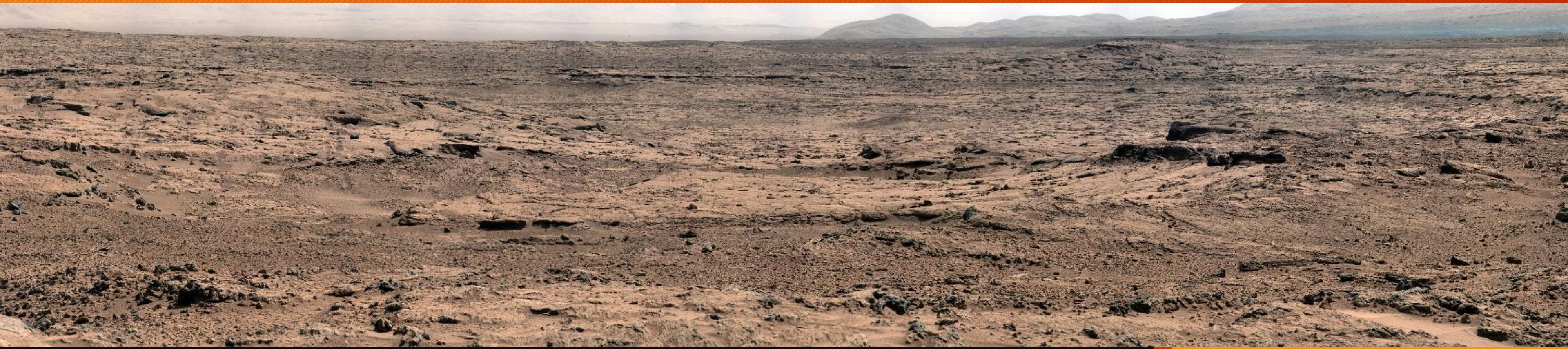

Surface Power for Mars

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National Aeronautics and Space Administration
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Overview

This presentation covers two related papers

- **NETS 5074, Integrated Surface Power Strategy for Mars**
  - Presented at Nuclear and Emerging Technologies for Space (NETS) 2015 Conference, Albuquerque, New Mexico, February, 2015
  - Outlines the advantages of multiple, small fission power systems versus previous schemes that relied on a single, large system
- **AIAA-2016-5452, Solar vs. Fission Power for Mars**
  - Presented at AIAA SPACE 2016, Long Beach, September, 2016
  - Revisits the solar versus fission surface power trade in light of new Evolvable Mars Campaign (EMC) mission concepts
- **Important to note these are very different missions**
  - First paper assumed Apollo-style Mars exploration missions
    - ✓ Each crew explores a different landing site
  - Second paper assumed "pioneering" approach with multiple expeditions to a single landing site (allowing equipment re-use)

Integrated Surface Power Strategy for Mars

Acronyms to know:

MAV	FSP	ISRU
Mars Ascent Vehicle	Fission Surface Power	In Situ Resource Utilization

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Background: Notional Crewed Mars Mission

Conceptual Mars surface mission assumes two each 40 kWe Fission Surface Power (FSP) Systems

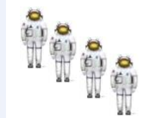
– Primary unit deployed on a Cargo Lander to make return propellant (oxygen)
– Contingency unit arrives later with the crew
– FSP is ~ 7,000 kg and must be operated >1 km from the Habitat

1 km

Radiation protection

Landers ~1km apart

(risky to land any closer)



1 MARS CARGO LANDER

2 MARS CREW LANDER

Lands before crew

- **Un-crewed Mars Ascent Vehicle (MAV)**
- **FSP and In Situ Resource Utilization (ISRU)**
  – Makes propellant for crew return
- **Mobility**
  – To relocate the FSP 1 km from Lander

Lands after MAV is fueled

- **Surface Habitat and Crew**
- **Spare FSP**
- **Mobility**
  - To transport Spare FSP and crew

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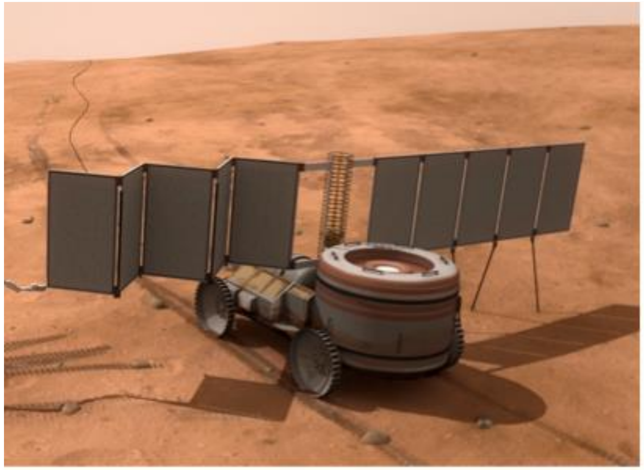
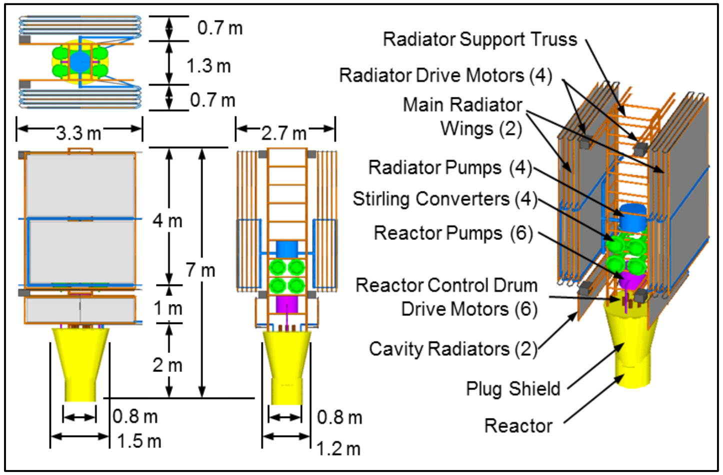
Issues and Study Objectives

1. Validate Mars Surface power needs
   - Is 40 kW enough…or is it more than we need?
2. Explore ways to reduce contingency mass
   - 7,000 kg is a lot of mass for a contingency item *that is never nominally used*
3. Explore ways to accelerate FSP deployment
   - Cargo Lander is self-sufficient for power until FSP is deployed and activated
   - Up to 40 sols: Impacts Cargo Lander Power, Thermal, and Structural mass
4. Explore ways to minimize FSP impact on mobility systems
   - FSP may be the largest item that Surface Mobility systems have to move
   - May drive mobility design in a way that is incompatible with other mobility tasks





Notional FSP Concept

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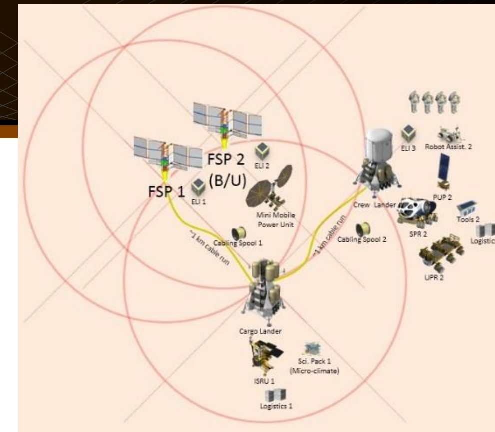
Surface Powered Equipment Needs



After mapping the physical locations of powered items relative to the Landers, it became clear that there were 3 distinct categories of powered equipment

This equipment drives FSP size

Mobile Equipment

Moves around the surface

- Rovers
  - Space Suits
  - Portable Tools

Drill, EVA tools, etc.

Recharge from Other Assets

Stationary Assets

Remains on/near Landers

- Cargo Lander
  - ISRU
  - **Ascent Vehicle**
- Crew Lander
  - Habitat
  - Lab

Fission Power

Deployed Equipment

Relocated once, then stationary

- Weather Stations
- Geo Stations

Traded solar arrays vs. RTG vs. Fuel Cells

Solar Arrays

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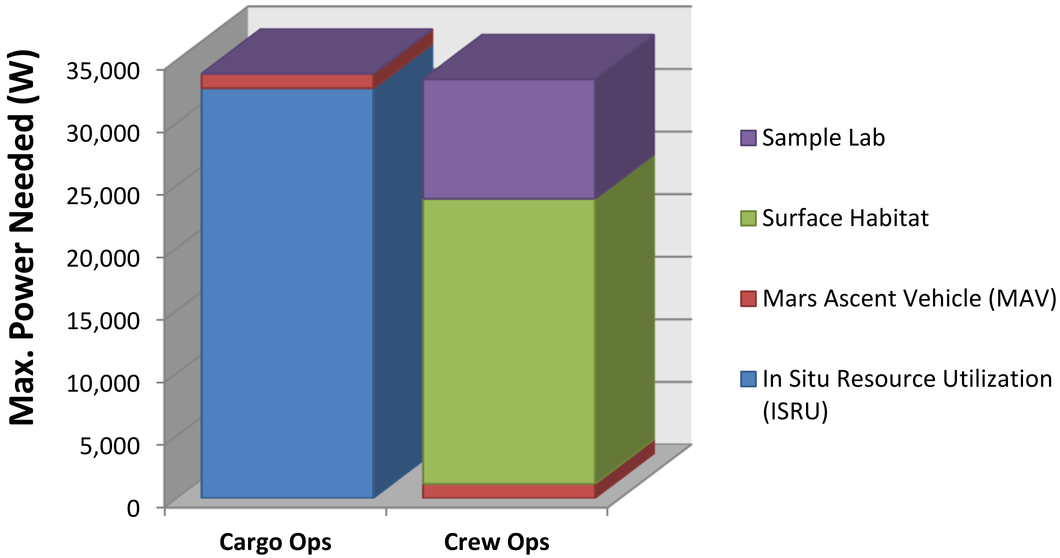
Objective 1: Validate Surface Power Needs



33.9 kW Max **33.5 kW Max**

- **Conclusion: < 40 kWe Needed *<u>for this particular reference mission and conceptual architecture</u>***
  - Includes 30% margin
  - ISRU is the Biggest Power Draw
    - Atmospheric ISRU
  - Architecture is notional
    - Forward work to better define elements and power needs

How Could We Reduce Power?

1. **Produce less propellant**
   - ✓ Smaller Ascent Crew Cabin
     - *Reduce time crew is in cabin*
     - *Reduce number of crew*
   - ✓ Ascend to Lower Orbit
   - ✓ Bring more propellant from Earth
     - *Requires more descent propellant*
2. **Take longer to produce propellant**

Even if ISRU is eliminated, still need almost as much power to support a Habitat and science operations

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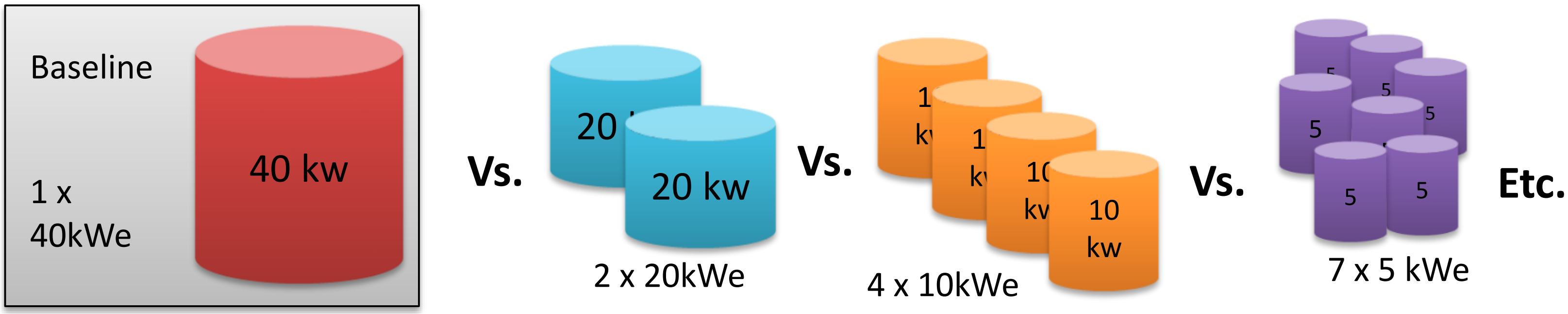
Exploring Alternatives

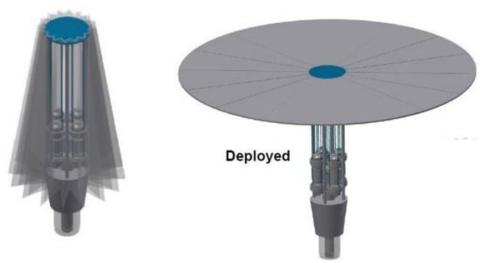
We need *at least* 33.9 kW (for this particular conceptual mission)

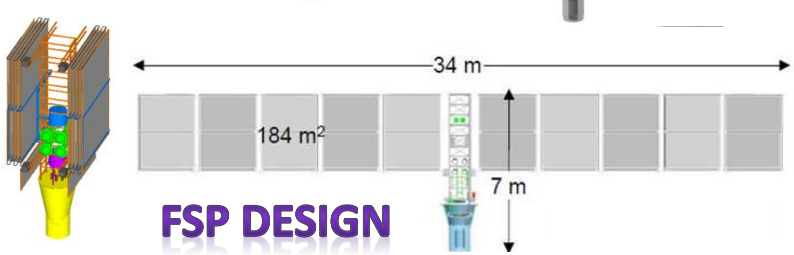
…but it doesn't necessarily have to be in a single package



"Kilopower" design is similar to the FSP, but more compact, and with fewer moving parts

KILOPOWER DESIGN





Type	Power (kWe)	Mass (kg)	Dimensions (m)		Radiators
			Dia	Height	
KP	3	751	1.2	*2.2 /4.9	9.6 m^2
	5	1,011	1.3	*2.7/5.9	13.5 m^2
	7	1,246	1.4	*3.0 /6.7	17.1 m^2
	10	1,544	1.5	*3.3 /7.3	20 m^2
FSP	10	3,300	1.0	7 m tall	37 m^2
	40	7,000	2.7	7 m tall	184 m^2

*Height w/Deployable/Fixed Radiators

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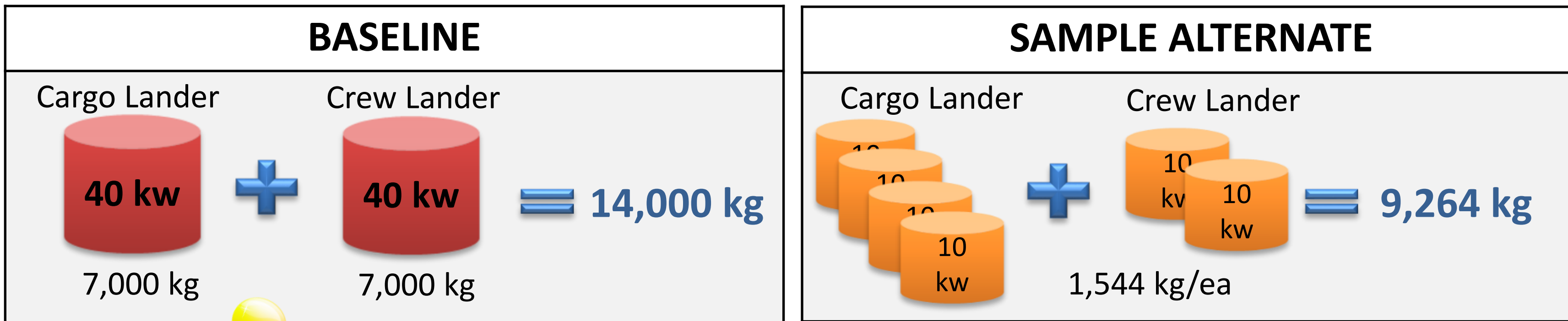
Objective 2: Reduce Contingency Power Mass

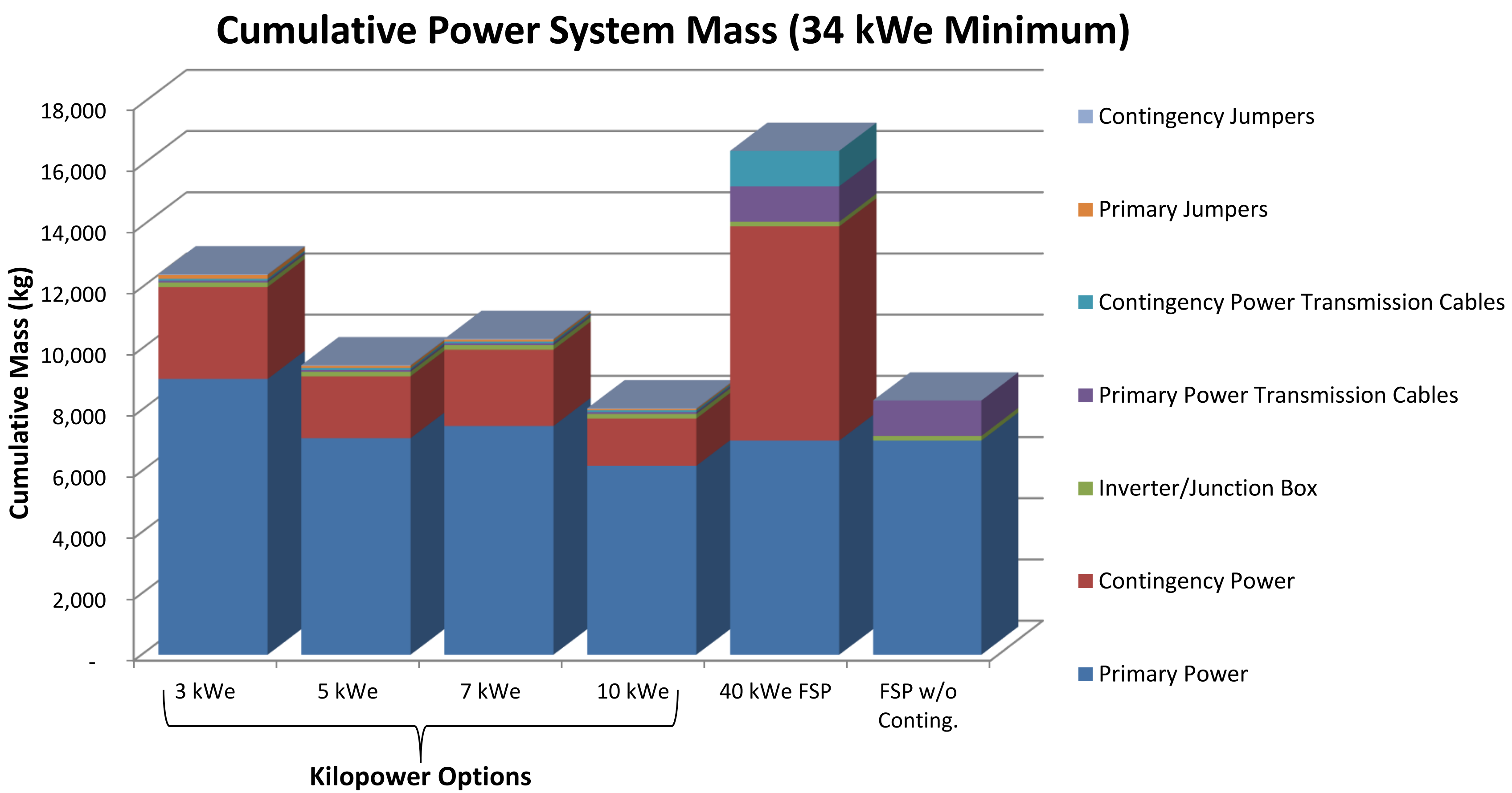
- **Baseline assumed a 40 kW contingency FSP on the Crew Lander**
  —Alternative: With 4 ea. 10 kW units on the Cargo Lander, it’s unlikely ALL will fail
  —*Don’t necessarily need to bring 4 more on the Crew Lander: 1 or 2 spares will do*



Mass saved in this example is equivalent to a pressurized rover

- **Savings are even more significant when cable mass is included**
  - **FSP Concept: Requires more than 1,000 kg of Cable**
    - 1 km, 400 VAC transmission cable from FSP to Lander PLUS a 1 km, low voltage DC auxiliary cable from Lander back to FSP
      - FSP Parasitic load: need auxiliary power for FSP fluid pumps, etc.
  - **Kilopower Concept: Less than 100 kg Cable**
    - Fewer moving parts (e.g. heat pipes replace pumps) don’t require auxiliary power cable
    - ~60 kg for 1 km of high VAC transmission cable
    - Plus inverter/junction box and jumpers

Objective 2: Reduce Contingency Power Mass



- **34 kWe Minimum of Kilopower + 10 kWe Minimum Contingency saves 4 to 8 metric tons compared to baseline 40 kWe FSP**
- **4 x 10 kWe Kilopowers + 1 contingency unit is ~200 kg less than an FSP with no contingency unit**

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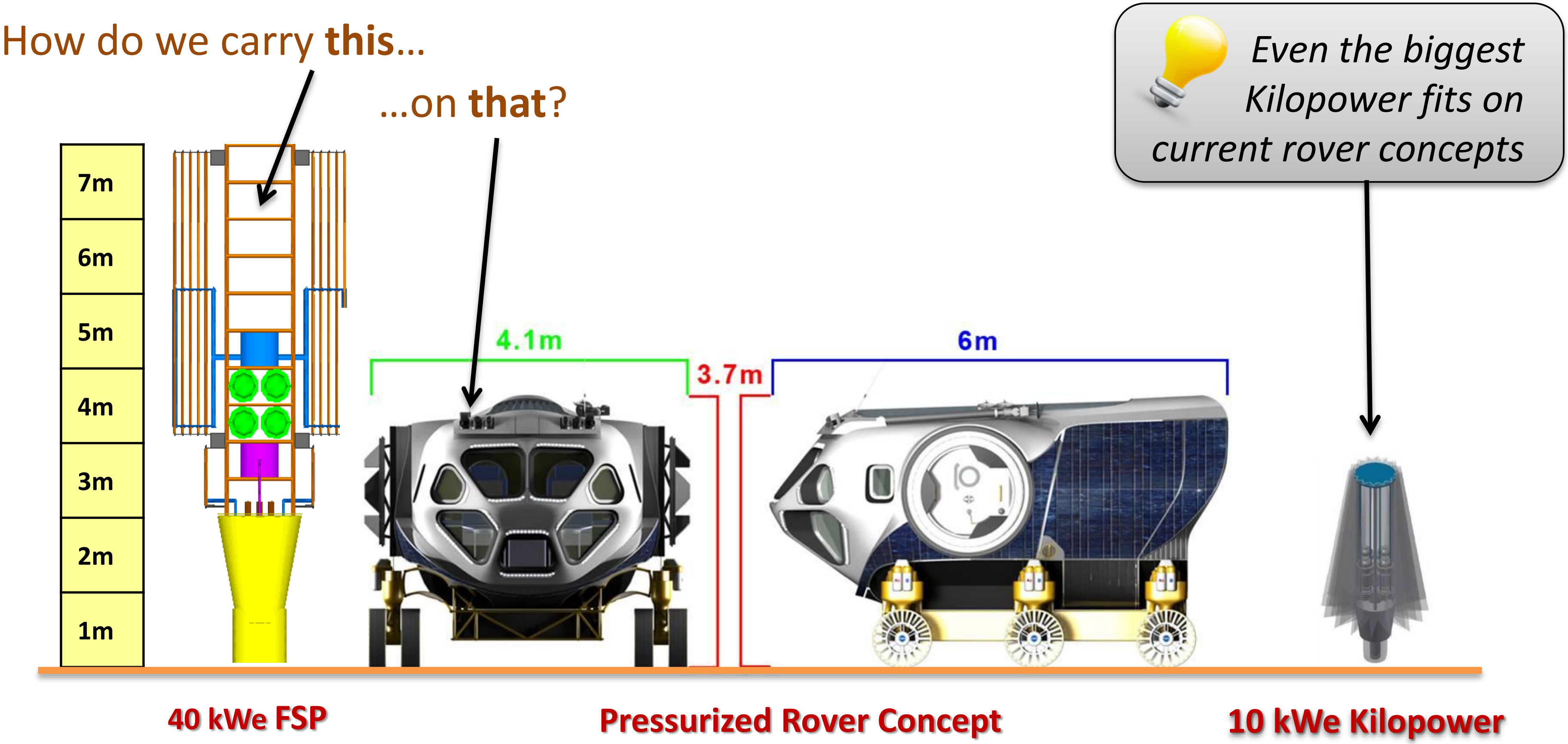
Objective 3. Minimize Lander Power Mass

- **Lander has to survive up to 40 sols while FSP is being unloaded, relocated 1 km, deployed, and activated**
  - Criticality: Mars Ascent Vehicle (for crew return) needs keep-alive power!
  - Lander power mass drives thermal & structural mass, all of which drives descent propellant mass
- **With multiple Kilopower units, we have an option to *turn one on near the Lander,* while remaining units are being deployed**
  - Crew hasn’t arrived yet, so we can relax separation distance from Lander
  - Relocate the first unit after the others are on-line

Still may take 40 sols to move all of them, but the Lander doesn’t have to be self-sufficient the entire time

4. Minimize Impacts to Surface Mobility

- At 7 m tall and 7 metric tons, FSP is bigger than pressurized rover concepts
- May force rover design or reconfiguration requirements
- Or drive the need for another kind of mobility system
- Current rover concepts with a davit can accommodate smaller Kilopower units



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Additional Kilopower Concept Advantages

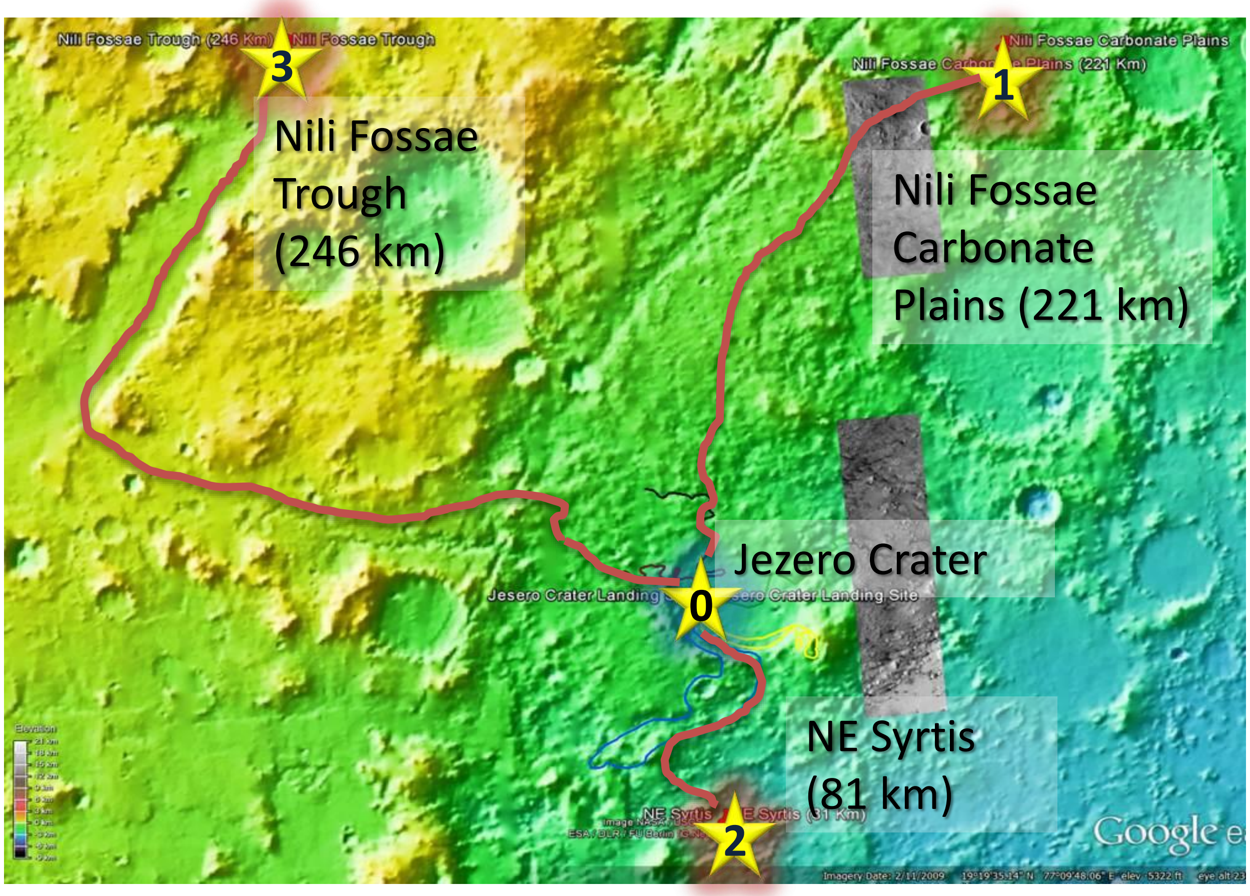
1. **Better transportability means Kilopower units can be redeployed**
   - Use to extend rover range or support remote science operations
   - Relocate from one landing site to another
     - After shut-down, safe for crew to approach after ~1 week
     - Safe for robotic approach after ~1 day
2. **Deployed Kilopower Units can significantly increase crew exploration radius**
   - Solar-only pressurized rover spends 80% of its time charging, 20% roving
   - 2 deployed Kilopower units increase rover driving efficiency from 14 km/day to 46 km/day and adds 37 km to the maximum excursion range from the Habitat
   - 4 units can increase the maximum range to 225 km
3. **Kilopower units require less startup power than the FSP**
   - 2 D-cell batteries vs. 5 kW solar array for FSP

Additional Kilopower Concept Advantages

4. Opens up the *possibility* of reducing the number of landing sites

- Example: 4 areas of interest are within 250 km straight line of each other
- Could potentially land at Jezero Crater and rover to the other 3

- ***Actual roving range will depend on***
  - *Terrain factor*
  - *How many Kilopower units are available*
  - *Rover design*
  - *Risk posture*
- But portable power opens up operational concepts not previously considered



Additional Kilopower Concept Advantages

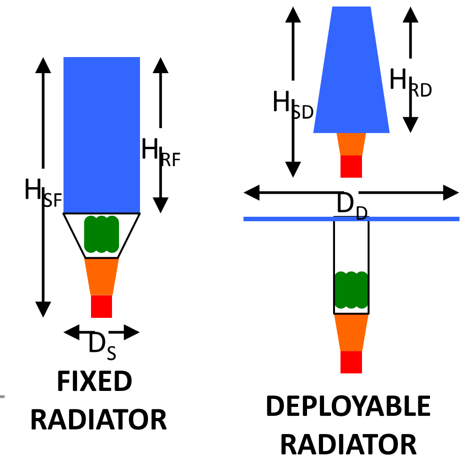
5. **Supports small pre-cursor missions without having to develop a sub-scale demo unit**
   - At 751 kg, the 3 kWe Kilopower unit fits on a Curiosity-class Lander with payload to spare
     - Could be retrieved later and added to a larger Kilopower farm
   - At 3,300 kg a small (10 kWe) FSP won't fit on a Curiosity-sized Lander
6. **Easier to "evolve" surface capability over time**
   - 40 kWe FSP requires commitment to 7 ton payload
     - And that's without cables or mobility to relocate it
   - With Kilopower units, a program can tailor power for different missions by only flying what's needed
     - One unit for a small precursor or demo mission; multiple units for a crewed mission
   - If constrained to a single landing site, can build up capability over time, and expand exploration area with deployable power systems

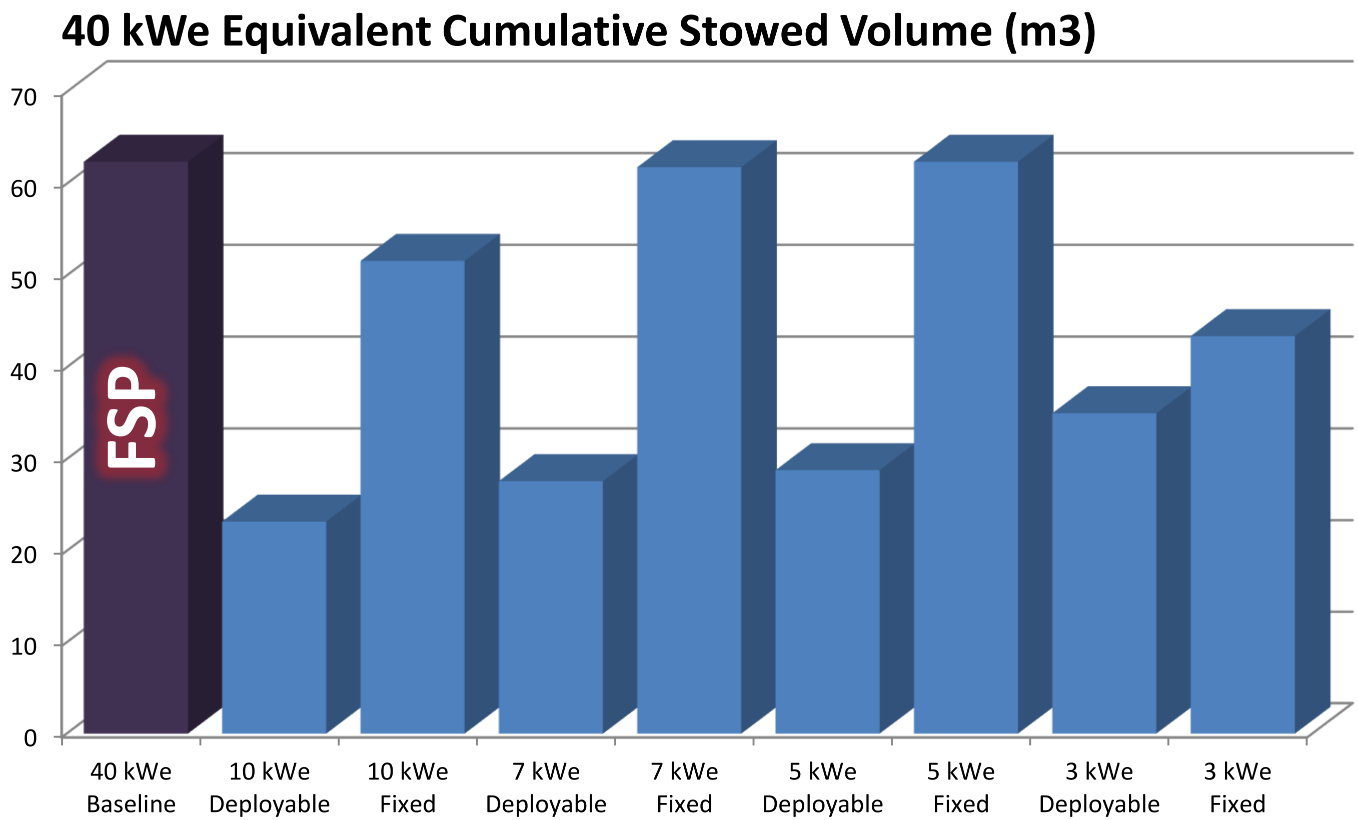
Additional Kilopower Concept Advantages

7. Lower *cumulative* stowage volume

— Deployable-radiator systems are compact

— *Note that volume savings could be off-set by packing efficiency for a given Lander design*





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Kilopower Concept Disadvantages

1. **Requires more HEU**
   — As much as 532 kg HEU for 40 kWe equivalent (+ spares) of 3 kWe units vs. only 220 kg HEU for a baseline FSP (+1 spare)

System Size	HEU Per Unit	Total HEU Needed	Assumptions
40 kWe	110 kg	220 kg	1 primary and 1 contingency unit
10 kWe	50 kg	250 kg	4 primary and 1 contingency units
5 kWe	44 kg	396 kg	7 primary and 2 contingency units
3 kWe	38 kg	532 kg	12 primary and 2 contingency units

2. **More HEU may mean more ground handling security overhead**
   — Especially if multiple units are in various stages of assembly, test, and transport
   — Could mitigate by keeping all units together (no partial shipments)
3. **More individual reactors means more launch safety overhead**
   — Each unit has to be located and retrieved in the event of a launch failure
   — Could mitigate with a containment shroud
   - Kilopower units will be packaged on a Mars Lander, which will be inside a launch shroud
   - Mars Entry/Descent/Landing (EDL) design could also include an aeroshell

Kilopower Concept Disadvantages

4. **More surface delivery (rover) trips to deploy**
   - FSP only needs 1 trip from Lander to installation site for deployment
   - Number of trips to deploy Kilopower will depend on which size is chosen and how many a rover can carry in one trip
     - Current rover concept can likely carry one 10 kWe unit, two 5 kWe units, and at least two 3 kWe units
   - Deployment is autonomous/robotic, and once the 1km route has been mapped, subsequent trips aren't especially risky
     - Just wear/tear on the rover
5. **Increased operational complexity**
   - Single FSP can land with cables already connected
   - Multiple units may require robotic field connections
6. **Potentially lower overall system reliability**
   - Kilopower unit is internally redundant, so individual units are highly reliable, but more units means more connectors that can fail
     - Can mitigate by making as many connections as possible pre-launch (one end of every cable), add redundant connection ports to each unit, and carry extra cables

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Kilopower Concept Disadvantages

7. 10 kWe scaling limit

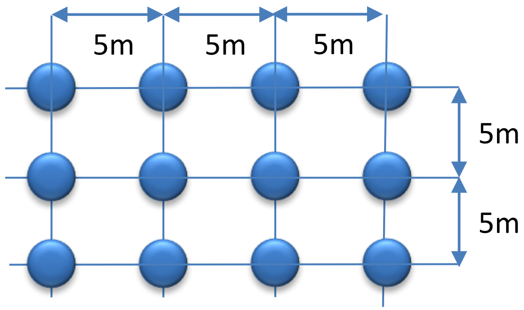
— Kilopower expected to scale readily up to 10 kWe, but not beyond
— Applications requiring higher power require FSP type design, or would have to accommodate multiple Kilopower systems ganged together
— Not an issue for surface application, but may not be practical for high-power, in-space applications

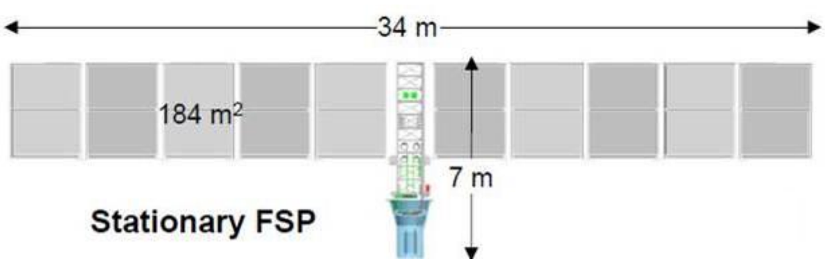
8. Large deployed system footprint

— Study assumed Kilopower units must be at least 1 body length apart
- Prevents domino effect if one is knocked over

— In the worst case of 3 kWe units, the overall system footprint is large
- Though still not as large as the FSP's deployed radiators that would require ~34 m linear area free of obstacles

3 kWe Kilopower Array





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Mars Surface Power System Unique Needs

1. **System Connectivity**
   - Surface power systems should be designed to operate alone, or in combination with like systems
   - *Rationale: Need to gang together multiple small systems to meet mission needs*
2. **Dust Tolerant Mechanisms**
   - Surface power system mechanisms should be tolerant to surface dust contamination
   - *Rationale: will be exposed to dust storms, some lasting months. Mechanisms such as deployable radiators and connector covers will be actuated if the systems are redeployed to different areas or to support different activities.*
3. **Robotic Handling**
   - Surface power system design should be robust to robotic handling
   - *Rationale: Power system must be robotically unloaded from the cargo lander, deployed and activated before crew arrives.*
4. **Surface Transport**
   - Surface power system design should be robust to Mars surface transportation loads
   - *Rationale: Power system will be transported a safe distance from the eventual crew habitation area, and may be re-deployed to remote areas to support exploration activities. There are currently no plans to groom roadways on Mars.*
5. **Compact**
   - In stowed configuration, surface power systems should be compact
   - *Rationale: Mars landers will be as much volume-limited as they are mass-limited.*

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Mars Surface Power System Unique Needs

6. **Restart Ability**
   - Surface power systems should be capable of being started, stopped, and restarted.
   - *Rationale: Restart ability allows power systems to be moved around the surface to support special activities (such as drilling), and also allows the crew to safely approach for inspections or repairs*
7. **Surface Environment Compatibility**
   - Surface power system design should be tolerant to Mars surface environmental conditions.
   - *Rationale: Unique design features must function in partial gravity, atmospheric pressure, etc.*
8. **Shelf Life**
   - Surface power system should be certified for at least 2.5 year [TBR, To Be Resolved] shelf life
   - *Rationale: Given payload processing time at the launch facility plus Mars transit time, there is likely to be a 2+ year lag between power system final check-out and surface activation*
9. **Operational Life Limit**
   - Surface power system components should be rated for a minimum of 10 years [TBR] operation. Operational life may be continuous, or intermittent over a 12 year [TBR] period
   - *Rationale: The surface power system will arrive on the first cargo lander, but must support subsequent missions. With launch intervals of ~26 months, the power system may have to operate for many years.*
10. **Planetary Protection**
    - Surface power system design should be sensitive to planetary protection constraints.
    - *Rationale: if the system generates enough heat to melt surrounding ice it potentially creates a localized "special region" that would have implications for how close crew, crew rovers, or habitats may be located.*

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Key Take-Aways

- **Conceptual crewed Mars surface mission requires <40 kWe Power**
  - *For this particular reference mission and architecture*
- **Power needed to make return propellant—and keep it cold—is a driver for surface power**
  - Eliminating ISRU saves power (but not much), and it won't save landed mass
- **There are better ways to reduce power mass**
  - Breaking the stationary power source up into multiple, smaller packages not only saves mass, it improves operational flexibility, increases exploration range, and supports staged build-up and relocation of surface assets
  - There are also disadvantages that would have to be mitigated
- **This type of application requires unique power system features that may not be necessary for other applications of this technology**
- **Choice between a single large reactor vs. several smaller reactors is an Agency-level decision based on factors beyond the scope of this study**

This exercise was not intended to recommend a particular concept. Final decisions must weigh programmatic considerations. Mars human system architectures may deviate from current concepts and significantly alter power system needs.

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Questions About the Kilopower Concept?

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Solar vs. Fission Surface Power for Mars

American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016, Long Beach

Background

- **2009: NASA's Design Reference Architecture 5.0 base-lined fission surface power for a crewed Mars mission**
  - Two landers to one site, then two more landers to a different site
  - Solar power did not trade as well as fission power for mass
    - ✓ Fission development costs would be shared with the Constellation Program's lunar surface mission, making fission more attractive
- **2016: NASA revisited the solar vs. fission trade based on new information**
  - Paradigm shift to Evolvable Mars Campaign
    - ✓ Multiple landers to the same site, allowing infrastructure build-up
  - Technology advances since the original studies were performed
    - ✓ Kilopower fission system, higher density batteries, more efficient solar arrays

COMPASS Team

The new study was performed by the NASA Glenn Research Center's Collaborative Modelling for Parametric Assessment of Space Systems (COMPASS) Team

NASA Glenn Research Center
- Steve Oleson
- Pat George
- Geoffrey Landis
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- Robert Jones
- Elizabeth Turnbull
- Jeremiah McNatt

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- Tom Packard

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Making Mars More Affordable
Utilize Martian Resources

- Mars Ascent Vehicle arrives on Mars with empty Liquid Oxygen propellant tanks
- Fission- or solar-powered In Situ Resource Utilization extracts carbon dioxide from the Martian atmosphere
  - ISRU processes the CO_2 into LOX propellant
  - Paired with Methane brought from Earth
- Once LOX tanks are confirmed full, the crew lands on Mars
  - ISRU production is suspended, and the power system is switched over to crew life support functions
  - Some power needed for cryogenic propellant conditioning
- For solar-power system, dust storm disruption up to 120 sols is assumed

Acronyms

MAV	Mars Ascent Vehicle
LOX	Liquid Oxygen
ISRU	In Situ Resource Utilization
CO_2	Carbon Dioxide

Study Approach

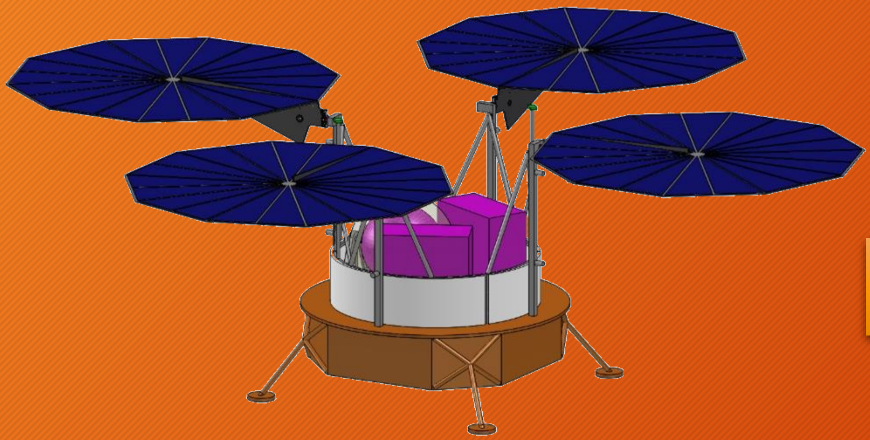
1 **Pre-cursor demonstration mission**

- Primarily an Entry-Descent-Landing demonstrator near the equator
- ISRU payload to demonstrate LOX production from atmosphere, at 1/5 scale of crewed mission
- Compare 10 kilowatt electric (kWe) Kilopower fission system to 3 solar options:
  - A. Daylight-only ISRU operation
  - B. Around-the-clock ISRU production (battery reserves for night)
  - C. Daylight-only, but 2x production rate to make up for night period

2 **Crewed Surface Mission**

- Cargo Phase: Around-the-clock production 23 t of LOX in 420 Earth days
- Crew Phase: Crew support functions + MAV keep alive and propellant conditioning (no ISRU)
- Evaluated the same crewed mission to two different landing sites
  - ✓ Jezero Crater, located 18.9° North
  - ✓ Columbus Crater, located 29.5° South
- Kilopower fission vs. [solar + batteries] vs. [solar + fuel cell]

kWe
kilowatt (electric)



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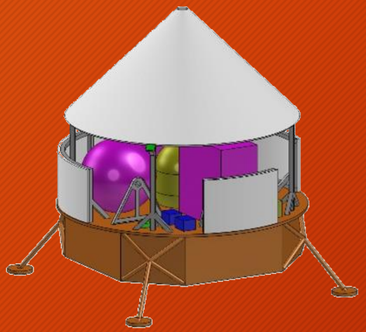


ISRU Demonstrator

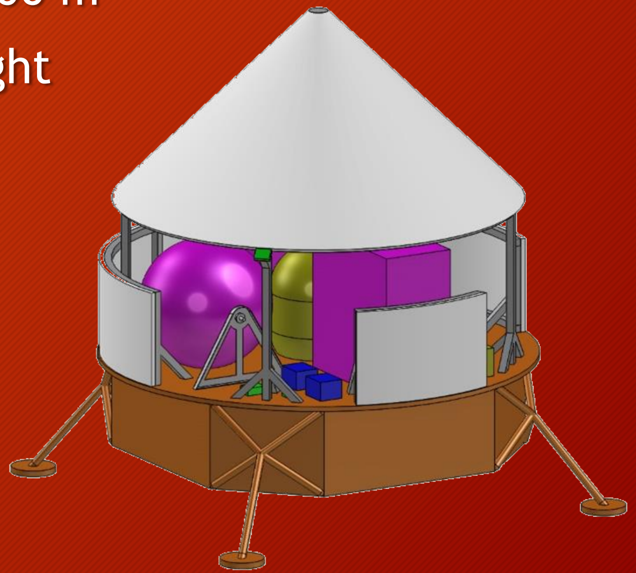
Assumptions
Demonstrator Mission

- **Land at Opportunity rover site at Meridiani (~2° south)**
  - Benefit of Opportunity's 12 years of actual solar array performance data, favorable night durations, and minimal seasonal variations
- **Mars environment based on Opportunity data**
  - Assumed one dust storm, 120 days in duration, maximum wind 20 m/s
  - Optical depth varies from 1.0 (clear skies) to 5.0 (dust storm)
  - Opportunity data: dust scatters light, so diffuse light during a storm is ~30-40% of direct light on a clear day
- **Average of 12 hours sunlight per sol**
  - But assume 10 hours/sol ISRU operation to allow for system warm-up

Dust storm time lapse as viewed by Opportunity

Fission Power Concept
Demonstrator Mission

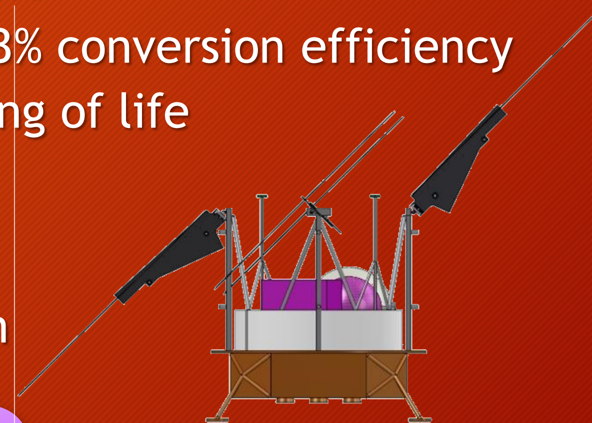
- **ISRU system sized for 0.45 kg/hr LOX production with a goal of 4,500 kg**
  - LOX tank only sized for 1,500 kg, with the balance vented overboard
- **10 kWe Kilopower unit providing 6.45 kWe (6.52 kWe at night)**
  - Fixed, conical upper radiator requiring no deployment
  - 1,754 kg including 15% mass growth allowance and radiation shield sized to reduce crew exposure to <3 mR/hr within 500 m
- 6 m diameter landed footprint x 5.14 m dia. height
  - 2.61 m center of gravity height
  - 106 W keep-live power after landing
- 2,751 kg total payload mass
  - Including growth allowance



Kilopower is oversized for this application
But it's an opportunity to demo crew mission technology

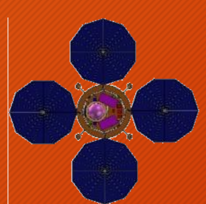
Solar Power Concepts
Demonstrator Mission

- **Same ISRU assumptions as for fission power case**
- **120V Orbital ATK UltraFlex™ arrays or equivalent**
  - Inverted Metamorphic Multi-junction solar cells of 33% conversion efficiency
  - Measured at Earth distance solar flux, 28°C, beginning of life
  - 45º Gimbal for sun tracking and dust removal
- **Panasonic cell type Lithium-ion batteries**
  - 60% depth of discharge, 165 Watt-hours per kilogram



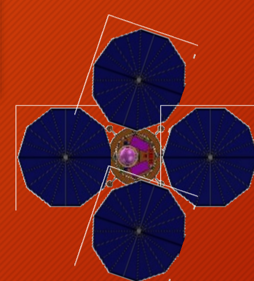
A — Daytime Only

4 x 5.6 m diameter arrays



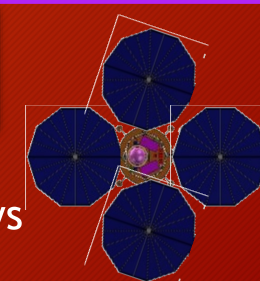
B — Around the Clock

4 x 7.5 m diameter arrays



C — Daytime Only 2x Rate

4 x 7.5 m diameter arrays + 2x ISRU



Solar vs. Fission Comparison
Demonstrator Mission

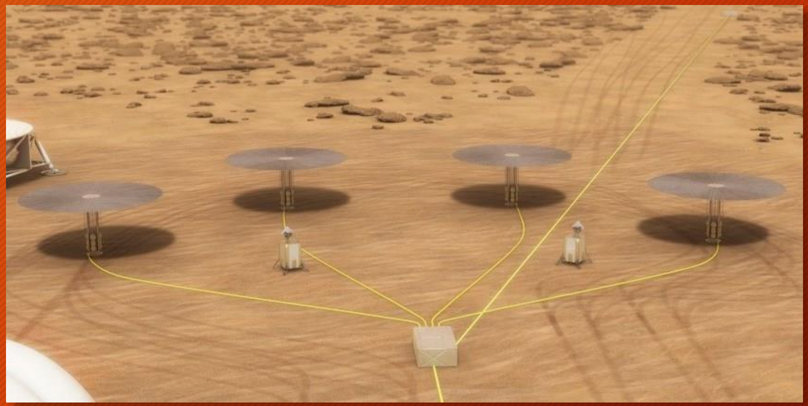
Closest "apples to apples" comparison

Option	Solar 1A: 1/5 rate Daytime Only	Solar 1B: 1/5 rate Around the Clock	Solar 1C: 2/5 Rate Daytime Only	Fission: 1/5 Rate Around the Clock Fission Power
Total Payload Mass (including growth)	1,128 kg	2,425 kg	1,531 kg	2,751 kg
Electrical System Mass	455 kg	1,733 kg	639 kg	1,804 kg
ISRU Subsystem Mass	192 kg	192 kg	335 kg	192 kg
Power	~8 kW Daylight	~8 kW Continuous (with 16 kW of arrays)	~16 kW Daylight	~7 kW Continuous
Solar Arrays	4 each x 5.6 m diameter	4 each x 7.5 m dia.	4 each x 7.5 m diameter	None
Night Production?	No	Yes	No	Yes
LOX Production	4.5 kg/sol	10.8 kg/sol	9.0 kg/sol	10.8 kg/sol
Time to Produce 4,400 kg LOX, including 120-Day Dust Storm Outage	1,098 sols	527 sols	609 sols	407 sols
ISRU On/Off Cycles	1,098	<5	609	<5

Observations
Demonstrator Mission

- **Daytime-only solar power concept offers lowest landed mass**
  - High number of ISRU on/off cycles could pose reliability issues
- **Fission power was at a mass disadvantage in this trade**
  - 10 kW Kilopower was oversized for 7 kW application, plus mass included crew protection shield that wasn't necessary for demo
  - Equatorial site represents minimum solar power mass
    - ✓ Expect higher mass at other latitudes
- **All options fit comfortably within allowable payload limits**
  - So mass alone is unlikely to drive a decision for an equatorial mission
  - Power system selection probably depends on other factors
    - ✓ Technology investment strategies, program budgets, and risk mitigation needs for later crewed missions
- **Demonstrator mission solar power hardware costs are ~$100M less than comparable fission power hardware costs**
  - Does not include technology development through Technology Readiness Level 6

Vs.



Crewed Mission

Mission Concept of Operations
Crewed Mission

	Expedition 1 *Four Landers*	Expedition 2+ *Three Landers per Expedition*
Cargo Phase	1. Power System + Cargo	1. MAV + ISRU
	2. MAV + ISRU	2. Cargo and Consumables
	3. Mixed Cargo and Consumables	
Crew Phase	4. Habitat Module + Crew	3. Habitat Module + Crew

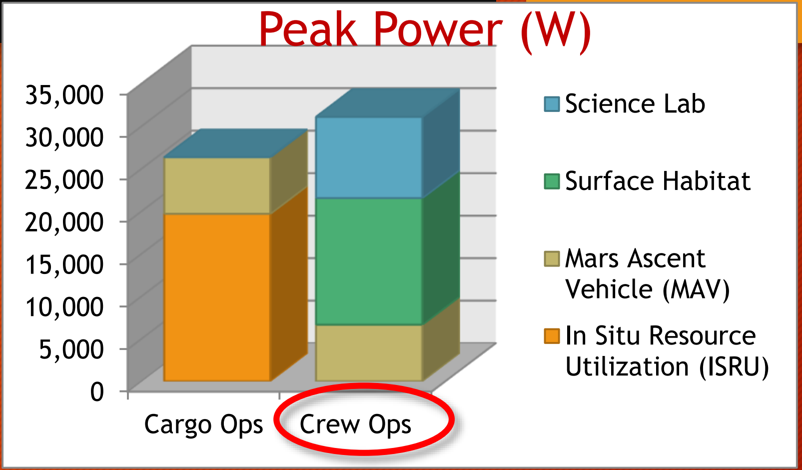
- **Landers located no more than 1 km from each other**
- **Fission: Kilopower units remain together on/near the first lander**
  - Robotic connections to subsequent landers
  - Power can be disconnected when a lander is no longer in use
- **Solar: arrays on every lander, at least through Exp 3**
  - All landers connected into a power grid
  - Remain connected even if lander is no longer active

Surface Power Needs
Crewed Mission

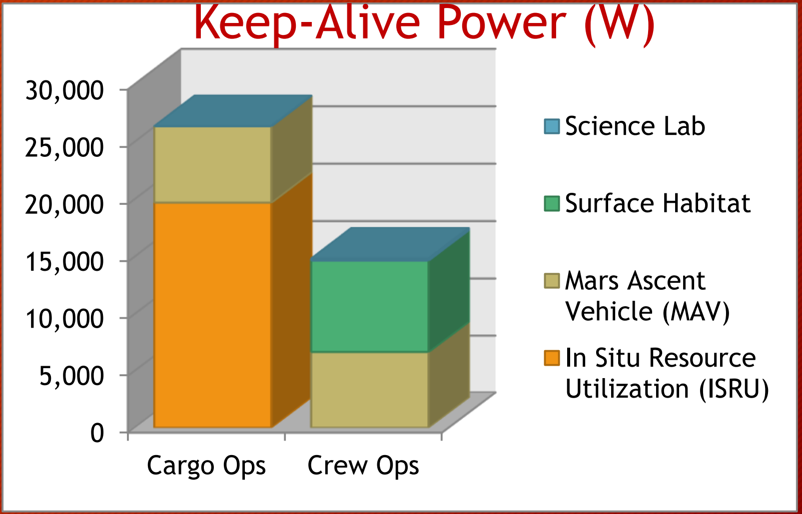
ISRU: Produce 22,728 kg of LOX in 420 Earth days

	Peak Power Needed (W)		Keep-Alive Power Needed (W)	
Element	Cargo Phase	Crew Phase	Cargo Phase	Crew Phase
ISRU	19,700	0	19,700	0
MAV	6,655	6,655	6,655	6,655
Surface Habitat	0	14,900	0	8,000
***Science Laboratory**	0	9,544	0	174
Total	26,355	31,099	26,355	14,829

**Optional element shown with all systems running. Assume power can be phased to stay below cargo ops total peak*



Note that eliminating ISRU doesn't reduce overall surface power need

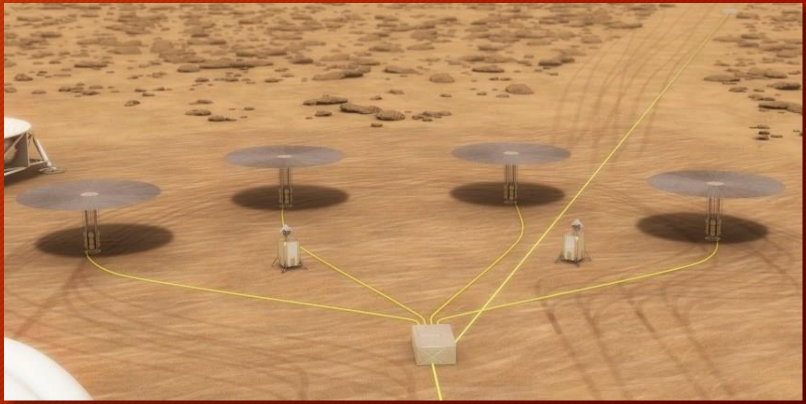


Fission-Powered Option
Crewed Mission

- **Four each 10-kWe Kilopower units would provide up to 35 kWe continuous power for all mission phases at either hypothetical landing site**
- **Fission power generation mass is 9,154 kg**
  - Includes one spare Kilopower and mass growth allowance
  - Not including power farm-to-lander Power Management and Distribution
- **Up to 1,038 kg PMAD could be needed on the Lander 1, depending on whether Kilopowers are relocated and whether any other cargo requires 1,000 – 120 VDC conversion**
  - Landers 2, 3 and 4 would each require 1 km spool of high voltage cabling, connectors, and voltage converters

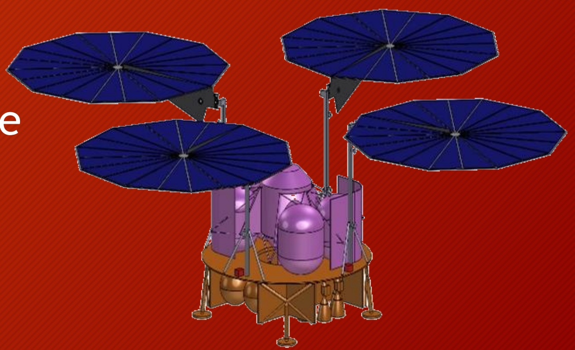
PMAD
Power Management and Distribution

Description	Lander 1	Lander 2, 3, 4	Expedition 1 Fission Power Generation Total
Power Generation			
50 kWe Kilopower	8,769	0	
Power Management			
Stirling AC Cable	62.4	0	
Stirling Controller	322.4	0	
FISSION SYSTEM TOTAL	9,154	0	**9,154 kg**



Solar-Powered Option
Jezero Crater Crewed Mission

- **Study team estimated that all four Expedition 1 landers would require four each 12 m diameter UltraFlex™ arrays or equivalent**
  - Deployed on a 9.1 m diameter lander would extend the overall footprint to ~33 m
  - With arrays in neutral position on a 2.66 high lander deck, overall height was ~9.69
  - Deploying arrays high minimizes interactions with surface or payloads
  - Gimbals help shed dust
  - Lander deck provides stable operating platform
    - ✓ Allows arrays to be brought on-line quickly
- **Under nominal Jezero Crater conditions, around-the-clock propellant production with the first two landers requires 34.2 kW during the day and 35 kW at night**
  - During dust storm, power would be reduced to 10,985 W during the day and 11,728 W at night.
  - Once crew arrived, combined loads of the first four Expedition 1 landers were 31,915 W during nominal daytime operation and 26,790 W at night
  - Loads drop to 22,945 W during the day, and 24,060 W at night during a dust storm



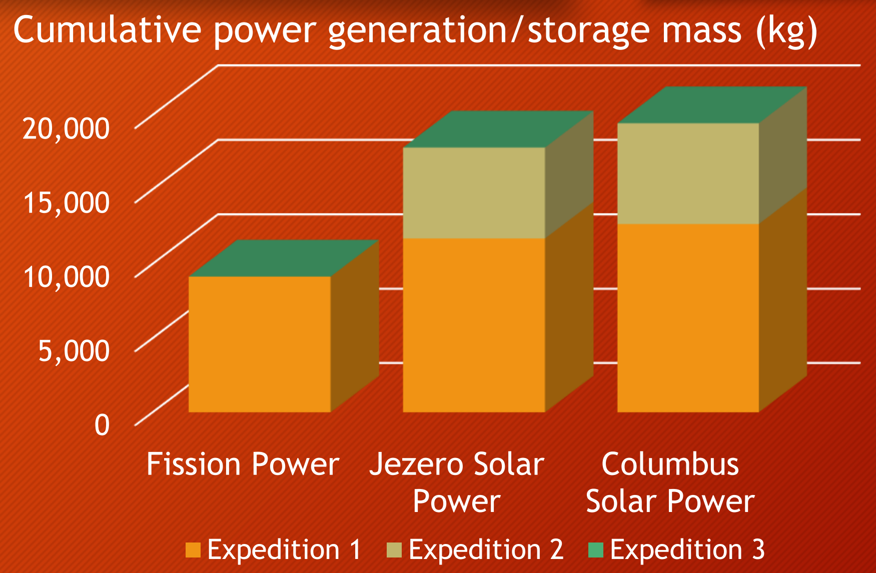
Solar-Powered Option
Jezero Crater- Expedition 1

Description	Lander 1	Lander 2	Lander 3	Lander 4	
Electrical Power Subsystem	4,890	1,512	1,512	1,512	**Jezero Crater Expedition 1 Solar Power <u>Generation and Storage</u> Total**
Power Generation	1,321	1,321	1,321	1,321	
Lander Internal Power Management and Distribution	401	192	192	192	
Energy Storage	3,168	0	0	0	
Structures and Mechanisms	660	476	476	476	
Secondary Structure	416	418	418	418	
Mechanisms	244	59	59	59	
Thermal Control (Non-Propellant)	61	45	45	45	
Active Thermal Control	2.4	3.4	3.4	3.4	
Passive Thermal Control	41.8	42	42	42	
Semi-Passive Thermal Control	16.8	0	0	0	
SOLAR POWER SYSTEM	**5,611**	**2,034**	**2,034**	**2,034**	**11,713 kg**

Does *not* include lander-to-lander PMAD
Mass grows to 12,679 kg at Columbus Crater

Solar vs. Fission Comparison
Crewed Mission

- **Mass**: Expedition 1 comparison doesn't tell the whole story
  - All fission power arrives with Expedition 1, but solar power performance doesn't catch up until Expedition 3
  - Extrapolate through 3 expeditions for apples-to-apples comparison



- **Performance**: comparable by Exp 3
- **Robustness**: fission power is more tolerant of dust, but the distributed solar power network is more tolerant to cable damage
  - Allows quick post-landing power, but arrays on MAV lander will have to be removed before MAV departs
    - ✓ Additional risk for crew/robotics to handle large arrays close to the MAV
- **Service Life**: 12-year Kilopower service life is probably about the same as solar power's rechargeable battery life

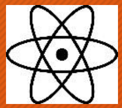
Observations
Crewed Surface Mission

- **50 kWe of fission power is ~20% less landed mass than 35 kW of solar power generation and storage for the 1st Expedition to Jezero Crater**
  - Not including lander-to-lander PMAD for either option, which could add a metric ton per lander
    - ✓ All solar powered landers become part of an integrated network, so they have to remain cabled together, even after cargo has been unloaded
    - ✓ Fission system only needs to be cabled to landers with active surface payloads
  - Assumptions will alter the analysis: landing site, propellant production rate, time available to make propellant, dust storm duration, transmission voltage
- **By the 3rd Crew Expedition, cumulative solar array mass is more than 2x fission power mass**
  - But enough solar array area will have been accumulated to accommodate a 120-sol dust storm with little disruption
- **Mass differential is greater at Columbus Crater landing site**

Conclusions
Solar vs. Fission Mars Surface Power

- **Solar-powered crew surface mission is more feasible under EMC than previous mission concepts**
- **Solar-powered crew surface mission is certainly *possible*, at least for some latitudes**
  - Forward work to evaluate all landing sites of interest
- **Advantages and Disadvantages**

Solar: High technology readiness, lower cost, and quick to switch from on-board stored energy to surface power; but high mass penalty may limit landing site options, and higher risk during a storm



Fission: Reliable, lower mass for most landing sites, same mass regardless of site, season, day/night, or weather; but lower technology readiness and higher development cost

- **Either power system will require substantial technology development and flight hardware investment**

Key Take Aways
From the two combined papers

- No Mars surface power decisions have been made
- Estimated power needs fluctuate, depending on assumed mission concept and operations
  - Need better definition on surface elements, transmission losses, etc.
  - 40 kW is probably the right ball-park for a long-duration, 4-crew Mars outpost with science activity
- Surface power generation and storage is an important decision that warrants careful consideration
  - If we select a particular surface power technology first, it could limit landing site options or operations
  - Conversely, if we select a landing site first, it could drive us to a specific surface power solution

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Questions?