

Integrated Surface Power Strategy for Mars

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Abstract. A National Aeronautics and Space Administration (NASA) study team evaluated surface power needs for a conceptual crewed 500-day Mars mission. This study had four goals:

1. Determine estimated surface power needed to support the reference mission;
2. Explore alternatives to minimize landed power system mass;
3. Explore alternatives to minimize Mars Lander power self-sufficiency burden; and
4. Explore alternatives to minimize power system handling and surface transportation mass.

The study team concluded that Mars Ascent Vehicle (MAV) oxygen propellant production drives the overall surface power needed for the reference mission. Switching to multiple, small Kilowatt fission systems can potentially save four to eight metric tons of landed mass, as compared to a single, large Fission Surface Power (FSP) concept. Breaking the power system up into modular packages creates new operational opportunities, with benefits ranging from reduced lander self-sufficiency for power, to extending the exploration distance from a single landing site. Although a large FSP trades well for operational complexity, a modular approach potentially allows Program Managers more flexibility to absorb late mission changes with less schedule or mass risk, better supports small precursor missions, and allows a program to slowly build up mission capability over time. A number of Kilowatt disadvantages—and mitigation strategies—were also explored.

Keywords: Mars, Kilowatt, fission

BACKGROUND

Early crewed Mars mission concepts developed by NASA estimated that two each 40 kilowatt electric (kWe) FSP systems would be needed to support up to six crew members for a 500-day Mars surface stay. To minimize mass, the crew's return vehicle would land on Mars with empty oxygen propellant tanks and a manufacturing plant that would produce propellant from in situ Martian resources. The primary FSP would be autonomously deployed on a dedicated mobility system to support propellant production; once the return vehicle's propellant tanks were full, the crew would arrive with a spare FSP, which would only be deployed if the primary unit failed. The primary unit would be located at least one kilometer (km) from the crew habitat, providing a safe crew separation distance. The time needed to relocate the FSP depends on the mobility system and terrain factors, but was estimated to take up to 40 sols to complete[1]. FSP design[2] (Figure 1) varies with mission, but is estimated at a mass of about 7,000 kilograms (kg) for a Mars surface mission. Measuring seven meters (m) tall by 3.3 m wide when stowed, the radiator panels would extend about 34 m when deployed.

STUDY OBJECTIVES

Four potential concerns with the baseline scheme prompted this study. First, a detailed survey of powered equipment was needed to validate the 40 kWe requirement and correctly size the power system. Second, seven metric tons is a large mass allocation for a contingency item that may never nominally be used. Third, the 40 sol

estimated FSP deployment timeline placed a mass burden on the cargo lander, which must be self-sufficient for power until the FSP is activated. Finally, because the FSP is one of the largest items that must be moved around the surface, it drives surface mobility design in a direction that is not necessarily compatible with other mobility system tasks.

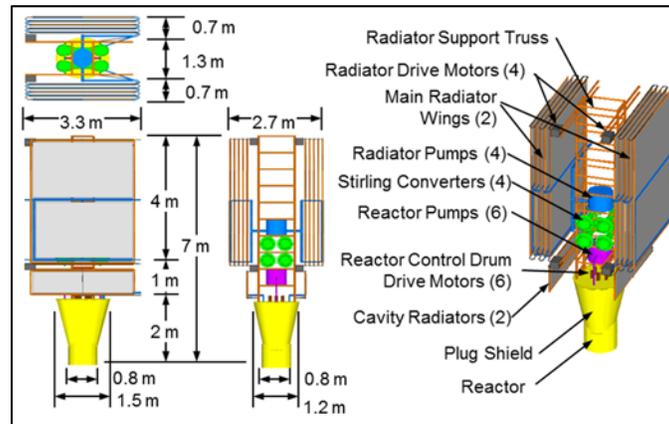


FIGURE 1. Baseline 40 kWe FSP, Stowed Configuration

To address these concerns, four objectives were identified for this study:

1. Validate estimated surface power needs.
2. Explore ways to reduce contingency mass.
3. Explore ways to accelerate FSP deployment.
4. Explore ways to minimize FSP impact on surface mobility systems.

SURFACE POWER NEEDS

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

1. **Stationary Equipment:** items that remain on or near the Landers, and therefore have ready access to the fission power system. This group comprises the bulk of fission surface power system users.
2. **Mobile Equipment:** items that move around the surface. These may be recharged from the fission system while visiting the Landers, but must be self-reliant away from the Landers, or have limited range from the Landers.
3. **Deployed Equipment:** relocated away from the Landers where they remain for the duration of the campaign. *Without access to the fission system they must be self-sustaining, and are therefore not addressed here.*

The Study Team found that a six crew, 500-day surface stay type of mission required a maximum of about 34 kWe during the un-crewed cargo mission and a maximum of about 33.6 kWe during the crewed surface stay; both of these estimates include 30% margin, but should be considered preliminary because the architecture is not well defined. Power could be reduced during the un-crewed phase if more time were available for propellant production. Crewed mission power needs could be reduced by phasing operations.

Stationary Powered Equipment

Table 1 summarizes estimated stationary powered equipment needs. Because stationary assets remain on or near the Landers, they define the bulk of FSP sizing. As shown in Figure 2, In-Situ Resource Utilization (ISRU) almost single-handedly sets the maximum cargo phase power requirement.

In-Situ Resource Utilization

Two ISRU systems arrive on the Cargo Lander. Once powered, the primary ISRU system extracts oxygen from the Martian atmosphere and fills the Mars Ascent Vehicle (MAV) propellant tanks. The second ISRU is a back-up, so only one ISRU would be in operation at a given time; once the MAV's propellant tanks are full, it is assumed that

ISRU can be powered down or put into standby mode. Ascent propellant load will vary with MAV crew cabin mass (which in turn varies with the number of crew and how long they must be inside the MAV[3]), and the orbit to which the MAV ascends (higher orbit requires more propellant). Using an estimate of 23,533 kg propellant for the largest MAV variant (a habitable, 6-crew vehicle bound for a one sol orbit), and a production time of 480 days, ISRU power needs are estimated at 25.2 kWe. With a 30% margin, propellant-only ISRU power for this largest MAV variant would be 32.76 kWe. For comparison, only about 19.63 kWe (including margin) would be required to produce propellant for a much smaller two-crew “taxi” MAV variant.

TABLE 1. Stationary Powered Equipment Summary

Power Consuming Equipment	Power Used (W)			Duty Cycle	Mission Phase
	Min.	Max.	Avg.		
In-Situ Resource Utilization	17,640	32,760	25,200	100%	Cargo
Mars Ascent Vehicle	623	1,157	890	100%	Cargo + Crewed
Geological/Meteorological Science Stations	20	105	69	100%	Cargo + Crewed
Surface Habitat					
Crew Accommodations	2,599	4,827	3,713	100%	Crewed
Environmental Control and Life Support	4,287	7,961	6,124	100%	
Avionics	3,375	6,267	4,821	100%	
Other	882	1,638	1,260	25%	
Extravehicular Activity	1,120	2,080	1,600	25%	
Mars Sample Laboratory					Crewed
Express Rack #1	0	720	720	100%	
Materials Science Research Rack	0	5500	550	10%	
Science Glovebox	0	1500	105	7%	
Illumination	13	130	65	100%	
Heaters	0	500	500	100%	
Control and Data Acquisition System	16	29	22	100%	
Sample Handler (Robonaut)	100	600	150	25%	
Communications	45	65	50	100%	
Planetary Protection	0	500	50	10%	Crewed

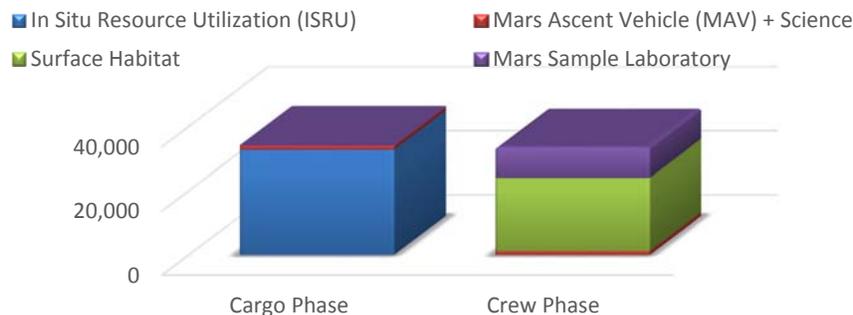


FIGURE 2. Baseline Maximum Power Needed (kWe) for Stationary Equipment

Mars Ascent Vehicle

From the time the MAV lands until it departs up to three years later, keep-alive power will be needed to heat the electronics, assess and communicate system health, and maintain propellants at proper temperature. In lieu of a detailed MAV design, keep-alive power estimates were drawn from previous ascent vehicle concepts. With 30% margin, MAV maximum keep-alive power is estimated at about 1,157 W. Note that the MAV draws power during *both* the cargo and crewed portions of the mission. One key area of uncertainty is the power required to maintain the MAV’s cryogenic propellants at proper temperatures; additional studies planned for 2015 are expected to refine MAV power estimates.

Mars Surface Habitat

A 2007 Mars Surface Habitat System Sizing Report[4] suggested 12.1 kW would be needed for a four crew Habitat, derived from Lunar concepts. 2011 modelling[5] increased Habitat power up to 14.2 kW for a six crew, 500 day

surface stay. More recent[6] models suggest 17.258 kW for a six-crew, long duration surface habitat. Note that this latest model assumes partially closed regenerative air and water loops; if fully closed loops were employed, more power may be required[7].

Mars Sample Laboratory

A separate laboratory space could mitigate crew contamination of Mars science samples. The Sample Laboratory is envisioned as an unpressurized tent-like structure with a robotic manipulator (such as NASA’s Robonaut) tele-operated from the Habitat to perform “hands-on” sorting, analysis, and packaging. In lieu of a laboratory design or equipment list, the Study Team used actual power requirements for three representative International Space Station racks. Because these were actuals, the 30% margin was not used for these line items.

Mobile Powered Equipment

Mobile powered equipment may be recharged from the fission system while visiting the Landers. For the purpose of this exercise, the 1,638 W “other” allocation in the Surface Habitat power budget is intended to cover mobile equipment recharging but, again, this is an area of uncertainty until mobility systems are better defined.

EXPLORING ALTERNATIVES

Having determined a fission system power budget of at least 34 kWe, the Study Team next pondered how best to minimize power system landed mass.

Kilopower Alternative

The surface power system must provide at least 34 kWe, but not necessarily in a single package. Mission needs could be met with various combinations of multiple, smaller power sources. One alternative to the single, large FSP is a smaller fission system called a Kilopower unit being developed at the NASA Glenn Research Center[8]. Like the FSP, the Kilopower concept employs Stirling power conversion; but in contrast to the FSP’s pumped Sodium-Potassium heat transport system, the Kilopower concept relies on simpler heat pipes directly coupled to the Stirlings. With fewer moving parts and a smaller reactor core, the Kilopower concept offers a compact, lower mass solution as compared to the equivalent FSP design (Figure 3). With its parasol-like deployable radiator, the 10 kWe Kilopower concept stows quite compactly. Current 3 and 5 kWe concepts feature fixed radiators, but could be designed for the more compact deployable radiators. Table 4 outlines system characteristics for the family of Kilopower concepts. Although too small for this application, the 1 kWe is shown only for comparison purposes.

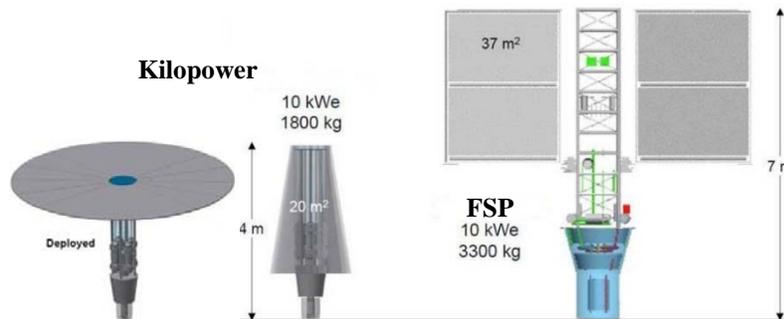


FIGURE 3. 10 kWe Kilopower vs. 10 kWe FSP Comparison.

One obvious advantage of breaking the power system up into smaller packages is that it allows power system development to proceed with lower risk, even before mission design has been finalized. For example, if the crewed surface mission requirements grow to require 43 kWe of power, the original scheme would have required a late-stage FSP redesign or a second 40 kWe unit to be manifested at a seven ton mass penalty, compared to only a 0.75 to 1.5 ton mass penalty to add an extra Kilopower unit to the manifest. Conversely, the need for only a few kilowatts on a precursor mission might drive overall program cost to develop a sub-scale FSP demonstration system, whereas even a small precursor lander could carry a full-scale Kilopower unit.

TABLE 4. Kilopower System Characteristics.

Power System Characteristics	User Power (kWe)				
	1.0	3.0	5.0	7.0	10.0
Reactor core power (kWt)	4.3	13.0	21.7	30.3	43.3
Separation Distance for a single unit dose <3mR/hr (m)	100	200	300	400	500
Radiator area (m ²)	3.2	9.6	13.5	17.1	20.0
Stowed diameter (m)	1.1	1.2	1.3	1.4	1.5
Stowed height (m) with fixed radiator	3.0	4.9	5.9	6.7	7.3
Stowed height (m) with deployable radiator	N/A	2.2	2.7	3.0	3.3
Mass Summary (kg)					
Reactor	136	175	198	215	235
Shield	148	272	364	443	547
Balance of Plant	122	304	449	589	763
Kilopower Unit Total Mass (kg)	406	751	1011	1247	1545

Optimizing Spares Mass

One option for reducing contingency mass is to increase FSP reliability and eliminate spares altogether. But the FSP could fail from external damage (such as debris plume from another Lander or a robotic rover mishap) and that could be catastrophic during a dust storm that prevents the crew from simply returning to orbit. If a single FSP were replaced with, for example, four each 10 kWe Kilopower systems, it's unlikely that all four would fail; therefore it isn't necessary to carry four spares. To obtain an "apples to apples" mass comparison between options, the following assumptions were used:

- The combination of primary power units must meet or exceed 34 kWe.
- Contingency power must meet or exceed 10 kWe total (arbitrarily selected as the largest Kilopower increment).
- High voltage transmission cable is assumed at 60 kg per km, while low voltage DC cable ranges from 1,028 kg for a basic 3:2 copper conductor to 1,349 kg for 1 km of armored cable; this study assumed 1,100 kg.
- In lieu of a specific design, it was assumed that an Inverter/Junction box would be about 150 kg for all options.
- In lieu of a detailed design, it was assumed that the jumpers ganging Kilopower units together were 10 m long (arbitrarily selected to be longer than the worst-case distance between units, plus margin to navigate around surface obstacles). Connectors were assumed to be 5 kg each to account for robotic handling and dust resistance.

As shown in Figure 4, all four Kilopower options result in lower cumulative mass when contingency power and cables are included. Even without contingency power, all but the 3 kWe Kilopower options have lower cumulative system mass than a 40 kWe FSP. In fact, four each primary plus one contingency 10 kWe Kilopower unit (50 kWe total), is about 200 kg lower cumulative mass than a single 40 kWe FSP with no contingency. Of the Kilopower options, the 10 kWe trades best for cumulative system mass. Sparing strategy will depend on risk tolerance but if only one or two spares are needed, overall landed mass could be reduced by as much as eight metric tons.

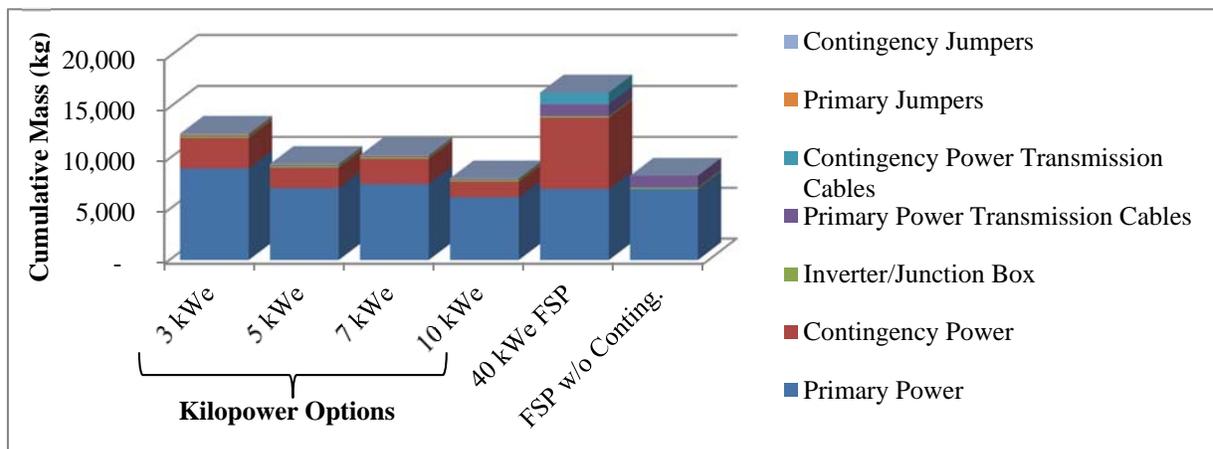


FIGURE 4. Mass Comparison of Fission System Options for 34 kWe Minimum Cumulative Power.

Optimizing Lander Power Mass

In the original scheme, the Cargo Lander must be self-sufficient for power for up to 40 sols while the single FSP is being relocated one kilometer, deployed, and activated. During that time, the Lander must provide keep-alive power to the MAV. Accelerating power system activation could dramatically reduce the Lander's internal power burden (which in turn could reduce Lander thermal and structural system mass, with flow-down impacts to descent propellant mass). Employing multiple, smaller units would allow an important operational change: one unit could be activated immediately near the Lander to sustain Lander functions while the remaining units were off-loaded and relocated. Once the rest of the systems were on-line, the first unit could then be turned off, repositioned, and reactivated. Because initial power system activation occurs on the cargo mission (before crew arrive), crew safety issues are minimized, though obviously Lander and other cargo electronics would have to be properly shielded.

Optimizing Surface Transportation Mass

At seven meters tall, the 40 kWe FSP is bigger than current pressurized rover concepts, making relocation a challenge. Either the FSP needs a dedicated mobility system, or the mobility systems used for other surface applications must accommodate the FSP, but both of these options are inefficient. By breaking the power system into smaller packages, these smaller units are more likely to fit onto existing mobility systems, eliminating the need for a dedicated mobility system.

Kilopower Concept Advantages

This study identified several additional advantages of the Kilopower concept over the baseline FSP.

Lower Startup Power

With fewer moving parts, a Kilopower requires the equivalent of two D-cell batteries for start-up. In comparison, the FSP requires an estimated 424 kg of solar arrays to supply the 5 kWe needed for startup.

Lower Cable Mass

Although both the FSP and Kilopower concepts require approximately one kilometer of 400 VAC power transmission cable, the FSP also requires a low voltage auxiliary power line due to parasitic power draw. At an estimated 60 kg per kilometer of high voltage cable versus more than 1,000 kg for the low voltage cable, the Kilopower option saves nearly a metric ton of landed mass for cabling alone. Even with the addition of a local inverter/junction box and cables to gang multiple units together, overall Kilopower cable mass is significantly lower than the baseline FSP cable, with additional mass savings for the spare FSP low voltage cable.

Precursor Mission Opportunities

At seven metric tons (eight with cabling), a full-scale 40 kWe FSP requires a relatively large Lander for Mars surface delivery. This precludes using smaller, one-ton class pre-cursor missions to demonstrate a full-scale fission surface power system. A sub-scale FSP unit could be developed for a smaller Lander, but the effort would dilute the flight design team from their primary task, and incur additional development cost. On the other hand, a single three or five kWe full-scale Kilopower unit could support pre-cursor missions with little additional development cost.

Increased Operational Flexibility

The ability to deploy small fission surface systems on precursor missions supports an "evolvable" Mars campaign by allowing a gradual buildup of assets over time. Conversely, a mission requiring a few kilowatts more than a baseline mission design would have to add at most a 1.5 metric ton Kilopower unit, rather than a seven metric ton FSP. Breaking the power system into smaller packages also opens up new opportunities: Kilopower units could be redeployed to support activities previously thought to be power-limited, such as deep drilling. Small, portable power systems could also be robotically transported over great distances, from one landing site to the next. One of the more intriguing aspects of the Kilopower concept is its potential to extend a surface crew's exploration radius around a particular landing site. Close proximity to the crew makes on-board radioisotope power problematic, so current Mars rover concepts favor solar power. However, Martian solar intensity, the possibility of dust storms, and the constraint that both recharging and driving can only be performed in daylight means that a solar-powered Mars rover will spend about 80% of its time standing still to recharge, limiting its range to only 14 km per day. The study team found that driving efficiency improved up to 46 km per day if two redundant Kilopower units were available as charging stations. Rover battery recharging could occur overnight while the crew sleeps, or battery packs could be swapped out at the charging station to minimize loiter time. For crew safety, a cable could be extended a safe

distance from the Kilopower station for charging. Four Kilopower units arrayed in pairs spaced 90 km apart could boost a pressurized rover’s maximum range from the Habitat to 225 km—more than double the estimated performance of solar-powered pressurized rovers. Although these are relatively modest gains, excursion distance becomes an important factor if a campaign is limited to a single landing site. To illustrate the example, consider the distances between three areas of scientific interest and Jezero Crater, which was a Mars Science Laboratory mission candidate landing site: Nili Fossae Carbonate Plains (221 km), northeast Syrtis (81 km), and Nili Fossae Trough (246 km). Depending on the actual “terrain factor” (distance driven/range achieved), a pressurized rover with four deployable Kilopower units may be able to sweep all three sites plus Jezero Crater from a single landing point to the northwest of Jezero Crater.

Reduced Crew Separation Distance

Crew separation distance from a reactor is guided by the inverse square law for radiation dosage. A baseline 40 kWe FSP must be at least 1,000 m from the crew Habitat to keep radiation exposure below safe levels but a single 10 kWe Kilopower unit only has to be 500 m away for the same dose. Although four each 10 kWe Kilopower units ganged together require the same separation distance as the single baseline FSP, individual Kilopower units redeployed to special operations—such as deep drilling—would require smaller crew keep-out zones than the large baseline FSP. What’s more, smaller units would be easier to bury or hide behind natural terrain features, which could further reduce crew separation distance.

Lower Cargo Handler/Surface Mobility Load

Autonomously handling each 751 to 1,545 kg Kilopower unit is likely to require smaller cargo handling and surface mobility equipment than what would be needed to unload/transport a seven metric ton baseline FSP, assuming the Kilopower units are unloaded individually. This mitigates the need for dedicated handling/transportation equipment.

Lower Cumulative Stowage Volume

Due to shroud packaging constraints, Mars landers are expected to be almost as volume-limited as they are mass-limited. The baseline FSP has a relatively large stowage footprint compared to the compact Kilopower units. As shown in Table 5, 40 kWe cumulative Kilopower systems require less stowage volume than the baseline FSP in all but one case. Concepts employing deployable radiators can save up to 60% stowed volume over the baseline FSP, but even the fixed radiator concepts stow as well or better than the baseline. What’s more, a seven metric ton FSP must be carefully counter-balanced on a Lander to prevent landing instability problems, whereas multiple Kilopower systems are more easily distributed around the Lander cargo deck as needed for proper balance.

TABLE 5. Power System Stowed Volume Comparison

Power System Size	Concept Preliminary Dimensions	Per Unit	40 kWe Cumulative
40 kWe Baseline FSP	2.7 m Wide x 3.3 m Deep x 7 m Tall	62.4 m ³	62.4 m ³
10 kWe Kilopower	1.5 m Dia. x 3.3 m Tall (Deployable Radiators)	5.8 m ³	23.2 m ³
	1.5 m Dia. x 7.3 m Tall (Fixed Radiators)	12.9 m ³	51.6 m ³
7 kWe Kilopower	1.4 m Dia. x 3.0 m Tall (Deployable Radiators)	4.6 m ³	27.6 m ³
	1.4 m Dia. x 6.7 m Tall (Fixed Radiators)	10.3 m ³	61.8 m ³
5 kWe Kilopower	1.3 m Diameter x 2.7 m Tall (Deployable Radiators)	3.6 m ³	28.8 m ³
	1.3 m Dia. 5.9 m Tall (Fixed Radiators)	7.8 m ³	62.4 m ³
3 kWe Kilopower	1.2 m Diameter x 2.2 m Tall (Deployable Radiators)	2.5 m ³	35.0 m ³
	1.2 m Diameter x 2.7 m Tall (Fixed Radiators)	3.1 m ³	43.4 m ³

Kilopower Concept Disadvantages

Higher Cumulative HEU Mass

The smaller the reactor, the less Highly Enriched Uranium (HEU) is required but the correlation is not linear. Although each 10 kWe Kilopower unit only needs 50 kg HEU compared to the 110 kg required for a 40 KWe FSP, four Kilopowers would need 200 kg between them, or 250 kg if one spare unit is included. In the worst case (twelve each of the 3 kWe units), the Kilopower concept requires more than twice as much HEU as the baseline scheme.

Increased Security/Launch Safety Overhead

Breaking the power system into multiple packages could complicate ground handling and processing if it requires more oversight to follow and secure multiple units in different stages of production. Depending on how the power system is packaged on the launch vehicle, there may be increased safety overhead to analyze launch failure dispersion of reactor materials, or to design, test and certify packaging to ensure that all units stay together in the event of a launch failure. Note that for transportation architectures utilizing an aeroshell for Mars entry and descent, the aeroshell itself could help keep Kilopower materials together without additional mass penalty. One approach considered for minimizing security overhead was to switch from High to Low Enriched Uranium (LEU). A preliminary estimate of a 1 kWe LEU system found that the core fuel mass increased from 30 to approximately 300 kg, with the reactor mass increasing from 136 to approximately 700 kg. Overall system mass more than doubled, from 406 kg with HEU to over 1,000 kg with LEU. The mass increase for larger Kilopower systems can be extrapolated to more than 3 tons for a 10 kWe system, eliminating many of the advantages of the Kilopower concept. Aside from the complications of transporting a 300 kg reactor core, the mass eliminates an LEU Kilopower as a candidate for smaller in-space science payloads, or surface precursor missions.

Additional Surface Delivery Trips

A baseline FSP requires a single delivery trip to relocate it from the Lander to the installation site, though it is likely to be a slow trip with a seven metric ton payload. The number of trips required to deliver the entire complement of Kilopower units will depend on reactor size and how many units can be transported at one time. Current pressurized rover concepts could carry at least one 10 kWe unit, or at least two of the 3 or 5 kWe units. Once the rover has mapped a route on the first delivery, subsequent delivery trips should be relatively straightforward, with the main penalty being wear and tear on the rover.

Increased Operational Complexity

The baseline FSP requires two cables with a total of four connections (one at each end of each cable). A “Kilopower Farm” consisting of multiple small units only requires a single power transmission cable back to the Lander, but would need an inverter/junction box to gang together the individual power systems. The total number of connections will depend on the number of Kilopower units in the power farm; for example, four each of the 10 kWe units would require a total of 10 connections: two for power transmission (one at each end of the power transmission cable), and eight to gang together the four reactors (one at each end of the four jumpers between the reactors and the inverter/junction box). In the worst case of 12 each 3 kWe units, a total of 26 connectors would be required. Connector mass is not necessarily an issue, but so many field connections increases operational complexity, particularly when made robotically in a dusty environment. Risk can be reduced by making as many connections as possible in advance. For example, at least one end of each Kilopower-to-Inverter Box connection can be made on Earth, as can both ends of the power transmission cable (per the original FSP operations concept), reducing the number of field connections to no more than 12. Further reduction is possible if several Kilopower units can be deployed together with the junction box, already connected.

Potentially Lower Overall System Reliability

Due to its internally redundant design, the reliability of each Kilopower unit is expected to be quite high. The weak link from a system reliability standpoint then will be in the connections between the individual Kilopower units. As noted in a United States Air Force study[9] of electronic component failure rates, connectors are a leading cause of reliability problems for many avionics systems. As with the baseline FSP design, Kilopower connectors must resist Martian temperature cycling, launch/landing vibration, and corrosion. But as noted above, the risk of contaminant-induced failure is likely to be higher with the Kilopower systems due to the number of robotic field connections. Risk can be reduced by manifesting extra Kilopower-to-inverter box cables with connectors, or by adding redundant connectors to the Kilopower units themselves. Regardless, a robust connector design, capable of robotic operation and tolerant to surface dust contamination will be critical to the Kilopower concept for Mars surface applications.

10 kWe Scaling Limit

The Kilopower concept is expected to scale readily up to 10 kWe, but not beyond. Applications requiring very high power may be better served with an FSP design, unless multiple Kilopower systems can be ganged together.

Large Deployed System Footprint

The original scheme called for an FSP to be placed on a clear, level spot at least one kilometer from the Crew Habitat. Although the FSP's reactor core is a modest 0.8 m diameter at the base, the 34 m wide deployed radiators

require a relatively large area free of obstacles taller than about 3 meters. With their fixed or parasol-like deployed radiators, individual Kilopower units are considerably more compact, but ganging several of them together would require a large cumulative footprint. Separation distance between units will depend on final reactor and radiator designs, but will need to ensure radiators do not cross-communicate, and that failure of one unit cannot compromise nearby units.

Planetary Protection Considerations

Like all other crewed mission equipment, the power systems must comply with NPI 8020.7/NPD 8020.7G[10]. Planetary protection considerations are expected to be the same regardless of whether FSP or Kilopower units are used. As a general rule, neither the Crew Habitat nor the power system(s) will be located in a “special region” where water—and thus potential organic material—are likely to occur. The difficulty comes in preventing the power system itself from creating a localized special region by melting nearby ice. This may impact radiator design (to ensure heat radiates up, rather than down towards the regolith), or it may impact reactor baseplate design.

SURFACE POWER SYSTEM UNIQUE NEEDS

This study identified a number of power system features unique to a surface application that wouldn’t necessarily be required for orbital or interplanetary systems, and are noted here for the purpose of commonality discussions.

Dust Tolerant Mechanisms. Because the surface power system will be exposed to dust storms--some lasting months-- power system mechanisms must be tolerant to surface dust contamination. For example, deployable radiators and connector covers must be robust to surface dust.

Robotic Handling. Because the surface power system is intended to support propellant production before the crew arrives, it must be robotically unloaded from the cargo lander, deployed a safe distance from the eventual crew habitation area, and activated. During crewed phases of the surface mission, individual power systems may need to be robotically re-deployed to remote areas to support exploration activities.

Surface Transport. The power system must be robust to surface transport, as it 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.

Restart Ability. The ability to stop and start surface power systems allows mission planners the flexibility to relocate assets, add new assets, or allow crew to safely approach for inspections or repairs.

Surface Environment Compatibility. Unique design features must function in the Mars environment (gravity, atmosphere, temperature variations, etc.)

Planetary Protection. If the power 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. At best, this could complicate certification; at worst, it could drive cable mass.

System Connectivity. Surface power systems may be required to operate alone, or in combination with like systems. To minimize mass, it is desired to tailor power systems for a particular mission. This may involve ganging together multiple systems to support a large power load, or operating a single system to support a particular activity.

CONCLUSIONS

MAV propellant production is the single largest driver for surface mission power. Maximum surface power needs are estimated to be at least 34 kWe during the un-crewed cargo phase. Power needs drop only slightly to at least 33.6 kWe during the crewed portion of the surface mission; selective operations could reduce power needed near the Habitat to as low as 24 kWe. Estimates include 30% margin, but should be considered preliminary pending additional studies planned for 2015. Switching to multiple, small Kilopower systems are estimated to save 4 to 8 metric tons of landed mass, as compared to the baseline 40 kWe FSP concept, depending on sparing strategy. Breaking the power system up into smaller packages also helps minimize power system activation time, reduces

mobility system impacts, and allows Program Managers flexibility to absorb late mission changes, with less schedule or mass risk. All of the Kilopower concept options considered trade more favorably than the baseline FSP for landed mass and stowed volume. The baseline FSP offers lower complexity, but sacrifices operational flexibility. Of the Kilopower options, the 10 kWe solution trades best for landed mass, stowed volume, and operational complexity. Deploying four Kilopower units into the field allows a conceptual pressurized rover to explore up to 225 km from the Lander, more than doubling the 98 km range offered by solar-only pressurized rover concepts. This could be important for campaigns limited to a single landing site. Small Kilopower units offer additional operational advantages, including the possibility of supporting a 1-ton (Curiosity-class) precursor mission, or building up capability over time. On the other hand, there are several disadvantages to the Kilopower concept that must be carefully balanced against the mass and volume savings before selecting a system for the Mars surface application.

It must be emphasized that this exercise was not intended to recommend a particular Mars surface power system. The intent was to explore ways to minimize power system mass and volume. The results of this exercise will feed into a Mars Lander cargo packaging study and operations model, to compare different mission options. Final decisions regarding Mars surface power must weigh programmatic considerations such as funding availability, desired commonality with other missions, development schedules, life cycle costs and both ground and flight safety. Mars human system architectures may deviate from current concepts which could significantly alter power system needs for future crewed Mars surface missions.

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