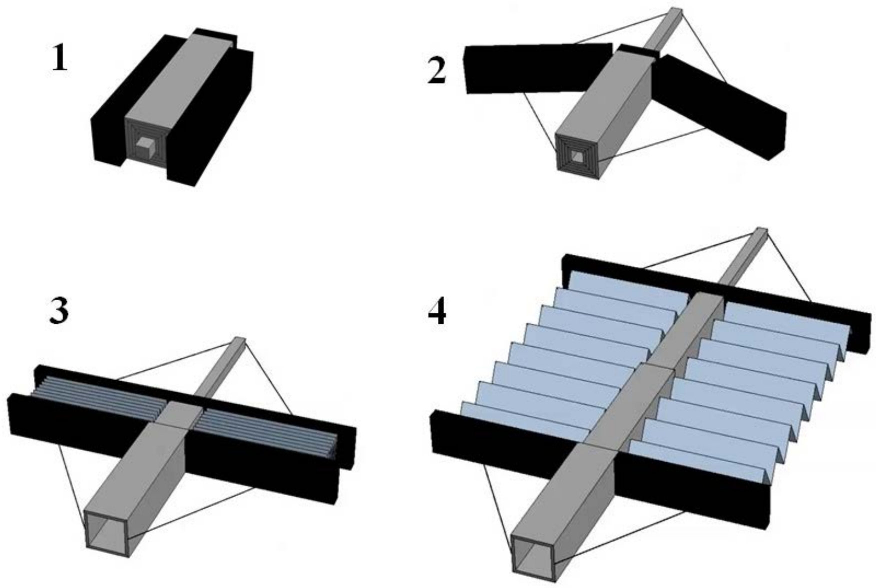
Recent 0-g Concepts: UltraFlex, ROSA, CTA

Assess SBIR Contract Innovations

Compare with Guidelines and Assumptions

CTA: Compact Telescoping Array – Baseline

- Array developed at NASA Langley Research Center for large in-space applications
- Chosen due to its innovative design, strength, and utilization of most cell technologies
- Adaptable to include ground supports



Positive Features

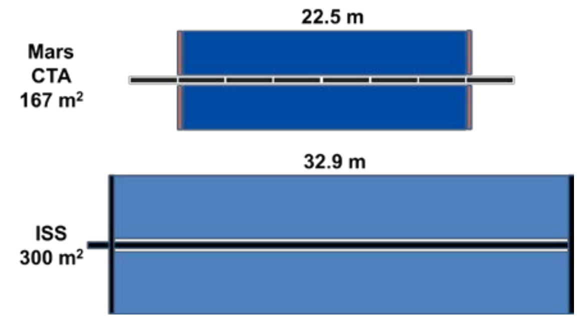
- Structure is its own deployment canister
- Telescoping boom widely used in construction equipment
- Compatible with launch vehicles for manned Mars missions
- Capable of high axial deployment force

Major Challenges include

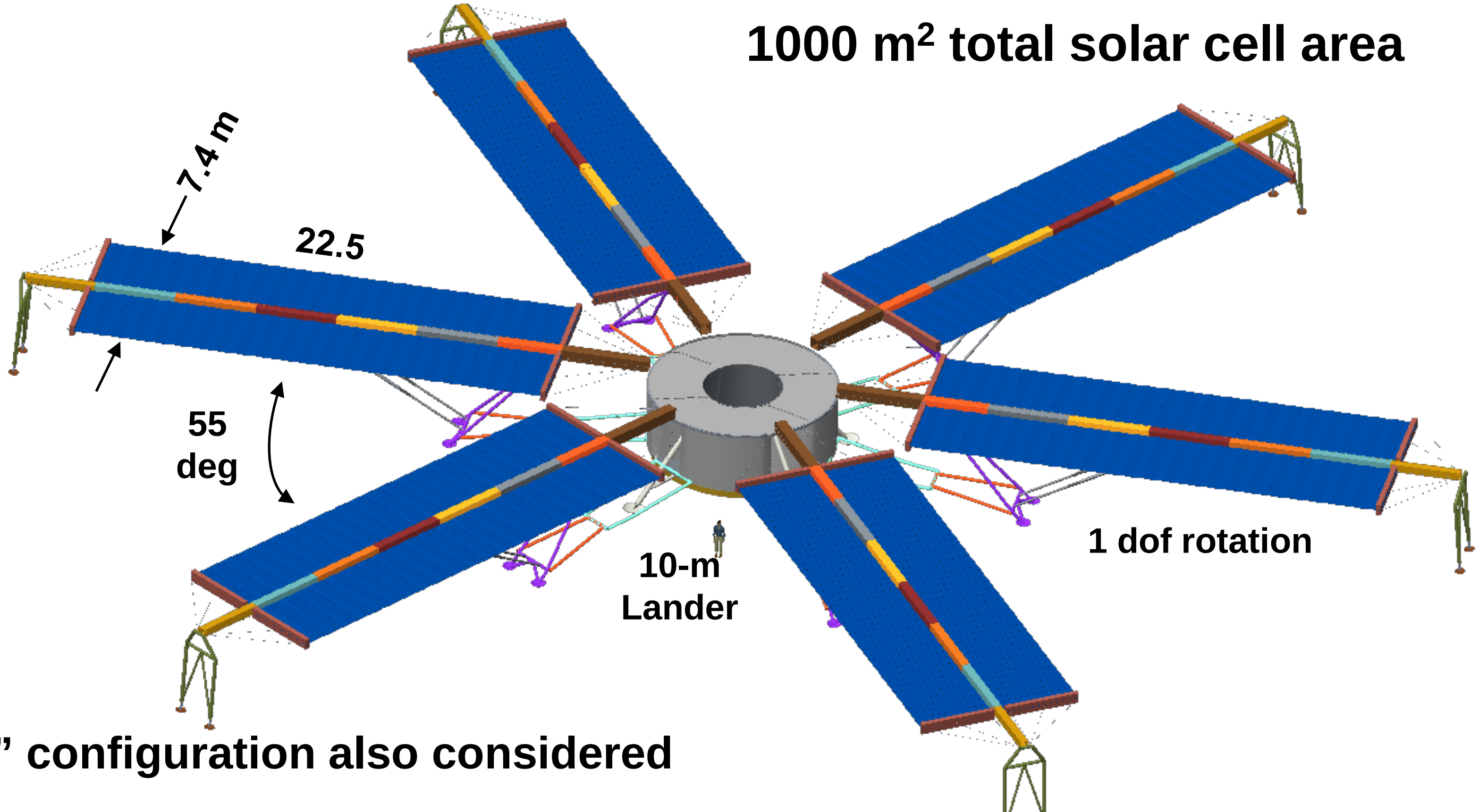
- Lightweight “linear motor” for actuation
- Lateral stability of deploying boom segments before lockup
- Telescoping composite trusses, compact blanket support arms, mechanisms
- Guy wire packaging, deployment, and tensioning
- Deployable, drop-down legs that allow array rotation

Configuration: Solar Array

- **This represents one configuration that provided the necessary deployed area of solar array**
- **Each CTA array is 167 m², more than half the size of an ISS solar array**
- **Uses IMM solar cells**

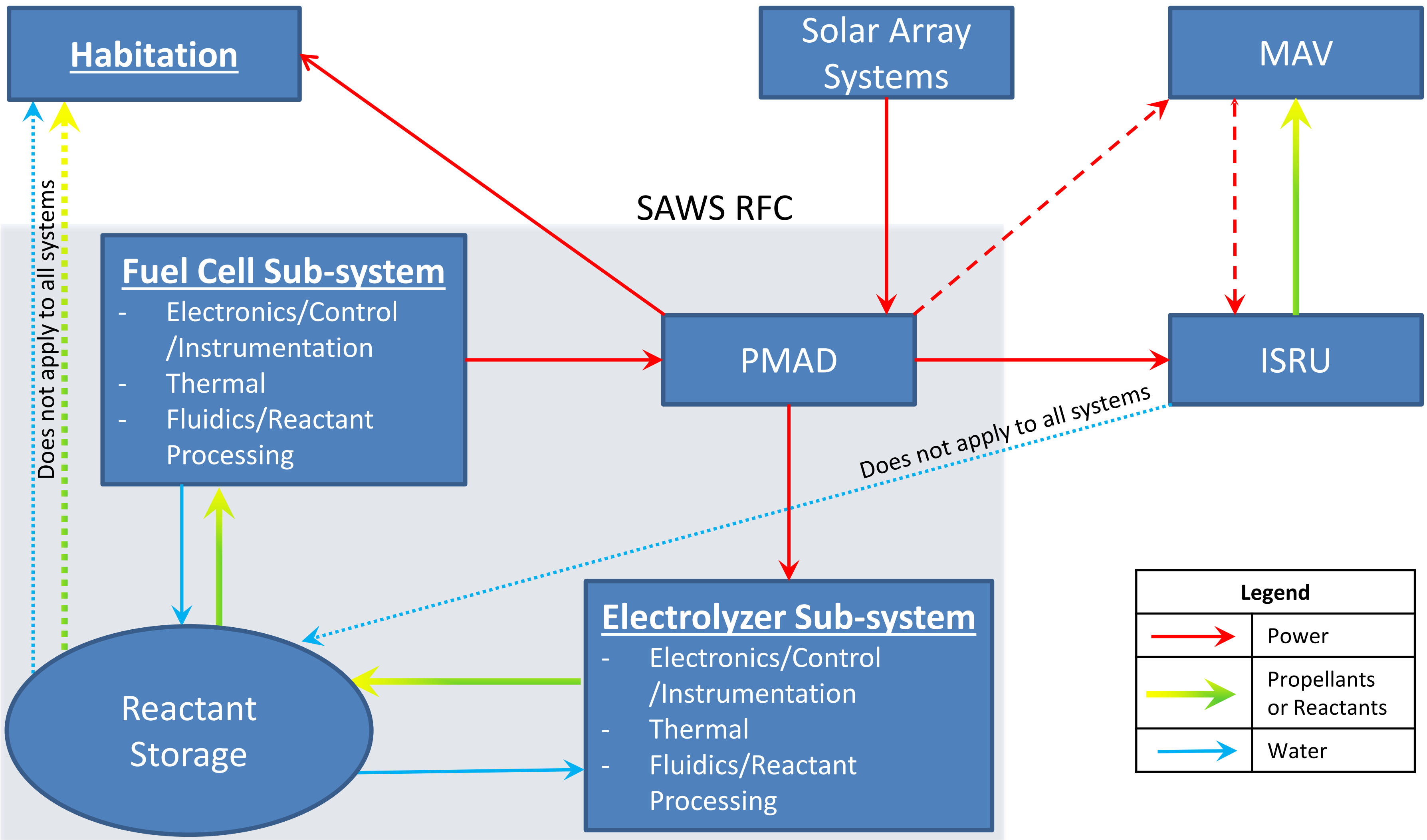


1000 m² total solar cell area

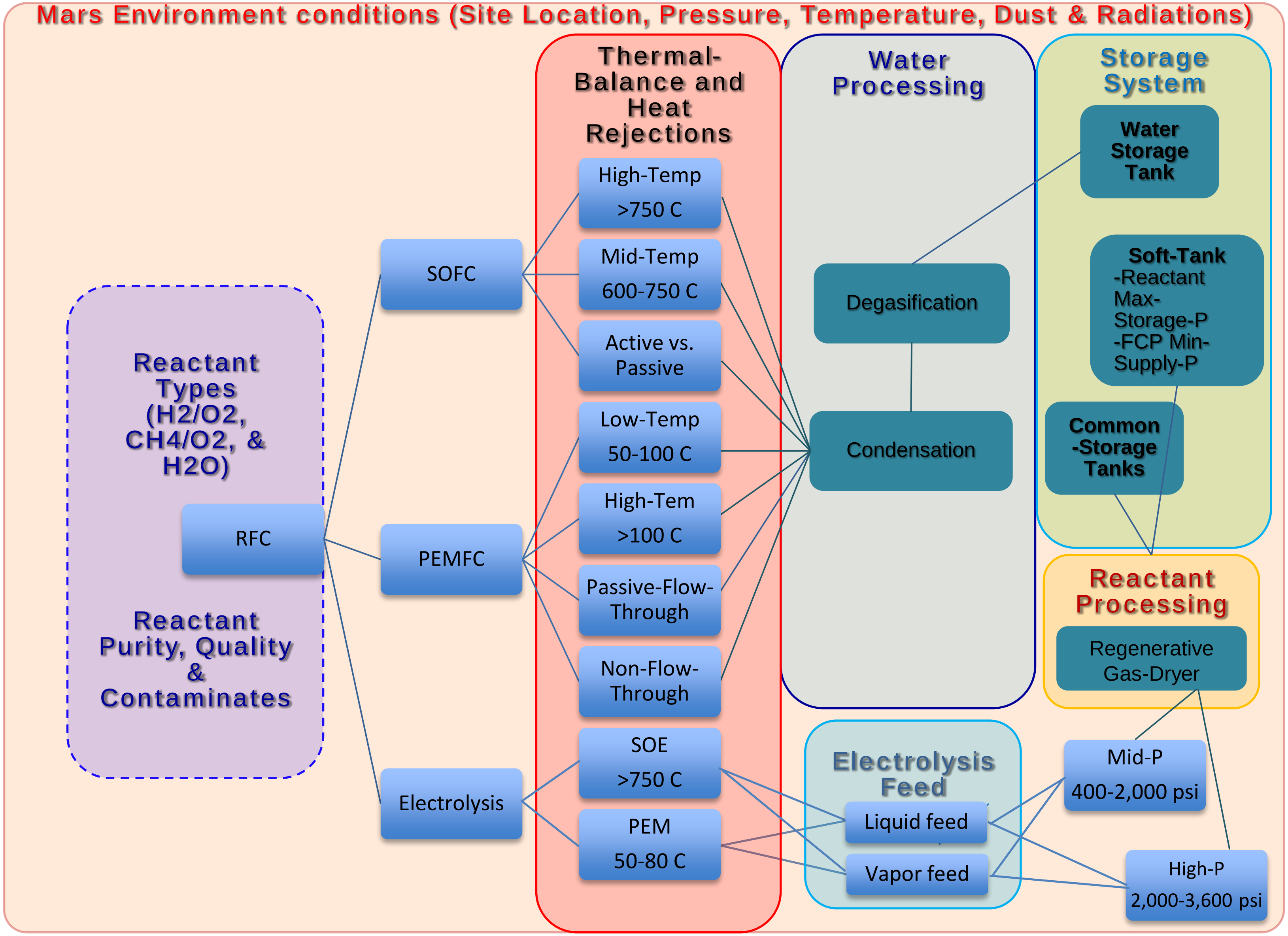


“H” configuration also considered

Top Level Power Architecture



SAWS RFC Technology Evaluation Decision Gates



Technology Summary Chart for Aerospace RFC Applications

Each RFC sub-system traded across multiple parameters

Reactant Storage

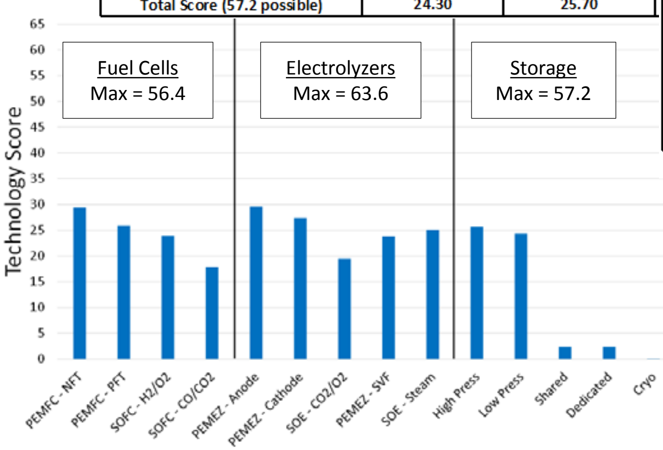
Weight Factor	Evaluation Factors	Low-pressure Storage (300 psig) Total	Low-pressure Storage (300 psig) Rank	High-pressure Storage (3,000 psig) Total	High-pressure Storage (3,000 psig) Rank	Cryogenic Storage Total	Cryogenic Storage Rank	Shared with Propellant Total	Shared with Propellant Rank	Dedicated Propellant Total	Dedicated Propellant Rank
	Long Life/Performance	3.80		9.20		5.10		6.90		6.90	
0.9	Longevity (>50,000 hour run time)	0.9	1	3.6	4	1.8	2	2.7	3	2.7	3
0.9	Reliability	0.9	1	3.6	4	1.8	2	2.7	3	2.7	3
0.5	Shock/Vibration Tolerance	2	4	2	4	1.5	3	1.5	3	1.5	3
	Reactant Storage	4.50		0.00							
0.5	Dewar/Speciaized Tank	2	4	0	0						
0.5	COPV Tank	2	4	2	4						
0.5	Soft Tank/Bladder	0.5	1	-2	-4						
	Water System Processing	8.50		8.00							
0.5	Reactant Storage Thermal Balance	2	4	2	4						
0.5	Passive Thermal Rejection	1.5	3	1	2						
0.5	Active Thermal Rejection	2	4	2	4						
0.5	Filtration/Purification Simplicity	0	0	0	0						
0.5	Ambient Thermal Storage	2	4	2	4						
0.5	RFC Reactant Thermal Efficiency	1	2	1	2						
	Integrated System	3.50		4.50							
0.5	Freeze Tolerance	2	4	2	4						
0.5	Total System Round-Trip Efficiency	2	4	0	0						
0.5	System Specific Energy (w/ storage)	1	2	0.5	1						
0.5	Balance of Plant Complexity	1	2	1	2						
0.5	System Mass optimization	-1	-2	1	2						
0.5	System Volume optimization	-1.5	-3	0	0						
	Fluid Transfer Complexity	4.00		4.00							
0.5	Cryogenic Hydrogen	-2	-4	-2	-4						
0.5	Cryogenic Methane	-2	-4	-2	-4						
0.5	Cryogenic Oxygen	-2	-4	-2	-4						
0.5	Gaseous Carbon Dioxide	2	4	2	4						
0.5	Gaseous Carbon Monoxide	2	4	2	4						
0.5	Gaseous Hydrogen	2	4	2	4						
0.5	Gaseous Methane	2	4	2	4						
0.5	Gaseous Oxygen	2	4	2	4						
0.5	Water Vapor	0	0	0	0						
	Total Score (57.2 possible)	24.30		25.70							

Electrolysis

Weight Factor	Evaluation Factors	PEM - Anode Feed Total	PEM - Anode Feed Rank	PEM - Cathode Total	PEM - Cathode Rank	PEM - Static Total	PEM - Static Rank	Solid Oxide - H_2/O_2 Total	Solid Oxide - H_2/O_2 Rank	Solid Oxide - CO_2/O_2 Total	Solid Oxide - CO_2/O_2 Rank
	Long Life/Performance	12.90		12.90		10.20		11.60		10.70	
0.9	Stack Longevity (>50,000 hour run time)	2.7	3	2.7	3	1.8	2	2.7	3	1.8	2
0.9	Reliability	2.7	3	2.7	3	1.8	2	2.7	3	2.7	3
0.9	Shock/Vibration Tolerance	2.7	3	2.7	3	1.8	2	1.8	2	1.8	2
0.9	Load Cycle Durability (>1,000 cycles)	3.6	4	3.6							
0.4	Thermal Cycle Durability (>625 cycles)	1.2	3	1.2							
	Thermal Balance	-0.10		-0							
0.5	Active Thermal Rejection	-0.5	-1	-0.5							
0.5	High-Temp Operation (650-750 °C)	0	0	0							
0.5	Low-Temp Operation (60-80 °C)	2	4	2							
0.5	Passive Thermal Rejection	-1	-2	-1							
0.5	Thermal Control when off-line	-1	-2	-1							
0.1	Rapid Startup (< 5 minutes)	0.4	4	0.4							
	System	15.20		13							
0.9	Freeze Tolerance	-1.8	-2	-1.8							
0.9	High Pressure Operation (>1,000 psia)	3.6	4	3.6							
0.9	Longevity (>50,000 hour run time)	2.7	3	2.7							
0.9	Sub-System Specific Energy (no storage)	1.8	2	1.8							
0.7	Balance of Plant Complexity	2.1	3	1.4							
0.7	Medium Pressure Operation (>300 psia)	2.8	4	2.8							
0.5	System Mass optimization	2	4	1							
0.5	System Volume optimization	2	4	1.5							
	Reactant Purity Capability	1.60		1.							
0.8	Clean Liquid Water	3.2	4	3.2							
0.8	Clean Water Vapor	0	0	0							
0.8	Impure Liquid Water	-1.6	-2	-1.6							
0.8	Impure Water Vapor	0	0	0							
0.1	Carbon Dioxide	0	0	0							
	Total Score (63.6 possible)	29.60		27							

Fuel Cells

Weight Factor	Evaluation Factors	PEMFC - NFT Total	PEMFC - NFT Rank	PEMFC - PFT Total	PEMFC - PFT Rank	SOFC - H_2/O_2 Total	SOFC - H_2/O_2 Rank	SOFC - CO/O_2 Total	SOFC - CO/O_2 Rank
	Long Life/Performance	15.30		14.40		10.80		8.10	
0.9	Stop/Start Durability (>1,000)	3.6	4	3.6	4	2.7	3	2.7	3
0.9	Thermal Cycle Durability (>625)	3.6	4	3.6	4	1.8	2	1.8	2
0.9	Longevity (>50,000 hour run time)	2.7	3	2.7	3	1.8	2	0.9	1
0.9	Reliability	2.7	3	1.8	2	1.8	2	0.9	1
0.9	Shock/Vibration Tolerance	2.7	3	2.7	3	2.7	3	1.8	2
	Thermal Balance	0.20		0.20		3.00		3.00	
0.6	Low-Temp Operation (60-80 oC)	2.4	4	2.4	4	0	0	0	0
0.1	Rapid Startup (< 5 minutes)	0.3	3	0.3	3	-0.1	-1	-0.1	-1
0.4	High-Temp Operation (750-850 oC)	0	0	0	0	1.6	4	1.6	4
0.5	Active Thermal Rejection	-0.5	1	-0.5	1	0	0	0	0
0.5	Passive Thermal Rejection	-1	-2	-1	-2	1.5	3	1.5	3
0.5	Thermal Control when off-line	-1	-2	-1	-2	0	0	0	0
	System	12.70		10.10		8.90		6.10	
0.9	Sub-System Specific Energy (no storage)	3.6	4	2.7	3	0.9	1	0.9	1
0.7	Hermetic sealing	2.8	4	2.8	4	0.7	1	0.7	1
0.9	Round-trip efficiency	2.7	3	2.7	3	2.7	3	0.9	1
0.7	Minimum Balance of Plant Complexity	2.1	3	1.4	2	0.7	1	0.7	1
0.5	Operating Pressure (50 - 100 psia)	2	4	2	4	1	2	0.5	1
0.5	System Mass optimization	2	4	1.5	3	1	2	1	2
0.5	System Volume optimization	2	4	1.5	3	1	2	0.5	1
0.9	Freeze Tolerance	-1.8	-2	-1.8	-2	3.6	4	3.6	4
0.9	Longevity (>50,000 hour run time)	-2.7	-3	-2.7	-3	-2.7	-3	-2.7	-3
	RFC Reactant Capability	1.20		1.20		1.20		0.70	
0.2	Hydrogen (H2)	0.8	4	0.8	4	0.8	4	0	0
0.1	Oxygen (O2)	0.4	4	0.4	4	0.4	4	0.4	4
0.1	Carbon Monoxide (CO)	0	0	0	0	0	0	0.3	3
0.1	Hydrocarbon (CH4)	0	0	0	0	0	0	0	0
	Total Score (56.4 possible)	29.40		25.90		23.90		17.90	

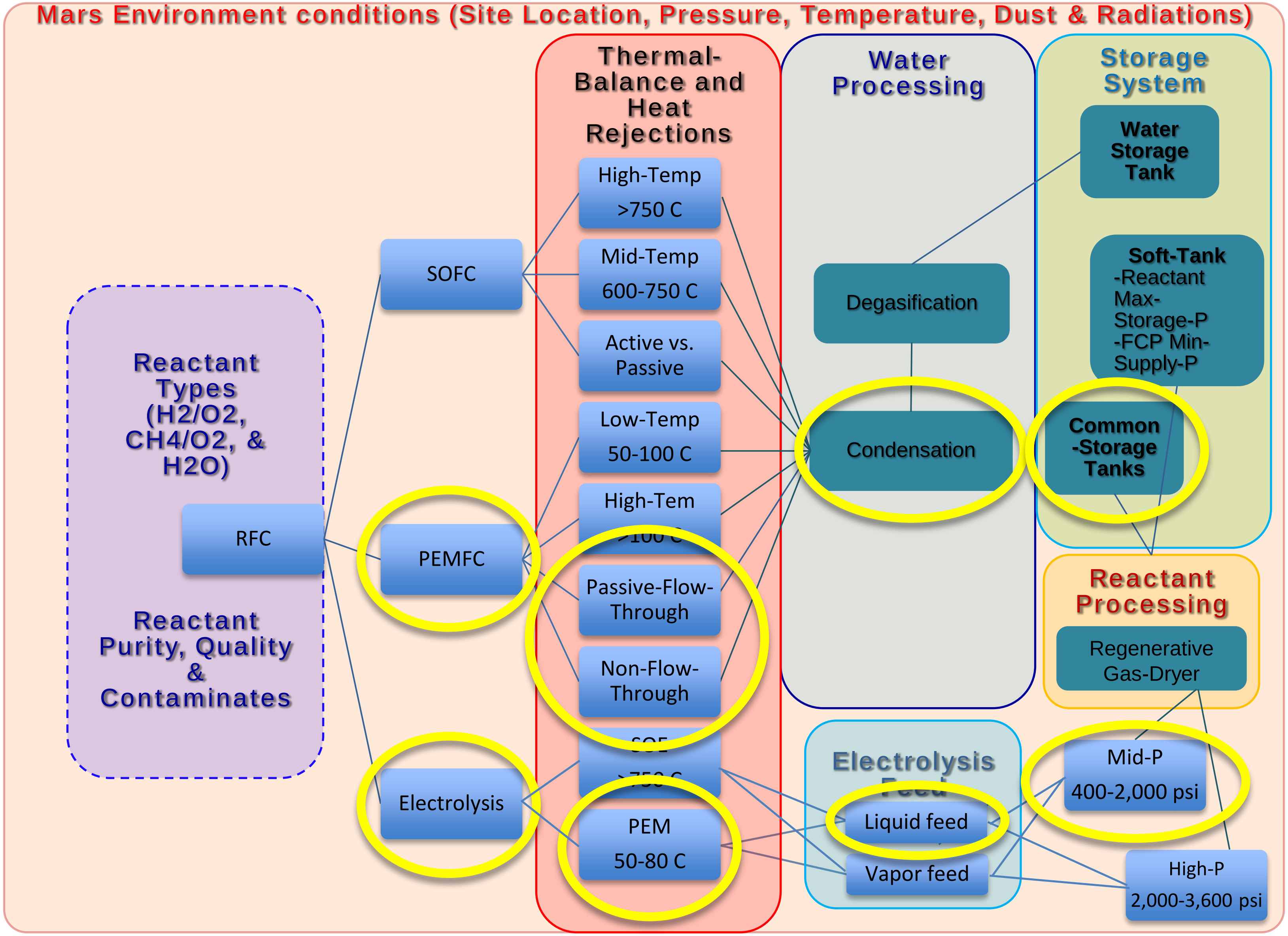


Evaluation Factor Ranking

- 4 = Mature Technology with Heritage
- 3 = Successful Field Deployment
- 2 = Successful Field Demonstration
- 1 = Successful Laboratory Demonstrations
- 0 = Not Applicable
- -1 = Unproven Solution Available
- -2 = Significant Development Required
- -3 = Major Advancement Required
- -4 = Prohibitive / Not Possible

* Reversable process (Fuel Cell/Electrolysis)

RFC Technology Evaluation Selections



RFC Summary

- **Architecture**
  - Top-level system block diagram and Interfaces defined
- **Fuel Cell**
  - PEMFC selected as higher TRL technology for aerospace applications
  - SOFC technology promising if using Hydrocarbon (CH_4) and/or Martian atmospheric CO_2 for energy storage
- **Electrolyzer**
  - PEM electrolysis selected due to insufficient solid oxide pressure capabilities
  - Long-term water quality issues as Environmental Control and Life Support System (ECLSS) water requirements different than RFC
  - Solid Oxide electrolysis technology is promising using Martian atmospheric CO_2 (MOXIE) for generating O_2 & CO (in reverse operation is a $CO+O_2$ SOFC)
- **PMAD**
  - Conceptual energy flow and electrical layout developed
- **Reactant Storage Tankage**
  - Hard-shell tanks selected
- **Technology**
  - Gaps Identified with Infusion paths

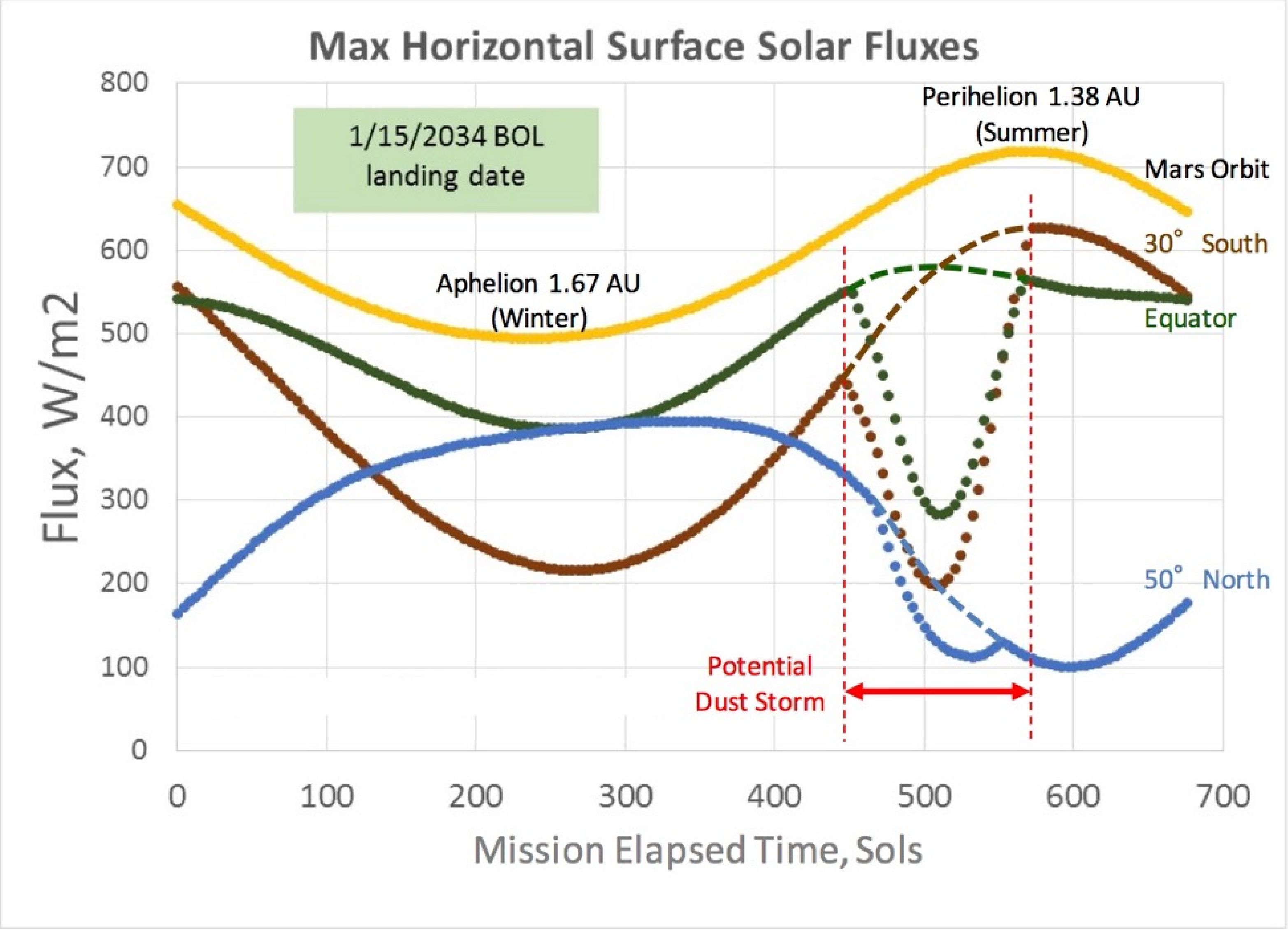
Calculating Performance

- Utilized Mars Surface Electrical Power System (MSEPS): NASA Fortran code created in the late 1990s to support the NASA Human Exploration of Mars Design Reference Mission 3.0 study
  - Tom Kerslake and Lisa Kohout "Solar Electric Power System Analyses for Mars Surface Missions," NASA-TM-1999-209288
  - Derived from "SPACE" code use to predict ISS solar EPS performance
  - Several code updates implemented in 2017 to support SAWS study
  - Code predicts the performance of solar power systems on the surface of Mars
  - Models: orbit mechanics, spectral solar fluxes, dust storms, sun angles, environments, current/voltage/power of solar array wings, energy storage (regen fuel cell or battery) and PMAD system, EPS energy balance (minimum continuous user power levels)
- MSEPS was executed on a variety of parametric cases to understand the effects of these parameters on the total solar power generation

BASELINE INPUT

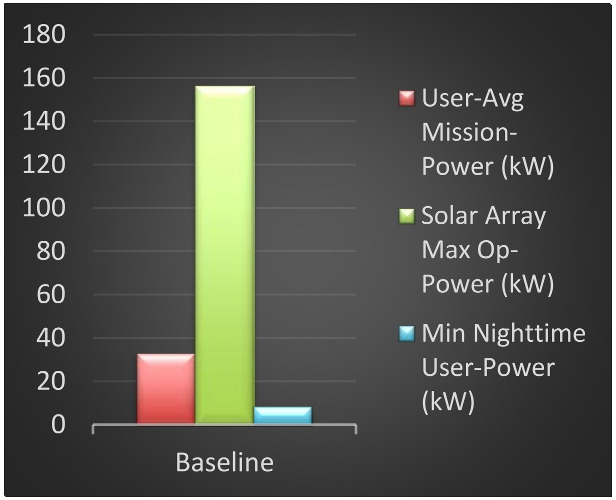
- ***1000 m^2 class solar array, 10 kW fuel cell stack for equatorial site***
  - Reasonable component sizes, not necessarily matched sizes for optimum EPS
- **Equatorial Landing Site – "Meridiani Planum" – 0˚ , 6˚ W**
- **Landing Date: May 23, 2038 (05/23/2038)**
- **Mission length: ~1 Mars year (680 sols)**
- **No major dust storms during mission**
- **Fixed nighttime user power level**
- **Fixed daytime user power level equal or greater than nighttime power**
- **60% of the sol day period recharges energy storage, provides daytime user power**
- **Energy storage system is fully recharged each sol**

Solar Power on Mars – Sunlight Intensity Varies



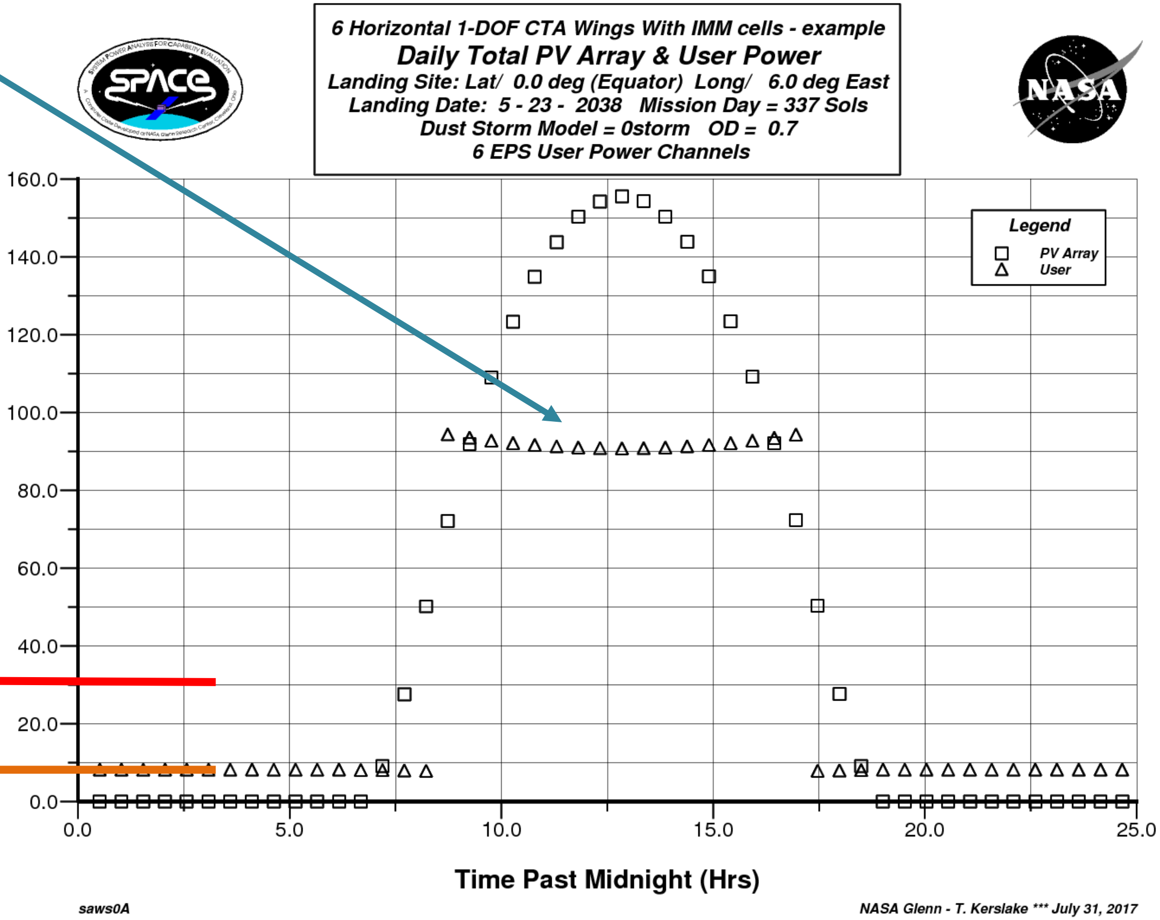
Baseline Performance Results

The equivalent day is 60% of the daylight period centered on noon

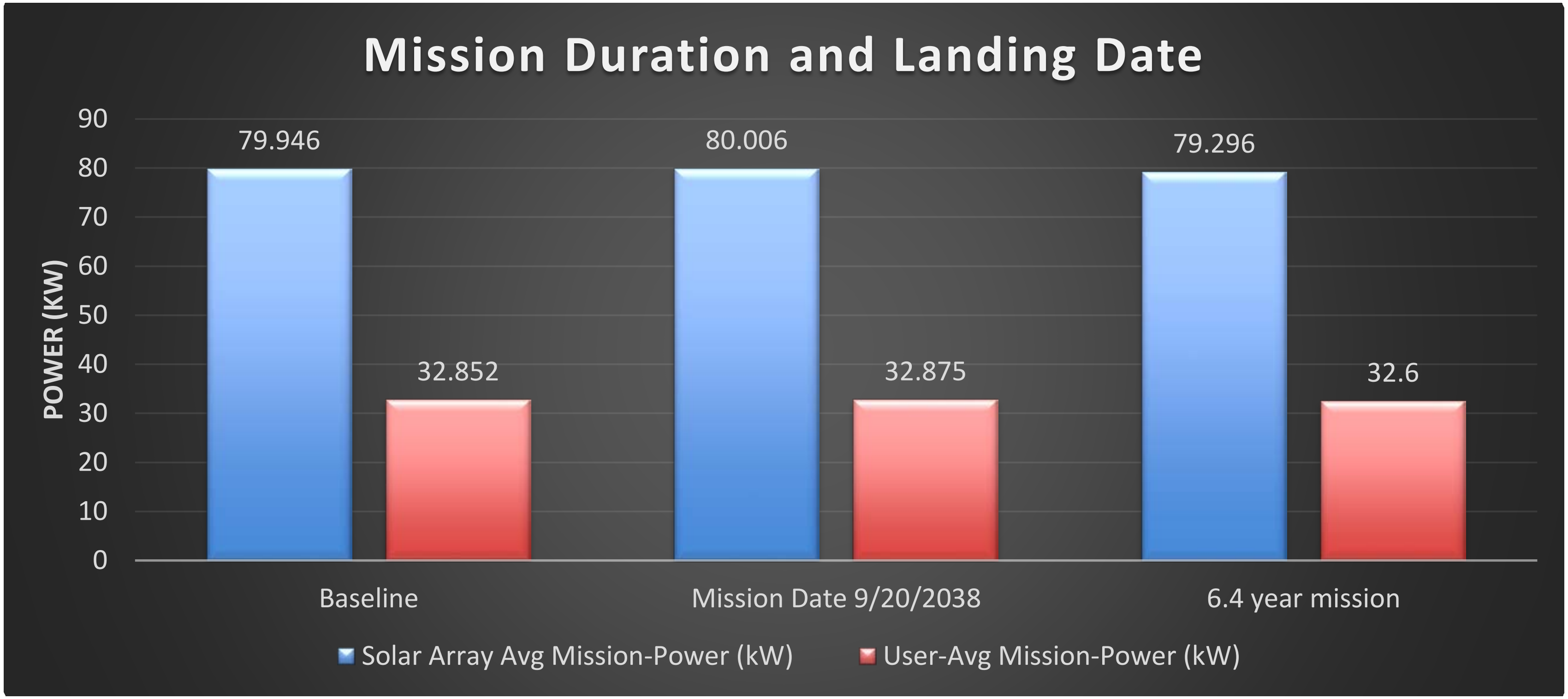


Mission Day Averaged

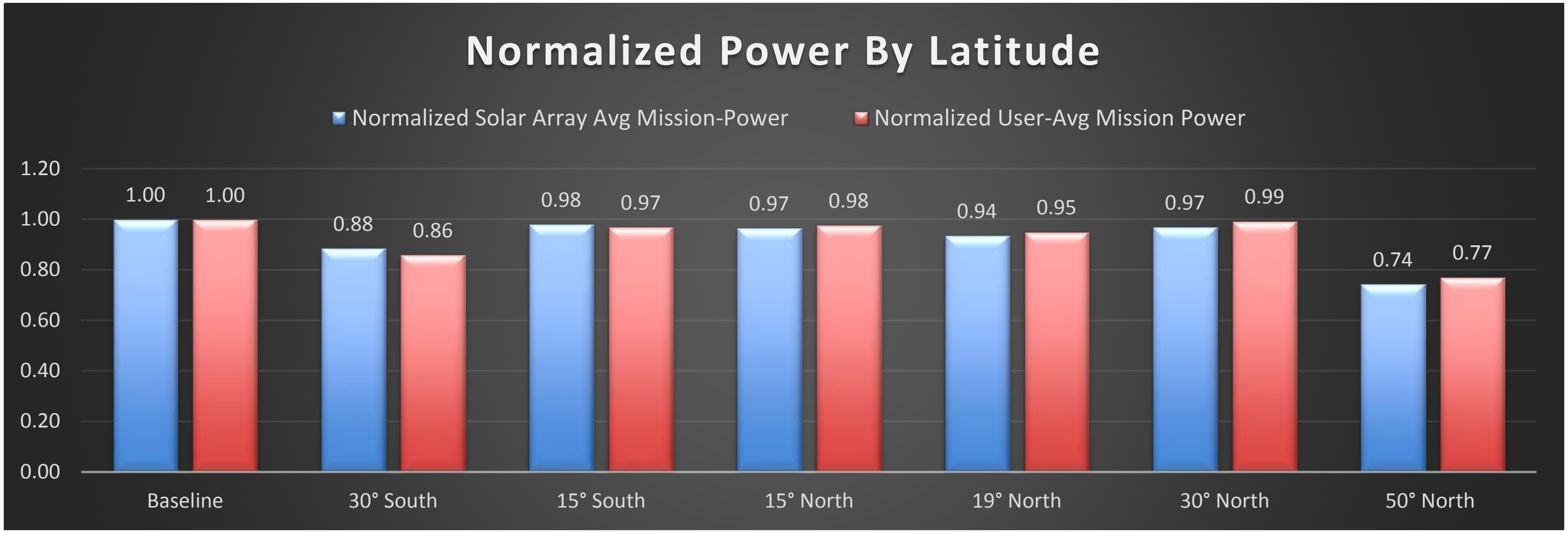
Nighttime Min



Power System Parametric Studies

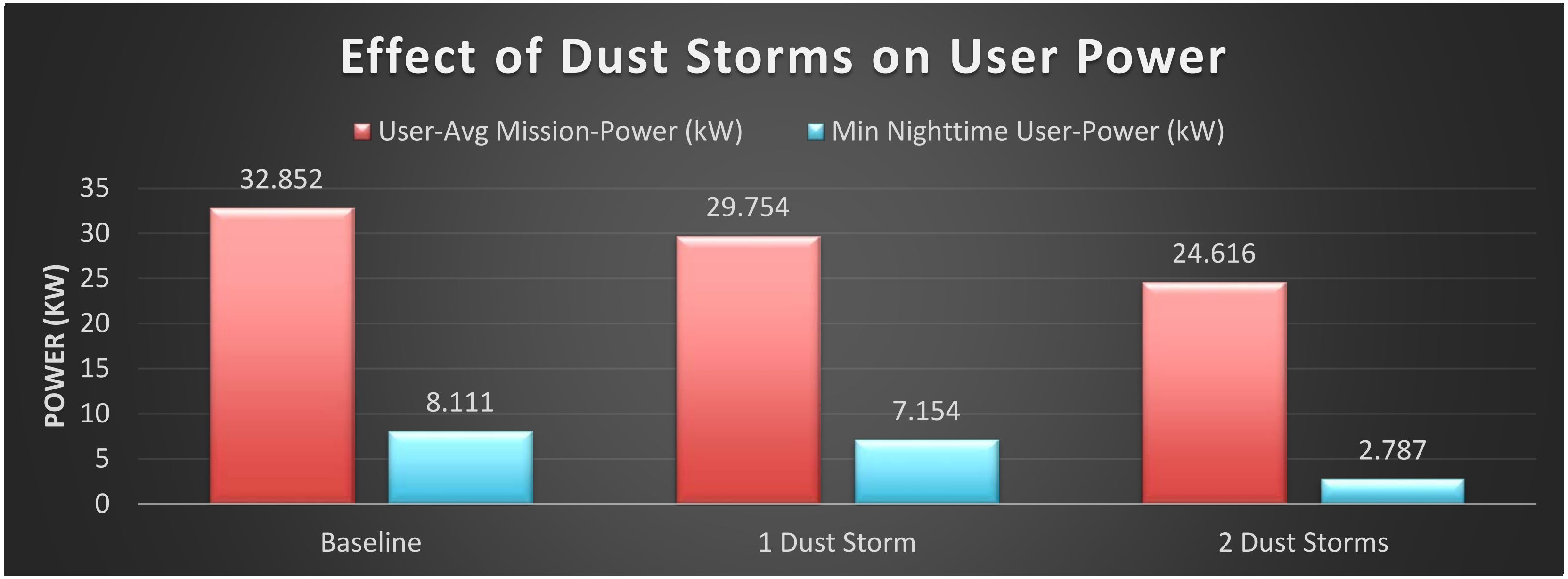


Power System Parametric Studies



- **Average solar array and mission power modestly increases as latitude approaches the equator (for no major dust storm case).**
  - Maximum average mission power occurs at the equator
  - Small (<15%) variation in power performance over landing sites within ±30°
  - Larger power variation will occur with dust storm effects included
- **Lowest minimum nighttime user-power occurs at 50° N latitude.**
  - A larger energy storage system and solar array would be needed to meet 10 kW class human base power requirements compared to that for an equatorial landing site base
- **Low to mid latitudes have small reductions in average user-power (less than 5%) compared to equatorial landing site.**

Power System Parametric Studies



- **1 major dust storm does not have a huge effect on average user-power during the mission.**
  - Average user-power reduced by ~9%
  - Nighttime user-power drops ~12%
- **A true Mars mission should design for 1 major dust storm per year.**
  - 1 major dust storm does not dramatically increase the required solar array area or fuel cell size for equatorial missions.
  - At least one major dust storm is likely for long duration missions (greater than 5 Mars years).
- **If LOM would occur with power below 10 kW, then the 2 dust storm case minimum night time power of 2.8 kW per module is just high enough to avoid LOM**
  - A power system with 4 SAWS modules would provide at least ~10 kW

Overall Conclusions and Recommendations

- **SAWS Study conducted a thorough technical evaluation on the viability and challenges of implementing a solar-based Mars surface power system**
  - Included significant technical detail to provide a realistic, unbiased technical evaluation of solar feasibility and challenges.
  - Attempted to quantitatively evaluate the impact of landing site location and surface environment conditions (i.e. dust).
  - All technology assumptions are realistic and well-documented. Considered reasonable technology advancements where appropriate and beneficial to system performance.
  - Study was tasked to only consider RFC technology for energy storage.
    - Advanced battery technology MAY improve overall power system performance for specific site locations, power levels, or conops. Needs to be studied further.

- **A solar-based power system utilizing "near-term" technology development for a 10-kW class module is viable and can readily meet the needs for a base at equatorial and mid-latitude landing sites given reasonable mission requirements and operations.**

- **Key critical "technology development" aspects identified during the study include:**
  - Various components of large solar array deployment under gravity surface conditions, while feasible, have yet to be demonstrated.
  - RFC component lifetime and long-term, maintenance-free operation have yet to be demonstrated.
  - Dust abatement/removal on the solar blanket surface is critical to maintaining predictable power generation. Periodic "cleansing" of dust as demonstrated on previous Mars rovers will not be adequate for these large solar arrays.

Acknowledgements

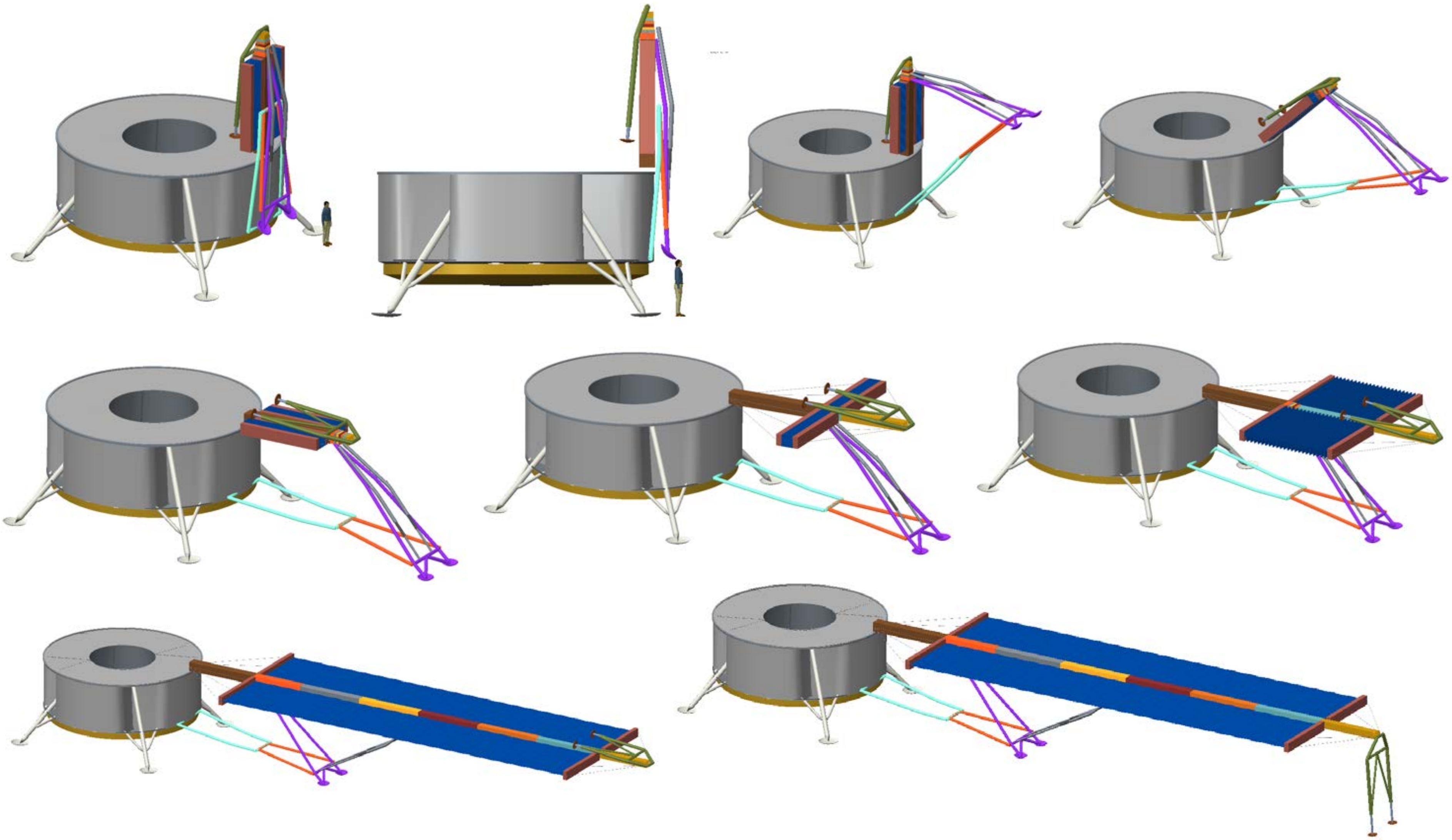
A complete study report is being prepared and will be accessible on the NASA Technical Reports Server (https://www.sti.nasa.gov/)

Thank You

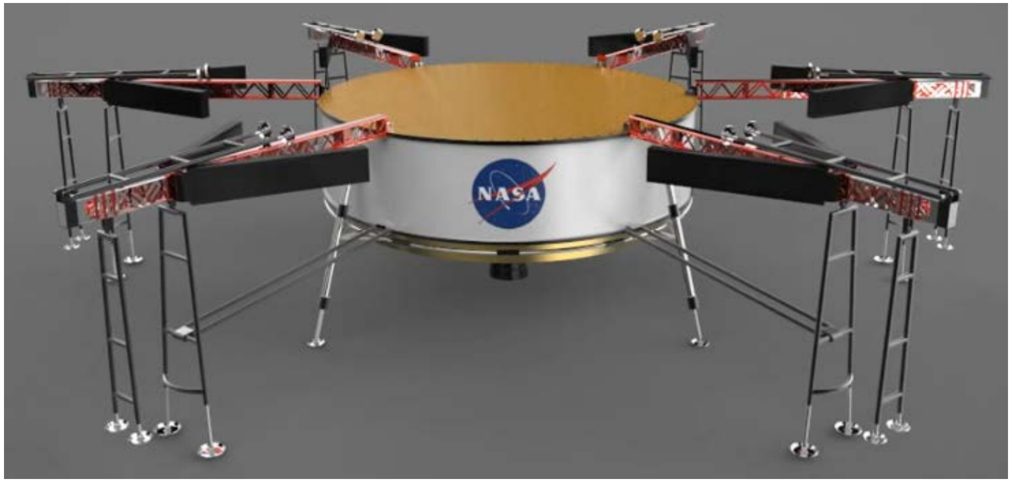
NASA Space Technology Mission Directorate and the Game Changing Development Program for funding this work

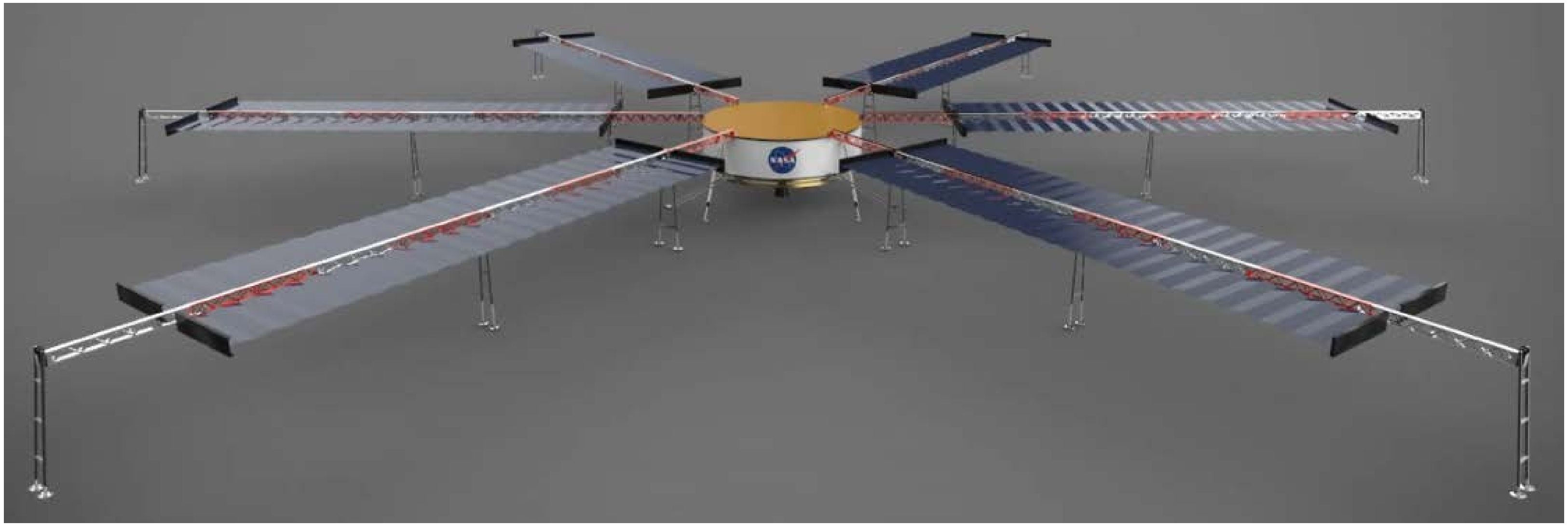
Team members at LaRC, GRC, and JSC for their contributions to the study

Baseline Solar Array Conceptual Deployment



High-Fidelity Rendering of Baseline Solar Array





High-Fidelity Rendering of Baseline Solar Array

Animation