Integrated Surface Power Strategy for Mars

michelle.a.rucker@nasa.gov

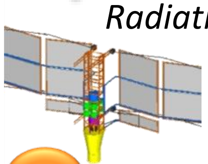
Background: Notional Crewed Mars Mission

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

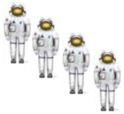
1 km

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

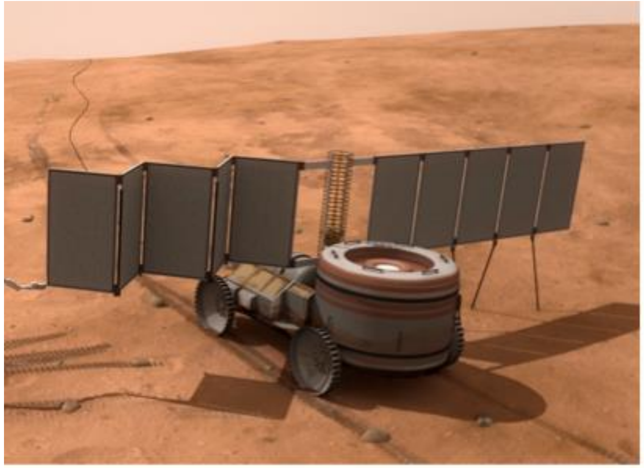
Issues and Study Objectives

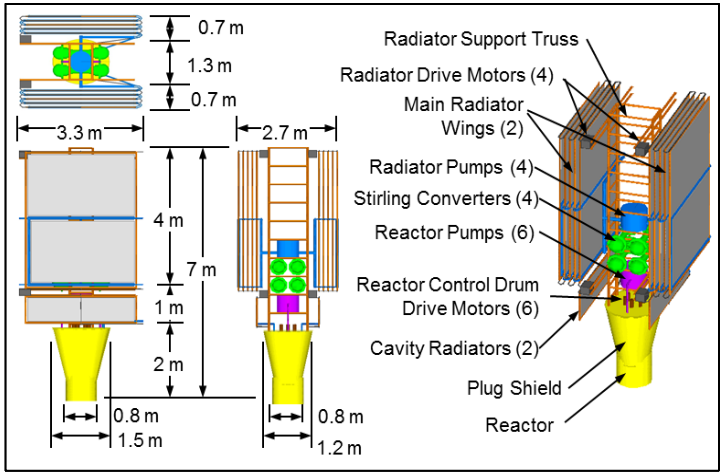
1 Validate Mars Surface power needs
- Is 40 kW enough…or is it more than we need?

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

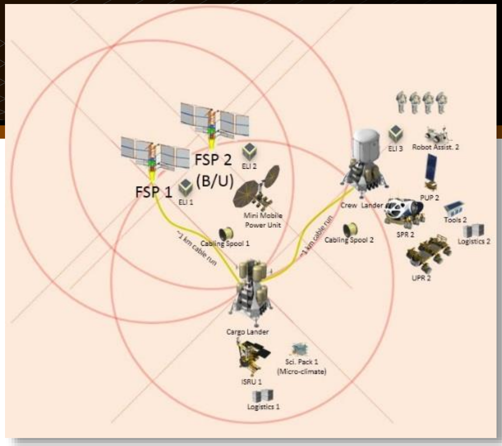




Notional FSP Concept

michelle.a.rucker@nasa.gov

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

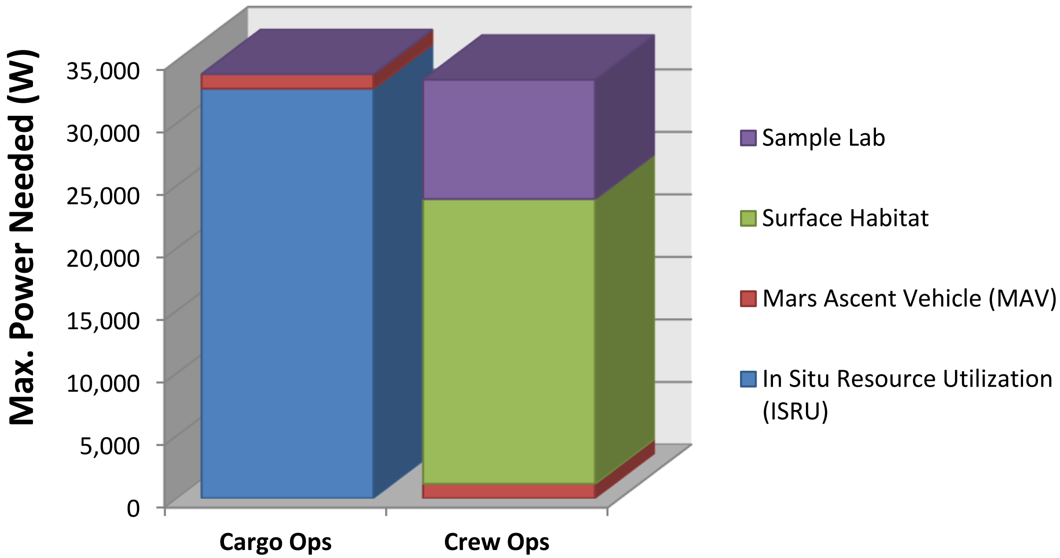
- Weather Stations
- Geo Stations

Traded solar arrays vs. RTG vs. Fuel Cells

Solar Arrays

michelle.a.rucker@nasa.gov

Objective 1: Validate Surface Power Needs



33.9 kW Max **33.5 kW Max**

- **Conclusion: < 40 kWe Needed** ***for this particular reference mission and conceptual architecture***
  - Includes 30% margin
  - ISRU is the Biggest Power Draw
    - Atmospheric ISRU
  - Architecture is notional
    - Forward work in 2015 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**

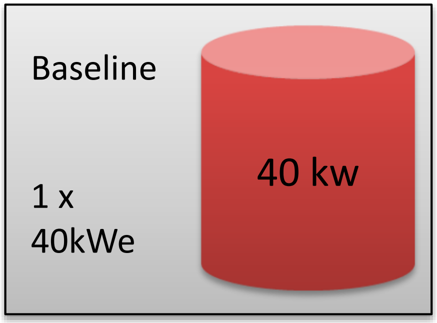
Even if ISRU is eliminated, still need almost as much power to support a Habitat and science operations

michelle.a.rucker@nasa.gov

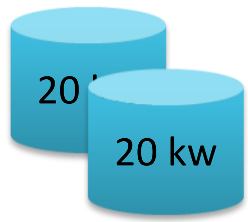
Exploring Alternatives

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

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

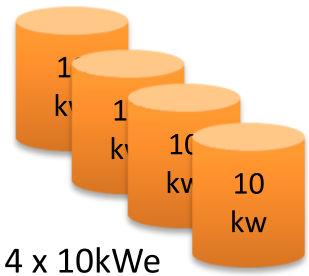


Vs.



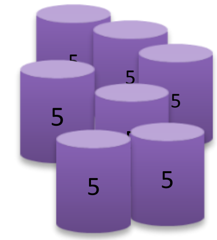
2 x 20kWe

Vs.



4 x 10kWe

Vs.

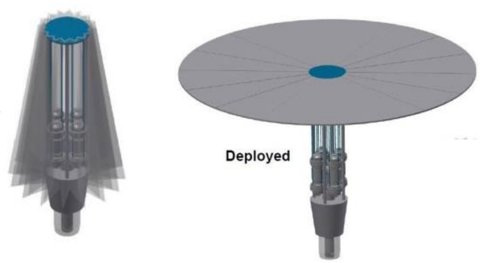


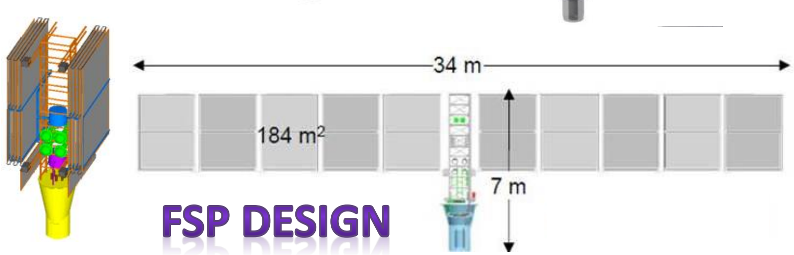
7 x 5 kWe

Etc.

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

KILOPOWER DESIGN





FSP DESIGN

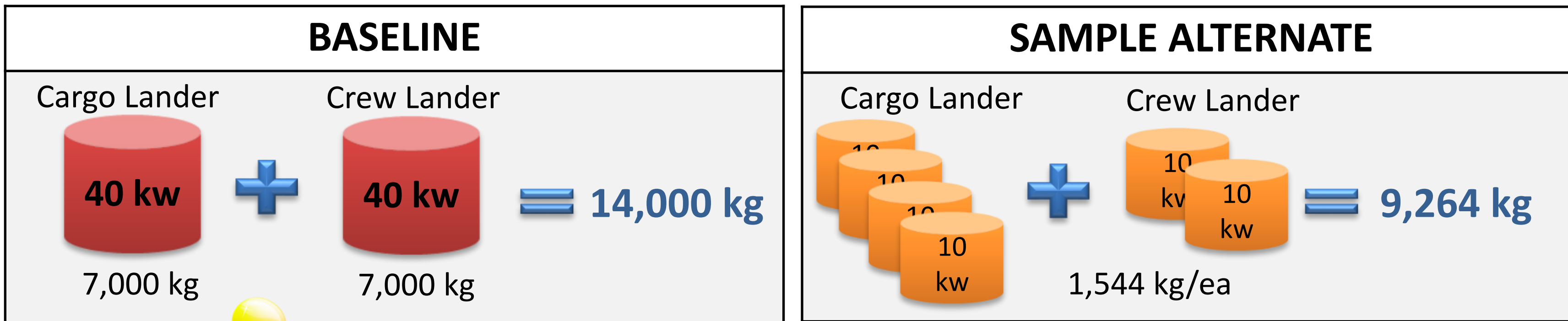
Type	Power (kWe)	Mass (kg)	Dimensions (m)		Radiators
			Dia	Height	
KP	3	751	1.2	*2.2 /4.9	9.6 m^2
	5	1,011	1.3	*2.7/5.9	13.5 m^2
	7	1,246	1.4	*3.0 /6.7	17.1 m^2
	10	1,544	1.5	*3.3 /7.3	20 m^2
FSP	10	3,300	1.0	7 m tall	37 m^2
	40	7,000	2.7	7 m tall	184 m^2

*Height w/Deployable/Fixed Radiators

michelle.a.rucker@nasa.gov

Objective 2: Reduce Contingency Power Mass

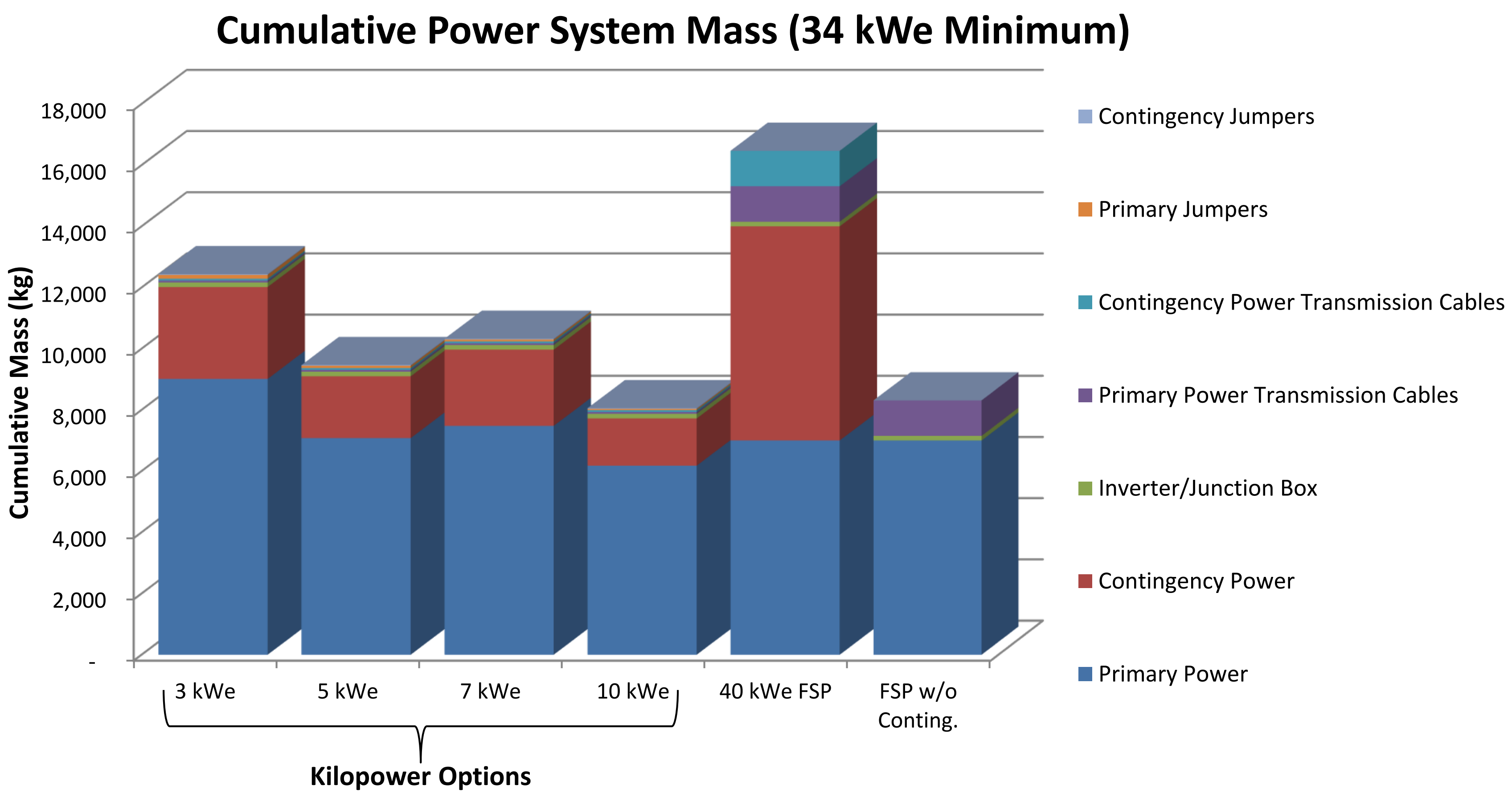
- **Baseline assumed a 40 kW contingency FSP on the Crew Lander**
  —Alternative: With 4 ea. 10 kW units on the Cargo Lander, it's unlikely ALL will fail
  —*Don't necessarily need to bring 4 more on the Crew Lander: 1 or 2 spares will do*



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**

Objective 3. Minimize Lander Power Mass

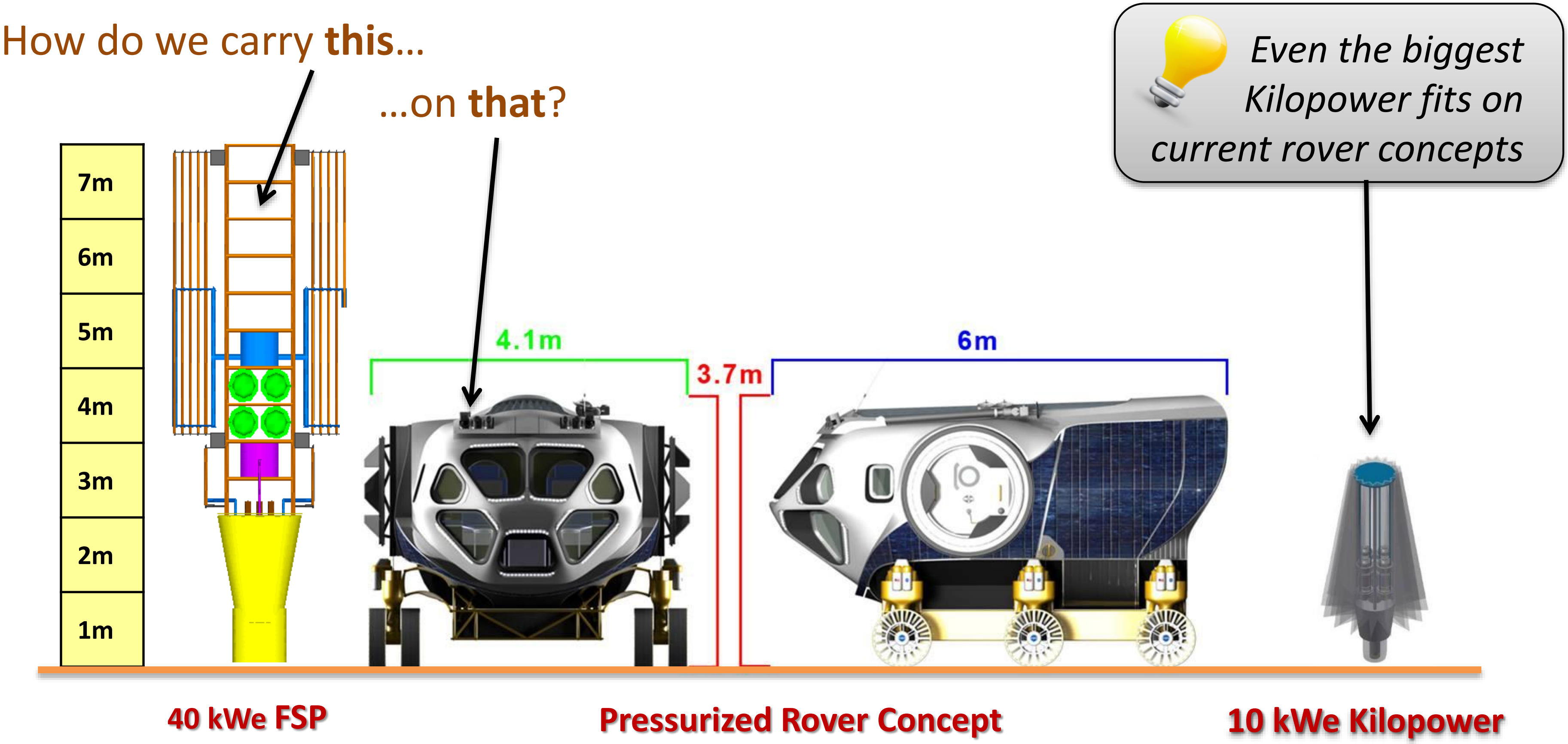
- **Lander has to survive up to 40 sols while FSP is being unloaded, relocated 1 km, deployed, and activated**
  - Criticality: Mars Ascent Vehicle (for crew return) needs keep-alive power!
  - Lander power mass drives thermal & structural mass, all of which drives descent propellant mass
- **With multiple 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

michelle.a.rucker@nasa.gov

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



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

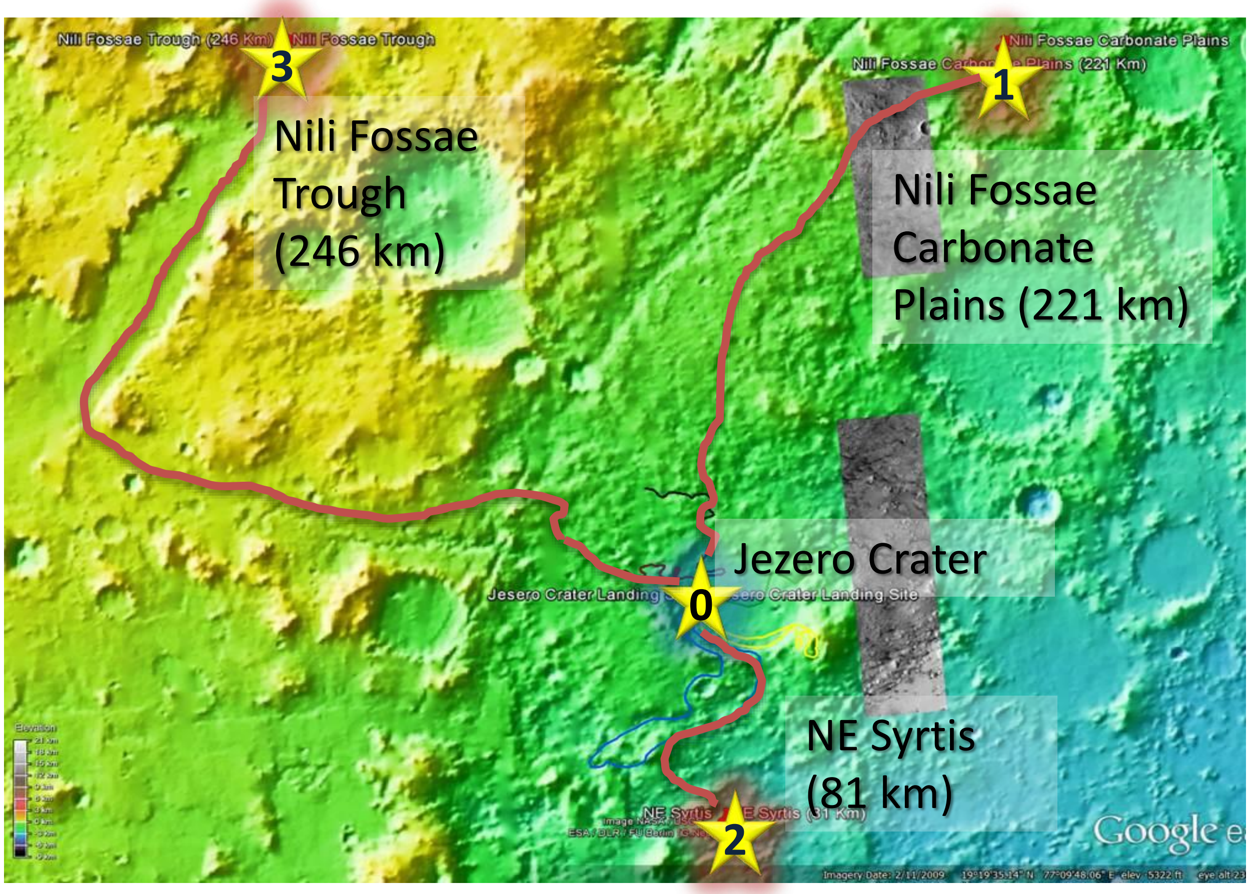
michelle.a.rucker@nasa.gov

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

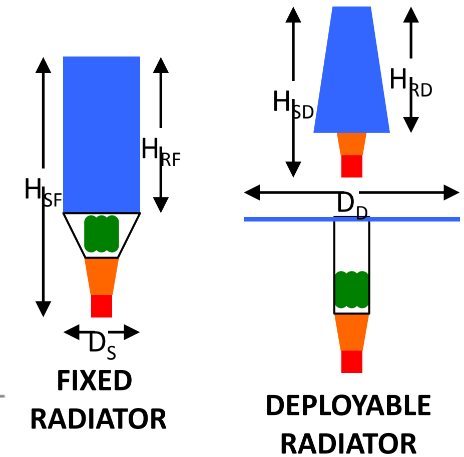
5. **Supports small pre-cursor missions without having to develop a sub-scale demo unit**
   - At 751 kg, the 3 kWe Kilopower unit fits on a Curiosity-class Lander with payload to spare
     - Could be retrieved later and added to a larger Kilopower farm
   - At 3,300 kg a small (10 kWe) FSP won't fit 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

michelle.a.rucker@nasa.gov

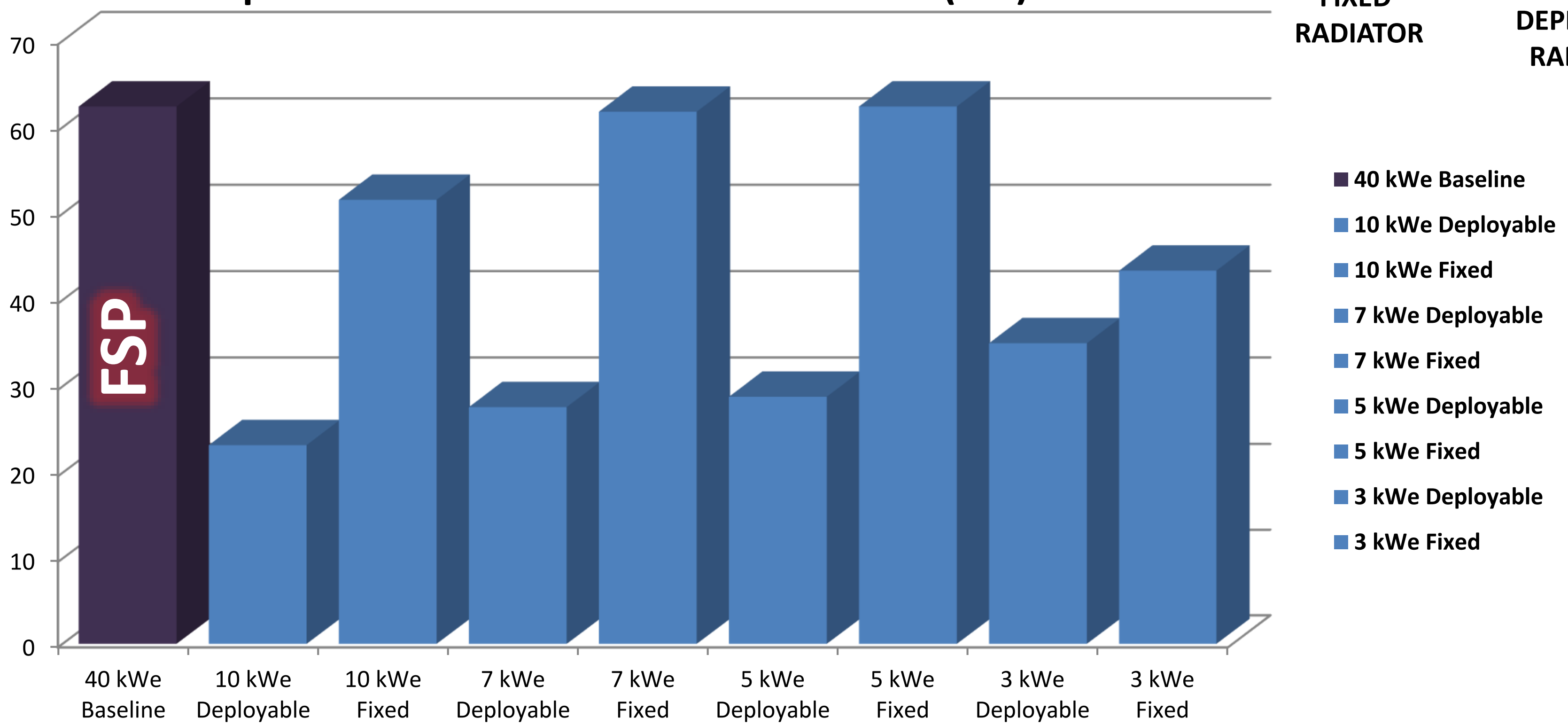
7. Lower *cumulative* stowage volume

— Deployable-radiator systems are compact

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



40 kWe Equivalent Cumulative Stowed Volume (m3)



michelle.a.rucker@nasa.gov

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

michelle.a.rucker@nasa.gov

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

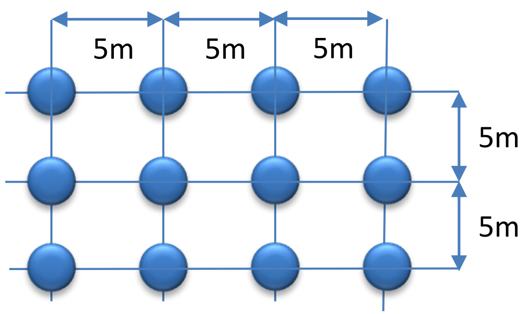
7. 10 kWe scaling limit

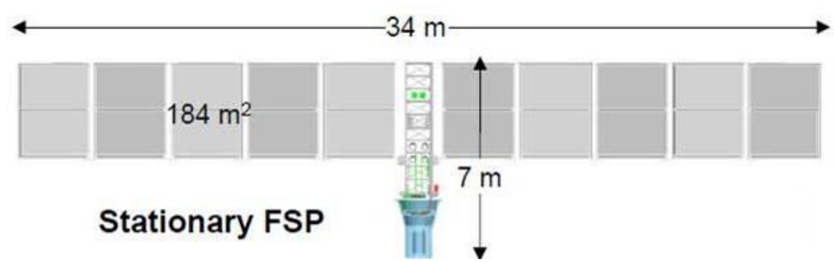
- Kilopower expected to scale readily up to 10 kWe, but not beyond
- Applications requiring higher power require FSP type design, or would have to accommodate multiple Kilopower systems ganged together
- Not an issue for surface application, but may not be practical for high-power, in-space applications

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





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.*

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 be located.*

michelle.a.rucker@nasa.gov

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.

michelle.a.rucker@nasa.gov

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Questions?

NASA/JSC/YX/Michelle Rucker

281-244-5569

Michelle.a.rucker@nasa.gov

Questions About the Kilopower Concept?

NASA/GRC/Don Palac
216-977-7094
d.palac@nasa.gov

NASA/GRC/Lee Mason
216-977-7106
lee.s.mason@nasa.gov