NASA/TM—2009-215803

Compilation of Trade Studies for the Constellation Program Extravehicular Activity Spacesuit Power System

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November 2009

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Abstract

This compilation of trade studies performed from 2005 to 2006 addressed a number of power system design issues for the Constellation Program Extravehicular Activity Spacesuit. Spacesuits were required for spacewalks and in-space activities as well as lunar and Mars surface operations. The trades documented here considered whether solar power was feasible for spacesuits, whether spacesuit power generation should be a distributed or a centralized function, whether self-powered in-space spacesuits were better than umbilically powered ones, and whether the suit power system should be recharged in place or replaced.

Contents

1.0 Trade Study 1: High Efficiency Solar Power Augmentation for the Advanced EVA Suit

Date: June 08, 2005

1.1 Introduction

The purpose of this trade study is to evaluate the feasibility of using solar power to reduce the burden on the energy storage system for the advanced EVA suit. The goal is to reduce the overall mass of the power system by replacing some of the capacity of the energy storage through the use of solar generated power.

1.2 Solar Cell Assumptions

High efficiency solar cells were assumed for this application. Lower efficiency cells were not considered because the required coverage area is impractical. Two kinds of solar cells were examined, 32 percent (reference efficiency) and 40 percent. The 32 percent efficiency is representative of a Lockheed Martin Marietta four junction GaAs/SiGe cell, selected because of its low cell density. Other SOA (state of the art) cells have efficiencies from 27 to 35 percent, but the selected one provides the highest SOA specific power (i.e., W/kg) due to its lower cell density. The 40 percent efficiency cell (currently at low TRL, technology readiness level, but being developed) was a hypothetical, optimistic projection (likely some variant of four junction cells) for far-term use.

1.3 Solar Panel Structure Assumptions

Two types of solar panel structure were assumed. One was the traditional “rigid” panel with a structural honeycomb mounting core and a thick facesheet. This is the standard method for solar panels attached to the surface of spacecraft or deployed in solar array “wings”. The second approach was a “flexible” panel. This is typically used in the Ultraflex design and essentially omits the core and facesheet by using a specialized method of attachment. The present maximum cell efficiency utilized for this approach is 20 percent. To be used (if possible) for higher efficiency 32 percent or projected 40 percent cells would require considerable development costs. Thus, it is likely flexible panels will only be for far-term use.

1.4 Solar Panel Design Assumptions

The packing factor for the solar panel was assumed to be 0.8. This is a typical value for small satellite solar panels. By reducing this value the solar panel area increases, but it enables reduction of the solar panel temperature using passive means. No thermal calculations to determine the best packing factor for the considered environments were attempted at this time.

Since no thermal design calculations were performed, the operating temperature of the solar panel was assumed. It was unknown how the thermal load would be controlled, although passive means are desirable. If the solar cells (and panel) were 100 °C then 32 percent cells would decrease in efficiency to 26.9 percent. All assessed cells were assumed to have the same temperature effects.

The following table includes other assumptions used in the analysis.

Packing factor	0.80
Solar panel utilization factor	0.95
Solar cell operating temperature	28 °C
Solar panel cell mismatch factor	0.98
Solar panel interconnect efficiency factor	0.97
Solar panel blocking diode drop	0.99
Solar panel harness	0.99
Other losses due to solar panel lifetime	0.0
Solar intensity (near Mars plane)	606 W/m^2
Solar intensity (near Earth plane)	1370 W/m^2

The layers of the solar panel are listed below. Note that the rigid and flexible panels differ by the core and facesheet layers. The core thickness for the rigid panels was assumed. A more detailed structural analysis is required for this value.

Coverglass (Ceria-doped microsheet)	2620 kg/m^3	0.1016 mm
Adhesive (DC93-500)	1080 kg/m^3	0.0127 mm
Cell	2330 kg/m^3	0.1397 mm
Back contact (copper)	8940 kg/m^3	0.1016 mm
Adhesive (DC93-500)	1080 kg/m^3	0.00381 mm
Facesheet (honeycomb K13C2U-3 ply)	1659 kg/m^3	0.2032 mm (grid) 0.0 mm (flexible)
Adhesive (DC93-500)	1080 kg/m^3	0.1016 mm
Core (Al-honeycomb-3/8-5056-1.0)	16 kg/m^3	10.0 mm (grid) 0.0 mm (flexible)

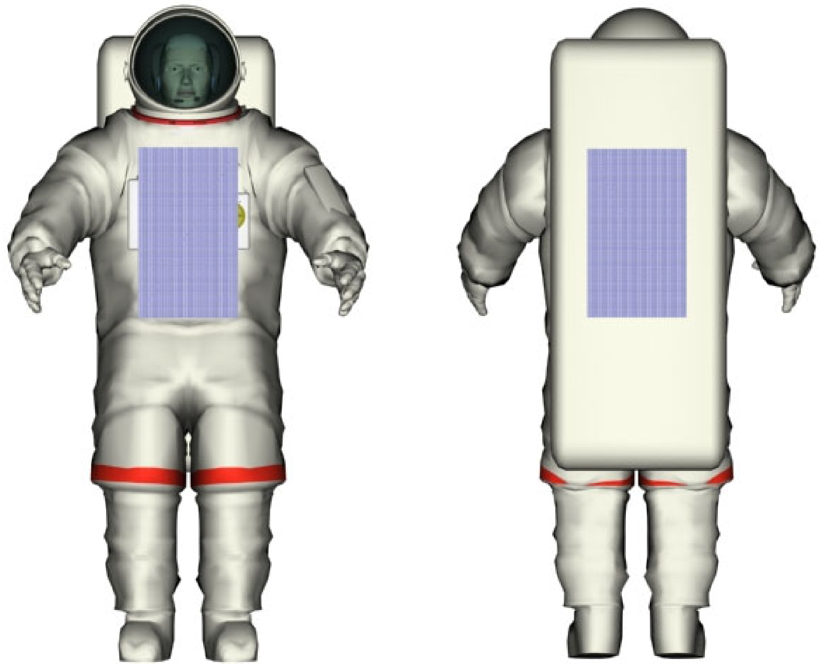
1.5 Configuration Assumptions

Four different “fixed” solar panel layouts were considered. The first was a flat solar panel which was envisioned to be either mounted on the suit front, back, or by way of a pole attached to the suit portable life support system backpack (likely slightly above the helmet and centered). The second was a two sided solar panel with one on the suit front and one on the suit back, or, alternatively, attached by way of a pole to the suit backpack. The third layout was a cube of panels attached on a pole to the backpack. The fourth layout was sphere (or greater than 12 faces) of cells attached to the backpack.

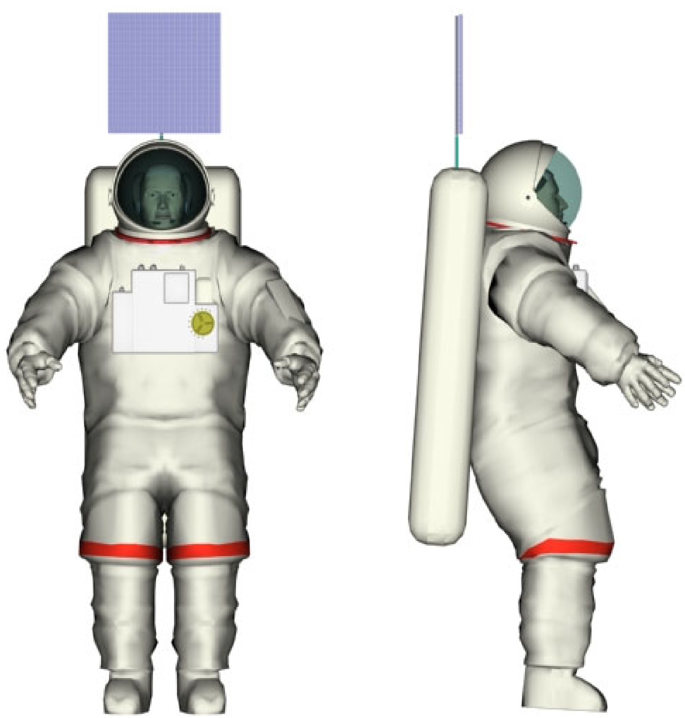
Other aspects of configuration include the ability to cant the flat panels, particularly for surface operations. It is assumed that, prior to the sortie, the astronaut sets the cant angle on the pole mounted solar panels (flat options) to maximize the incident solar energy. This depends on the latitude, longitude and time of year for either Mars or Moon location. For two sided panels, this canting can be in a tent-like formation. Therefore, at the North or South pole of the Moon or Mars, the astronaut would set the cant angle to 0 ° (aligned with local vertical) in order to maximize the incident solar energy for the flat panel options and at the equator when the Sun is overhead, he would set the cant angle to 90 °.

No consideration was given to suit clearance issues. It was assumed the pole mounted panels were attached after egress.

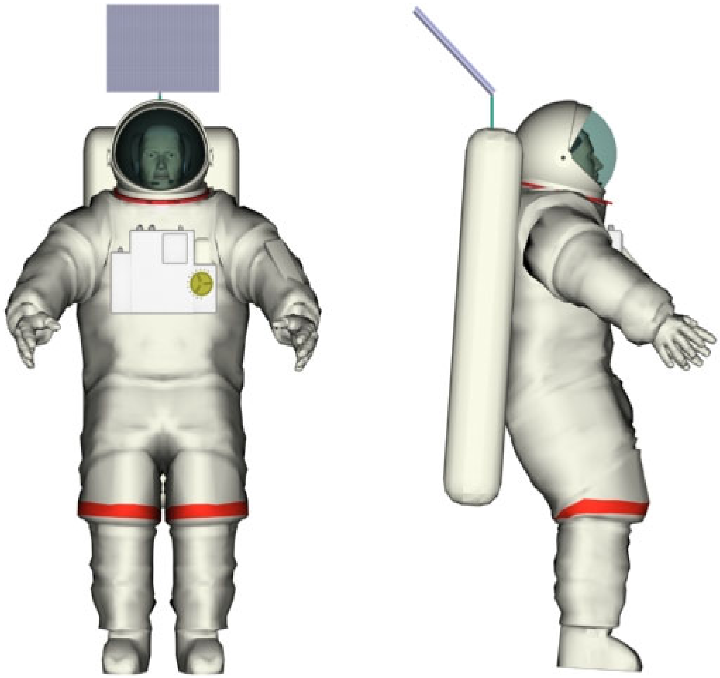
The following illustrations depict the variations of the solar panels. It should be noted that the layout of the suit mounted panels are not optimized for other considerations (equipment, switches, lines, access panels). The depicted image is more to give a sense of practical size limits. The depicted area is based on the projected area of 0.15 m^2.



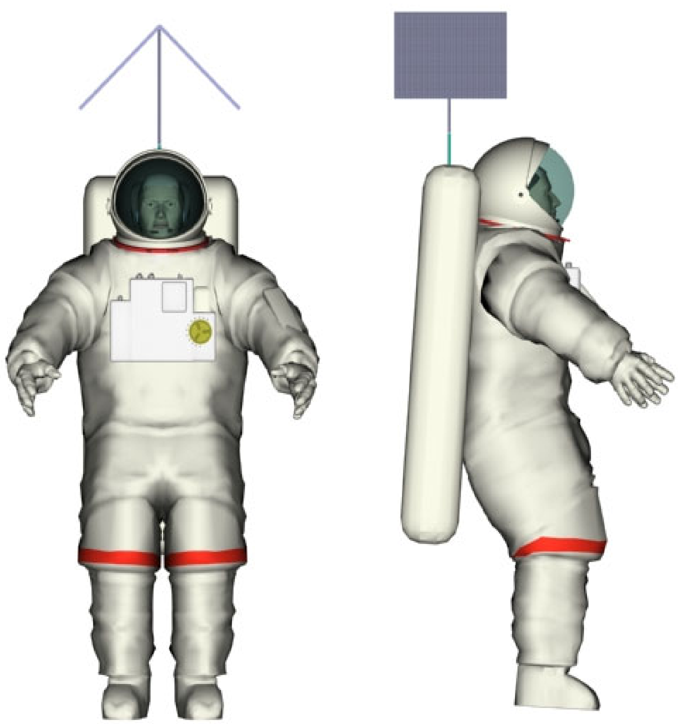
Suit Mounted Panel Option
(front and/or back)



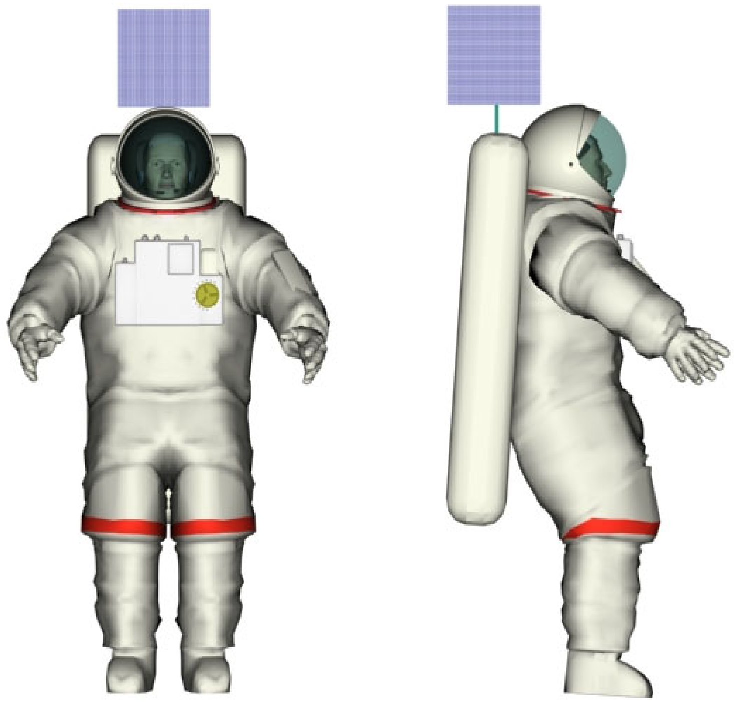
Boom Mounted Solar Panel Option
(one- or two-sided)



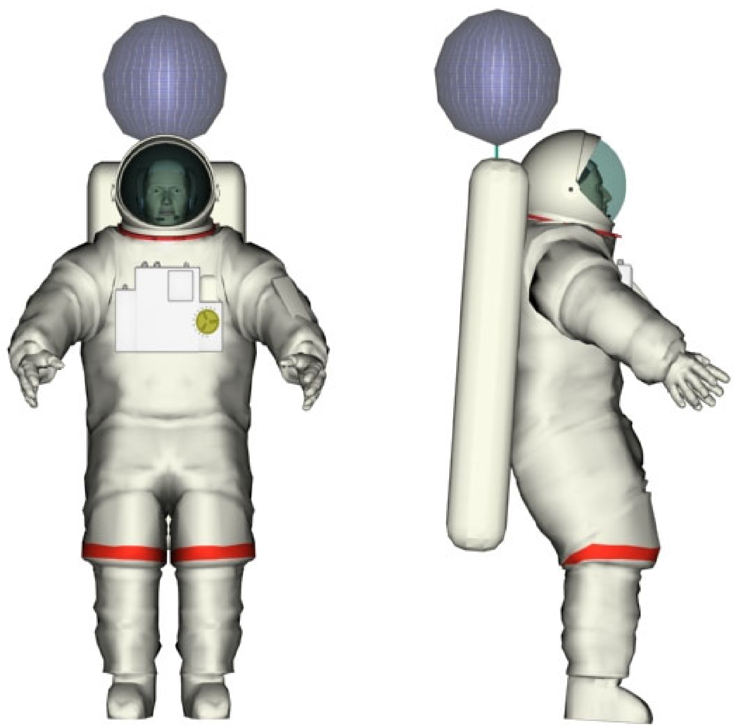
Boom Mounted Solar Panel Option
(surface operations, one-sided, 1 axis cantable prior to sortie)



Boom Mounted Solar Panel Option
(surface operations, two-sided, 1 axis cantable prior to sortie)



Boom Mounted Cube Solar Panel Option



Boom Mounted Sphere Solar Panel Option

1.6 Projected Area Assumptions

An assumed maximum projected area was used to size the solar panel. It is not known how much area is practical considering all the other uses of the surface. For all configurations, the maximum projected are for the solar panels was 0.15 m^2 (1.6 ft^2). This value was selected because it was the maximum likely coverage area for the front of the suit. Note that this ignores any other considerations for usage of the area on the suit. The projected area for the cube and sphere are the maximum possible area that the objects can show to the Sun. Thus, for a sphere of radius R, the projected area is PI*R^2.
For a cube, with side length L, the projected area is 1.5*L^2.

Note that energy losses due to shallow solar incidence angles were ignored in this study. Such losses would reduce the power level by about 5 to 10 percent.

1.7 Environment Assumptions

Key factors in sizing the solar panel include shadowing, albedo and pointing angle. The study assumed suit operations from LEO to the lower level of the radiation belt, from the upper level of the Earth's radiation belt to the Moon, on the Moon surface and on the Mars surface. Although it is recognized that these values vary continuously, in order to quantify these factors for sizing the solar panels, it is necessary to use an average estimate of these over likely averaging periods.

1.7.1 Shadow Factors

For LEO and Space operations, shadow factors are used to represent the amount of shadowing caused by the vehicle/suit passing into eclipse and the amount of shadowing due to proximity with the vehicle. For Moon and Mars operations, the shadowing is assumed to be caused by the terrain. Shadowing changes continuously based on many factors (astronaut location, orientation, time of year). It should be recognized that the shadow factor could vary from 0 to 1.0 if examined at points in time.

For LEO operations, the average time a spacecraft is in planetary shadow through the entire year is 38 percent of the time for the ISS altitude (400 km) but with 28° inclination (best for Kennedy launches and likely the value for CEV launches). The value goes down to 34 percent of the time for the lower level of the radiation belt (650 km). A conservative estimate for the amount of shadowing over an average sortie based only on eclipse shadowing is 38 percent of the time (a 0.38 shadow fraction). For some times of year and somewhat different inclinations, there are zero eclipse times, but it turns out that this is infrequent (the worse case is 39 percent). For shadowing due to hardware, it is assumed that the suit/astronaut is blocked from the Sun only about 25 percent of the time (of the insolation time period) due to the fact of being in close proximity to a large spacecraft (a 0.25 shadow fraction). This is somewhat optimistic but difficult to model. Statistical data on whether the astronaut suit is in insolation during an EVA is not available and the CEV vehicle orientation and configuration unknown. The total (a 0.63 shadow fraction) provides the estimate for the LEO operations shadow factor.

For In-Space/beyond LEO operations (i.e., translunar transit), the eclipse time would be negligible thus the only shadowing would still be due to the hardware (0.25). This same value could be used for In-Space use to Mars.

For Moon and Mars operations, it is assumed that shadowing due to terrain (boulders) and hardware occurs for no more than 10 percent of the time on average, thus the shadow factor is 0.10. Implicit in this assumption is the exclusion of any analysis cases where the astronaut is located in eclipse exclusive environments (craters, dark side or night operations).

1.7.2 Albedo Factor

The albedo factor is a measure of the amount of solar energy that is diffusely reflected from surrounding surfaces near the astronaut. This term is an average albedo over time during insolation.

For LEO operations, albedo energy comes from two sources: the Earth and the spacecraft. For the Earth this is assumed to be 0.2 at the ISS altitude (this is the fraction of albedo energy from the Earth surface albedo, 0.37, to reach a flat plate pointing at Earth at the ISS altitude). This must be adjusted during energy calculations using the pointing factor to account for random orientation of the astronaut (panel) with respect to the energy source. Note that for orbital in space EVA around the Moon, the albedo value of 0.03 is appropriate for 100km orbit, but since this is so small, it is assumed zero (equivalent to the albedo value outside the Earth's radiation belt and between the Moon and Mars orbit).

Spacecraft albedo energy depends on the thermal properties of the exterior of the vehicle. White paint would reflect 75 percent of the light and black paint 3 percent with a variety of materials ranging between these extremes. For this analysis 0.75 was assumed.

For non-LEO In-Space operations, the albedo only comes from the spacecraft and has the value as above. For Moon surface operations, the assumed average albedo is 0.07 (obviously it is higher and lower depending upon location). For Mars operations, the accepted average albedo is 0.15.

For surface operations, spheres are assumed to gather albedo from a hemispherical area and cubes gather this energy from three sides.

As an application note, it should be noted that just as with solar energy, the orientation of the panel with respect to the Sun is critical in determining the amount of solar energy that can impinge upon the solar panel, the same applies to the albedo energy. However, to determine the average albedo energy onto the solar panels, both the random orientation of the panel with respect to the hardware/vehicle surface and the random orientation of the hardware to the Sun must be accounted for (such pointing factors are described in the next section).

1.7.3 Pointing Factor

Pointing factor is the average of the cosines of the solar panel unit normal vector from the Sun vector. It is the average projected area divided by the maximum projected area (i.e., the maximum possible area that can see the Sun if one re-orients the object). This is used to account for random orientation of the astronaut during nominal operations. For any in-space operation, the likely orientation of a flat panel with respect to the Sun is any combination of rotations about the X and Y astronaut axis. These cannot be known beforehand, thus averaging is required. For any surface operations, the astronaut is assumed to randomly rotate about his local vertical axis (although it is known some bending is performed, this is assumed to be infrequent).

For in-space operations, the calculated pointing factor for one sided panels is 0.2. For two sided panels, it is 0.4. For a solar panel cube, it is 0.8. For a solar panel sphere, it is 1.0.

For Moon surface operations, it is assumed that the likely rotation of the astronaut is about the local vertical axis and this axis depends on the latitude and longitude of the astronaut. The solar angle to the surface changes little during a sortie. The flat solar panel(s) are assumed to be manually cantable prior to the sortie to be at the best orientation. At lunar noon at the equator, the cant angle is 90° (with reference to the vertical axis of the astronaut suit). At lunar noon at the poles (or 90° anywhere from the equator case), this angle is 0° (parallel to the vertical axis of the suit). This angle is all that is needed to define the orientation of the Sun with respect to the Moon and the sortie location. Thus, it is possible to examine the entire range of sortie locations without defining them by time of month, latitude or longitude. For a cant angle of 90°, the one sided flat panel has a pointing factor of 1.0. At 0° cant angle, the other extreme is encountered (0.32 for the one-sided flat plate). The pointing factor at 0° cant is 0.64 for a two-sided flat plate and 0.85 for the solar panel cube. Regardless of location on the Moon, the pointing factor for the solar panel sphere is 1.0.

For Mars surface operations, the conditions are similar to the Moon except that the solar angle to the surface changes considerably during a long sortie (~8 hr) on Mars (a "typical" day/night cycle versus the Moon's month long day/night cycle). For these analyses, it is assumed that the solar angle or time of day does not change during the sortie. Therefore, the pointing factor will be the same as in the Moon cases.

Other cant angles different from 0 and 90° were not presented in this report because 0 and 90 provide the extreme sizing points. Usually, 90° cant angle (by the equator) provide the most energy. Depending on the results of this analysis and determination of reasonable break point (minimum percentage of mass reduction by adding solar augmentation), future assessments at other cant angles can be used to map viable locations to use solar augmentation.

1.8 Operational Assumptions

The main trade study was performed assuming a nominal power level of 200 W were required for a time of 8 hr. Sensitivity analysis for a selected power system configuration was performed for 100 W for 2 hr, 150 W for 6 hr and 200 W for 8 hr.

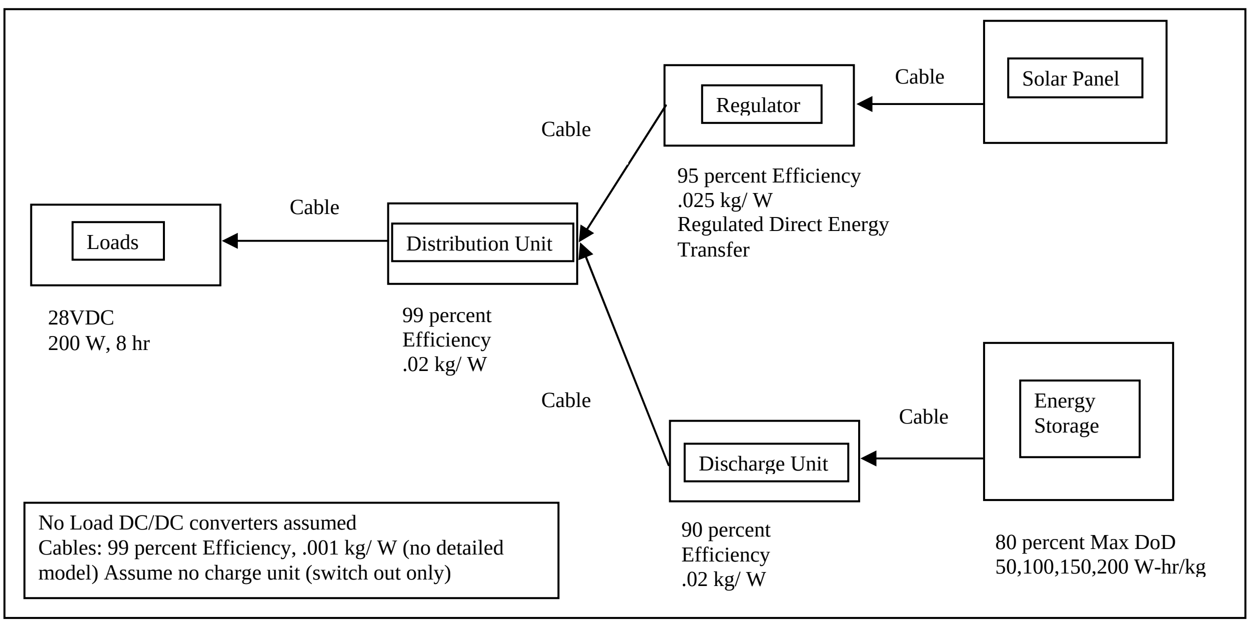
The contingency power level was assumed to be 60 W for 30 min met by a primary energy storage system of 220 W-hr/kg.

It was assumed that the EVA suit power/energy storage system was only used when separated from other power sources such as a rover. Thus, the energy storage time is referenced from that time of total separation. Otherwise, it can be assumed the EVA suit draws upon the power of the rover or other translation vehicle in order to extend the traverse capability.

The main energy storage system was assumed to have an 80 percent depth of discharge regardless of whether it could possibly discharge further because realistic operational limits do not allow EVA to be extended to the last watt-hr of energy.

1.8.1 Electronics Assumptions

The battery discharge unit efficiency was sized for a regulated bus. The solar panel electronics/regulator was assumed to be a regulated direct energy transfer (results in lower than 100 percent efficiency in utilizing the solar power because of inadequacy in matching the peak power point on the cell I-V curve).



1.8.2 Other Masses

Thermal masses were estimated to be 0.01 kg/ W for the energy storage part of the power system. For the boom mounted options, the solar panels are assumed to be thermally connected (e.g., cross straps) to permit thermal radiation from the noninsolation surface to help keep the cells at lower temperatures. For suit mounted options, either the panel is thermally connected to the suit or additional solar panel area is needed for inter-cell radiative surfaces. The thermal mass for the solar part of the power system (related just to the solar panels) was assumed to be 20 percent of the solar panel mass.

Structural masses for the energy storage system were assumed to be 10 percent of the mass of the entire power system. The structural mass (used to attach the solar panel to the suit or support the solar panel: the pole or mechanism) for the solar part of the power system was assumed to be 20 percent of the solar panel mass.

1.9 Calculation Method

To perform these calculations, standard solar panel and energy storage sizing relationships were used. The baseline cases assumed hypothetical energy storage systems of 50, 100, 150 and 200 W/kg. The reason for this is that the goal of this trade study is to find the point at which the solar panel mass is lower than the mass of the energy storage that is no longer needed because of the solar panels. It is recognized that some energy storage will be needed, but that solar arrays could reduce that need and that there is a trade-off in generation versus storage.

Margins were not considered in this analysis. Typical values of margin for either power or mass estimates are 20 percent.

1.10 Results

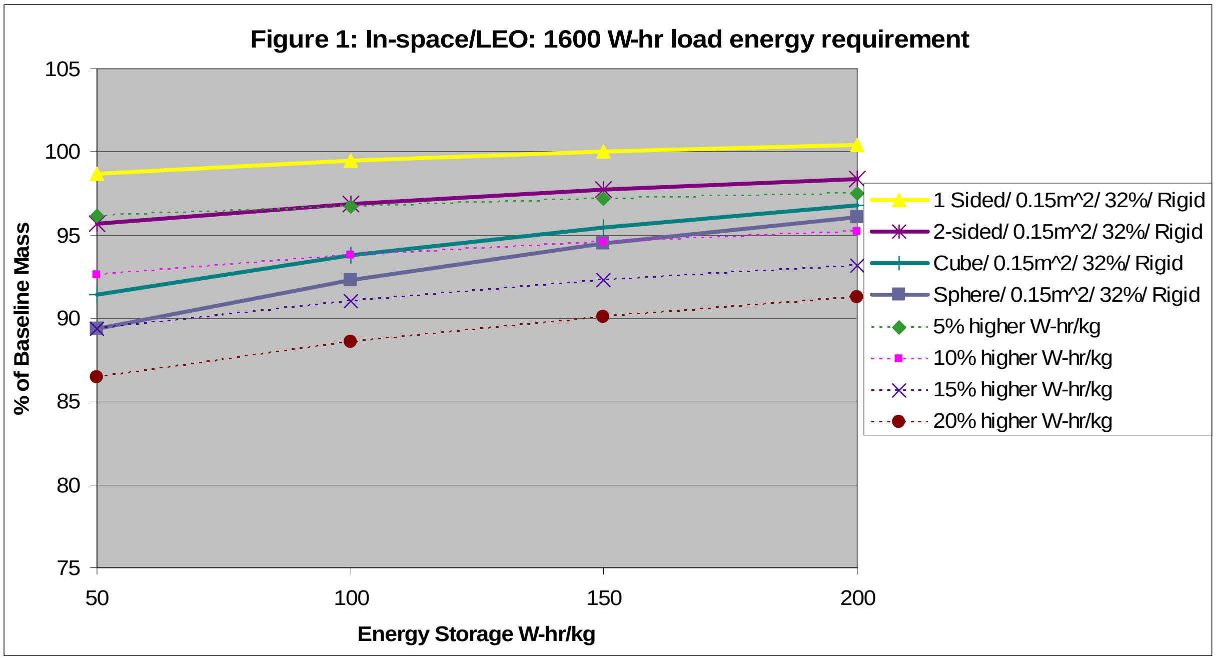
Figure 1 shows the results for the EVA suit based on near term technology for use outside the spacecraft in low Earth orbit operation below the Earth radiation belt (i.e., minimal coverglass/shielding). These assume that the rigid panel, 32 percent solar cells are all that will be available in the time frame. This figure shows the relative mass savings from the total baseline non-solar power system mass estimate. The horizontal axis has the various assumed energy storage specific energy values. If one assumes the current EMU lithium (Li) polymer battery is the state of art value for W-hr/kg, then 100 W/kg and above should be the range of likely application. The best savings in total power system mass (using a spherical solar panel) is 8 percent. However, the near term projection for Li polymer batteries is 200 W-hr/kg (based on NASA's, "Energy Storage Technology for Future Space Science Missions"). This reduces the maximum benefit to 4 percent.

The four dashed lines are used to illustrate the benefit of simply improving the standalone baseline energy storage system by various percentages rather than invest resources into solar augmentation. The baseline energy storage specific energy (as shown on the horizontal axis) was increased by 5, 10, 15 and 20 percent to create an improved energy storage system to which the baseline was compared. Examination of these lines shows that by improving the current EMU Li polymer battery (100 W-hr/kg) by about 13 percent in specific energy equals the benefit of adding the spherical solar panel.

Figure 2 shows the parametric variation of projected solar panel surface area for the EVA suit based on 32 percent efficient cells with spherical, rigid solar panels for use outside the spacecraft in low Earth orbit operation below the Earth radiation belt (minimal coverglass/shielding). Although the maximum likely projected area is 0.15 m^2, this chart shows that increasing the area by about 50 percent improves by about 4 more percentage points from the baseline mass (for the 100 W-hr/kg energy storage). Higher energy storage specific energies provide even less improvement.

Figure 3 shows the effect of the load power requirement and the duration of the load on the sizing of the solar augmented power system. Clearly, lower power levels are better suited for the solar augmentations than higher power levels and longer durations provide more benefit than short. The 100 W-hr/kg energy storage mass improves 8 percentage points from the baseline when going from high power (200 W) to low power (100 W) sizing for 8 hr load duration. This improvement is only 5 percentage points when the load duration is about 4 hr. For higher specific energy storage systems, the improvements for going to lower power level are less than 5 percentage points.

Figure 4 shows the results for the EVA suit based on near term technology for use outside the spacecraft between geosynchronous orbit altitude and the lunar orbit (i.e., beyond the Earth's radiation belt, thus requiring thicker coverglass/shielding). These cases assume the use of a rigid panel with 32 percent solar cells. This figure shows the relative mass savings from the total baseline non-solar power system mass estimate. The horizontal axis has the various assumed energy storage specific energy values. If one assumes the current EMU Li polymer battery is the state of art value for W-hr/kg, then 100 W/kg and above should be the range of likely application. The results are improved beyond the LEO In-Space power system primarily due to eclipse shadowing considerations. The best savings in total power system mass (using a spherical solar panel) is 13 percent. However, for the near term projection for Li polymer batteries, 200 W-hr/kg, the maximum benefit is 9 percent.



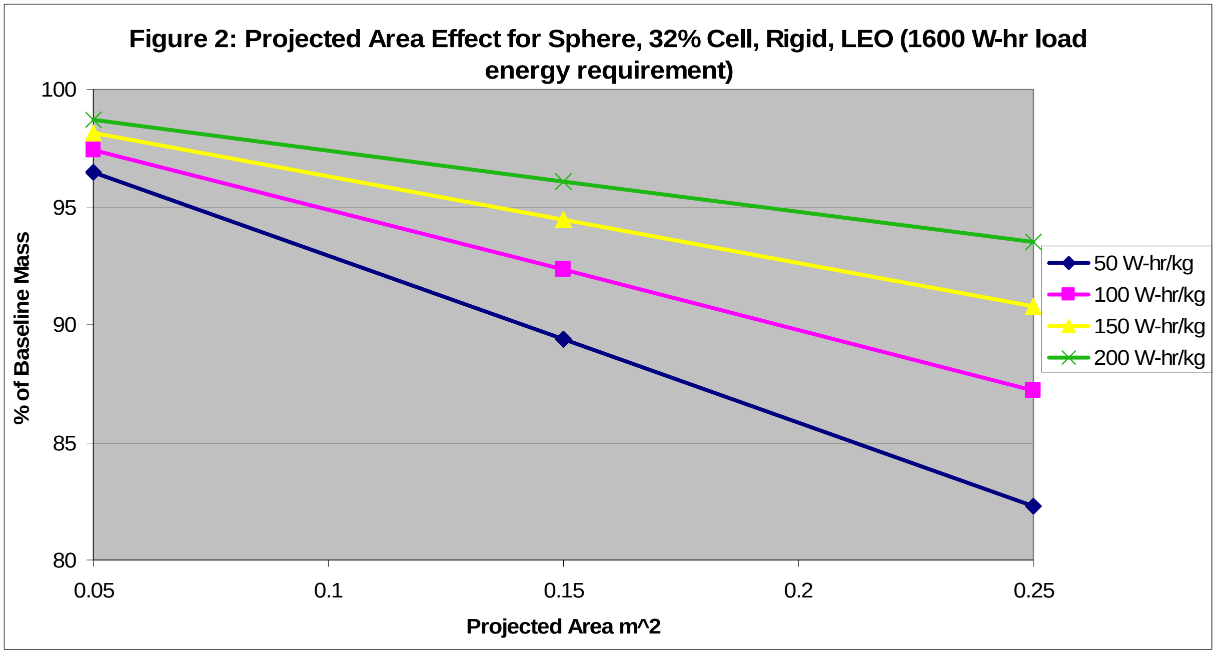


Figure 3: Load Level and Duration Effect on Spherical Solar Panel (32% cell, rigid, .15m^2 projected area, LEO)

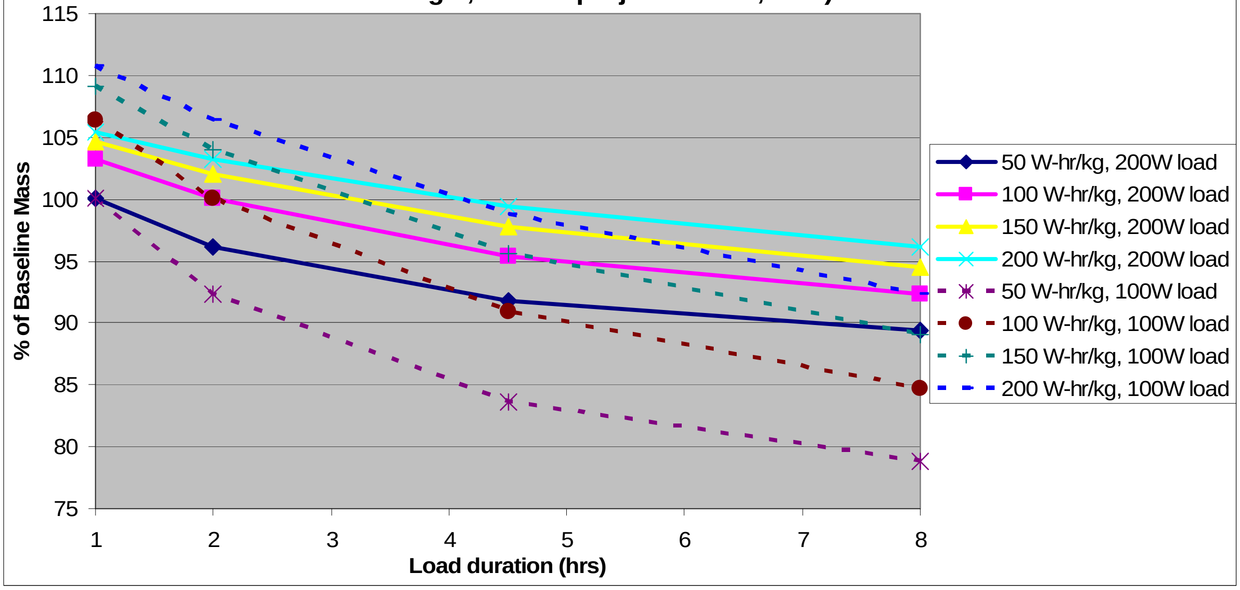
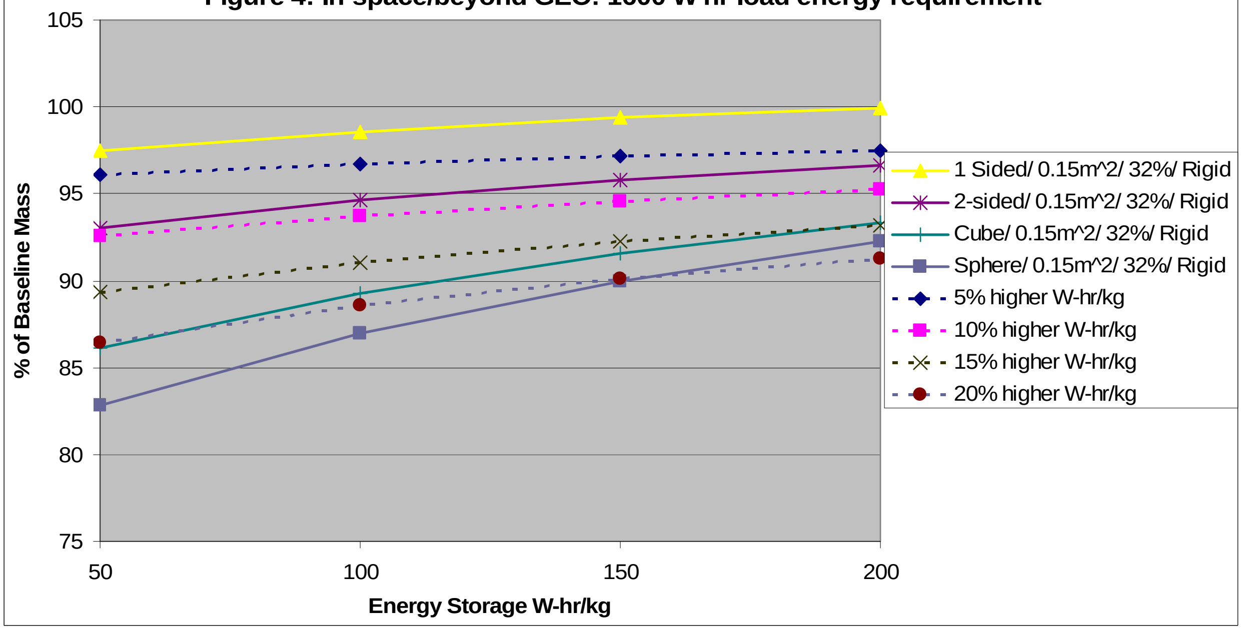


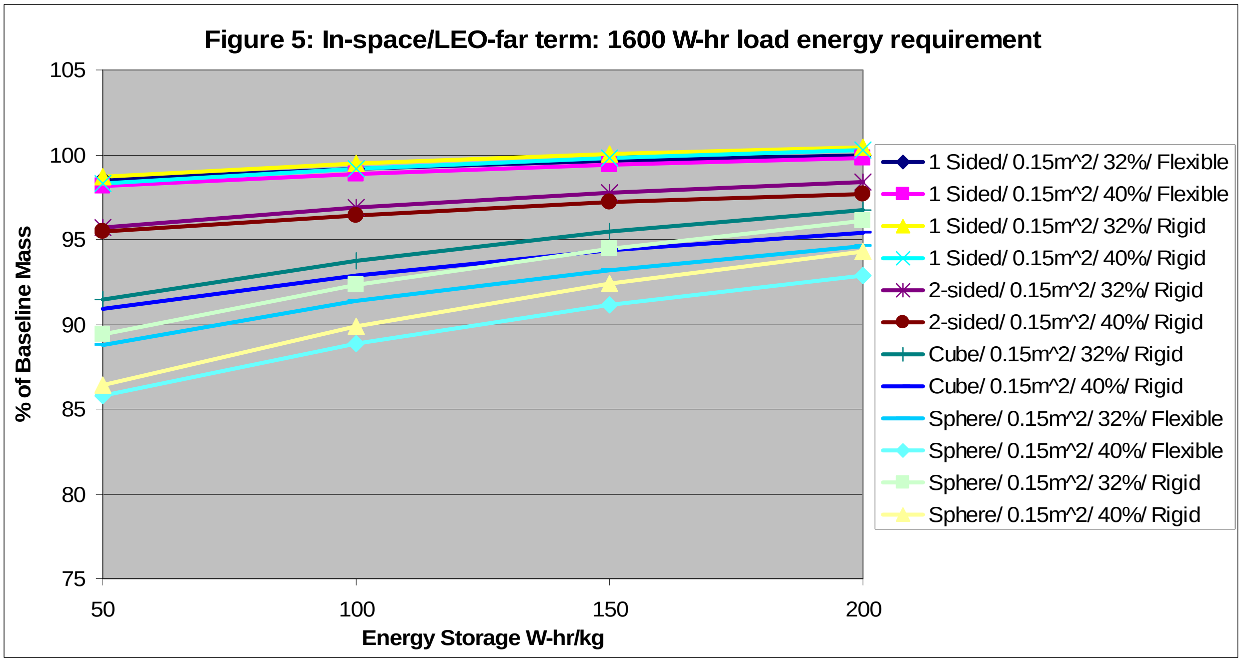
Figure 4: In-space/beyond GEO: 1600 W-hr load energy requirement



The four dashed lines are used to illustrate the benefit of simply improving the standalone baseline energy storage system by various percentages rather than invest resources into solar augmentation. The baseline energy storage specific energy (as shown on the horizontal axis) was increased by 5, 10, 15 and 20 percent to create an improved energy storage system to which the baseline was compared. Examination of these lines shows that improving the current EMU Li polymer battery (100 W-hr/kg) or an equivalent energy storage system by about 25 percent (by extrapolating the curves) in specific energy equals the benefit of adding the spherical solar panel.

Figure 5 shows the results for far-term mass benefits of using advanced solar cell and solar panel technologies for low Earth orbit in-space application. State of the art (near term) data is provided for comparison. Assuming the current EMU Li polymer battery (100 W-hr/kg), then maximum benefit is 11 percent. For the 200 W-hr/kg energy storage, this benefit is 7 percent.

Figure 6 shows the far-term mass benefits of using advanced solar cell and solar panel technologies for use outside the spacecraft between geosynchronous orbit altitude and the lunar orbit (i.e., beyond the Earth's radiation belt, thus requiring thicker coverglass/shielding). State of the art (near term) data is shown for comparison. Assuming the current EMU Li polymer battery (100 W-hr/kg), then maximum benefit is 18 percent. For the 200 W-hr/kg energy storage, this benefit is 12 percent.



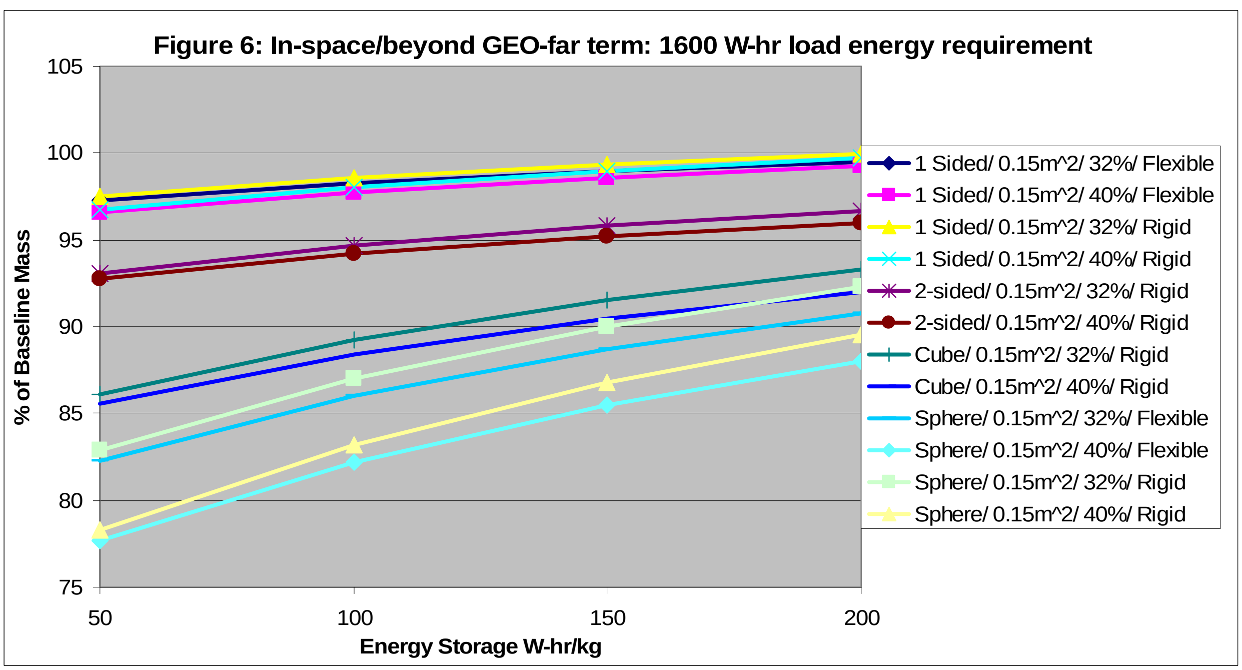
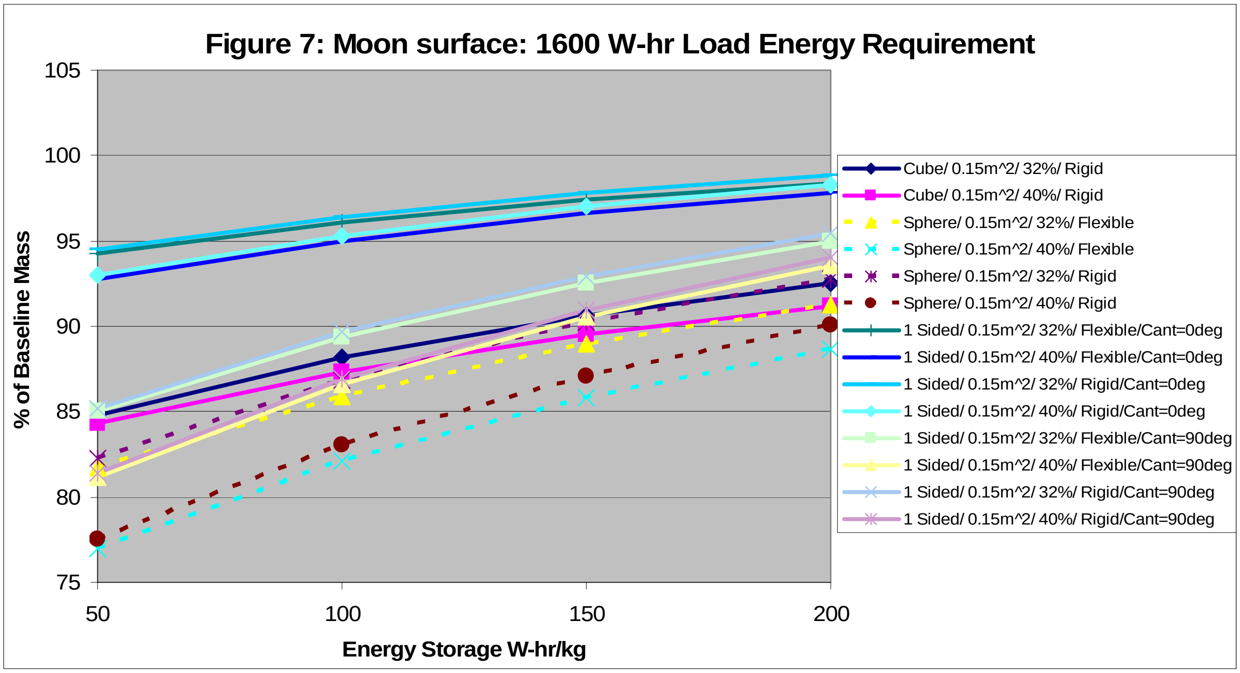
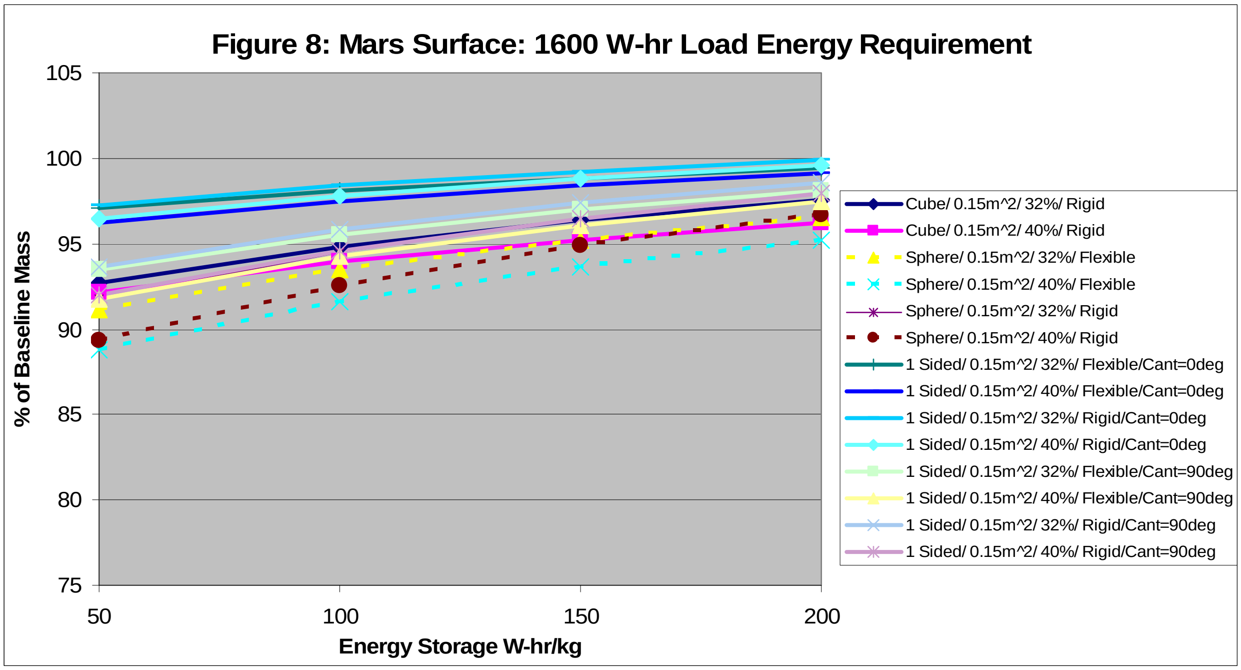


Figure 7 shows the Moon surface operations mass benefits of using advanced solar cell and solar panel technologies (as well as the state of art). Two cant angles (reflecting different locations on the Moon and times of year) are shown for the flat panel cases. A 90° cant is for noon at the equator and a 0° cant is for polar operation. Assuming the current EMU Li polymer battery (100 W-hr/kg), then maximum benefit is 18 percent. For the 200 W-hr/kg energy storage, this benefit is only 11 percent.

Figure 8 shows the Mars surface operations mass benefits of using advanced solar cell and solar panel technologies (as well as the state of art). Two cant angles (reflecting different locations on the Mars and times of year) are shown for the flat panel cases. A 90° cant is for noon at the equator and a 0° cant is for polar operation. Assuming the current EMU Li polymer battery (100 W-hr/kg), then the maximum benefit is 8 percent. For the 200 W-hr/kg energy storage, this benefit is 5 percent.





Note that all in-space operations were not considered. The suit power system will likely have requirements for Venus swing-by (near Venus orbit distance) and have higher solar energy possibilities. There may be operational restrictions on EVAs (shadow side of vehicle?). The data presented for the power system for in-space use are applicable only to the near Earth orbit (i.e., 1 AU). Other analyses are needed for Venus and Mars orbit operation extremes.

The only metric considered at this time was overall power system mass because this is main driver in considering solar augmentation to the power system.

1.11 Conclusions

Solar augmentation may provide as much as 8 percent for LEO and 13 percent for beyond GEO In-Space suit power system mass savings over an all-energy storage power system (assuming a minimum of 100 W-hr/kg energy storage is available for the near term). A far-term in-space suit has the potential of 7 percent for LEO and 12 percent for beyond GEO/near 1 AU (assuming 200 W-hr/kg energy storage is available for the mid to far term).

Solar augmentation can provide as much as 11 percent for the Moon surface suit and 5 percent for the Mars surface suit power system mass savings over an all-energy storage power system (assuming a minimum of 200 W-hr/kg energy storage is available, which is assumed possible for the mid to far term).

Because the benefit of using solar augmentation relative to a likely all-energy storage power system is relatively low and since improvements in energy storage can likely outpace any benefits of using solar energy in this application, it is not considered feasible to use solar augmentation for the EVA suit for near term applications. If the benefit of using solar augmentation had been at least 25 percent, then it may have had merit for practical application. Although it is possible that some benefit exists for using solar augmentation in the mid to far term surface suit applications, the technology pathway for applicability to Mars operations is not viable (due primarily to the reduced solar illumination).

In addition to these quantitative analyses, solar augmentation for the advanced EVA suit has numerous fundamental issues that discourage its use.

1) Operation during Lunar or Mars night or for long periods in craters or where high shadowing occurs obviates the use of solar panels.

2) The desire to be able to conduct mission planning with guaranteed power and energy levels is enhanced with fixed energy storage rather than fluctuating solar power. One cannot plan a mission on averages and estimates of solar power, one plans a mission based on fixed power. If the desire is to simply have “extra” energy beyond which you ***really*** need, then solar may be acceptable.

3) Suit complexity is increased significantly when both energy storage and energy generation are used. This reduces reliability and increases number of spare parts required as well as net development and life cycle cost.

4) Inability to have significant areas of solar cell coverage on the suit will reduce likely power levels from the optimistic projected area assumed in this trade study.

5) Clearance and ergonomic issues with pole mounted options imply this approach is infeasible, even though desirable from a power viewpoint.

6) High probability of damage of pole mounted options for in-space use likely prohibits their use (surface use only!).

1.12 Additional Information: Tracking Solar Panel Concept

After the main analysis of this report, another option was devised in which a one sided solar panel was deployed on a boom and articulated on two axes using gimbal drives. The concept used derivative Moog drives and required special gimbal pointing and control electronics. The concept assumed that perfect pointing was not needed (20° accuracy). The back of the panel would be used for solar panel heat rejection.

Results revealed that the penalty of power usage by the gimbal drives (which had to continuously aim at the Sun even with rapid astronaut movement) and electronics combined with the extra mass of these items made it less competitive than “fixed” cube and sphere solar panel options.

1.13 Additional Information: Solar Fiber Concept

Initially, a concept using a new technology of solar energy generating fibers woven into the astronaut suit was omitted from this study as impractical due to 1) low inherent efficiency, 2) unknown fiber durability (since they would be in high wear areas), 3) unknown fiber resistance to space environment (not space rated or qualified), 4) dust effects on energy reduction (especially on lower extremities), 5) maintenance complications (cleaning suit without damaging solar fibers), 6) thermal effects (cannot cover whole suit with fibers without increasing thermal load) and 7) lack of viability for technology pathway to Mars surface operations (inadequate solar energy for low efficiency fibers and limited suit area). However, this option will be reconsidered in the future given adequate technology projections of fiber efficiency.

2.0 Trade Study 2: Comparison of Localized and Centralized Power System Options for the Advanced EVA Suit

Date: August 25, 2005

2.1 Results Summary

The conclusion of the trade study was that only small total power system mass benefits (<11 percent) were possible with the localized power system option. The mass actually increases for the localized power system option when these systems are required to have maximal commonality (to reduce mission logistics mass/cost). Mass and volumetric concerns (at hands and feet) also limit the localized option to lower power levels and shorter durations. Centralized power system/energy storage with power distribution cables is the best option for a combined metric of total power system mass, hand/foot volume and mass, and logistics. A recommendation is made of minimizing unique power distribution cables for the centralized power system option by connecting fixed segments (~0.5 m) to reduce spares inventory and logistic cost.

2.2 Introduction

The purpose of this trade study is to evaluate the benefits of distributing the power systems/energy storage throughout the suit to specific regional sites instead of using a centralized energy storage system with power distribution cables.

This study does not consider the energy “redistribution” between the various localized energy sites (i.e., to enhance reliability and perform load sharing). The reason for this is that, qualitatively, it makes more sense to enhance reliability of a centralized energy storage site that runs the critical loads than depend upon complex switching and cabling needed to re-route energy throughout the suit. The other problem is that there would be too many fault propagation issues due to complex distribution topologies which would require detailed analysis to address.

This study also does not consider the distribution of power to many sensors via wiring or RF or other means. It is assumed that such wiring/powering methods are handled downstream of the power system/energy storage units.

2.3 Assumptions

Table 1 shows a listing of the assumptions and variables used for this trade study.

In order to perform this analysis, a DC power distribution cable design spreadsheet was modified to enable cable mass optimization/sizing of various power levels and cable lengths. Cabling and wires for instrumentation and control were excluded from consideration because of lack of definition of these elements. The power cables were designed with filler fibers to assist to strength, coatings/sheath/insulation to protect from shorting/wear/micrometeorites, and connectors. All distribution cables assume two separate power wire pairs (positive and ground) and a backup redundant wire pair (assumed manually switchable). Copper cable wires were assumed because copper optimizes to be a slightly lower mass than aluminum for this application. An insulator safety factor was assumed to assure adequate shorting protection. A cable power safety factor was applied to the peak power level to adequately size the wires. It was assumed that fuses activate past that maximum design power level to eliminate damage to the cable and loads. DC-DC converters used to provide low voltage regulated power for electronics applications (representing a small portion of site power) were included at each power load site. Note that specific powers (i.e.,W/kg) are applied to the input power of each component.

TABLE 1.—ASSUMPTIONS AND VARIABLES USED FOR THIS TRADE STUDY

Power System Parameters		
Voltage Type		Direct Current
Power System Voltage Level	V	28
Nominal Energy Storage Depth of Discharge	percent	80
Total Site Power Into DCDC Converter	percent	20
Nominal Energy Storage Specific Energies Considered	W-hr/kg	50,100,150,200
Energy Storage Durations Considered	hr	2,8
Total Load Levels Considered (Exact sized only)	W	100,200
Cable Parameters		
Cable Wire Material		Copper
Cable Wire Density	gm/cm^3	8.9
Cable temperature	K	279
Cable Power Safety Factor		2
Number of Redundant Cable Pairs/Transmission Line		1
Cable Jacket Filler Density	gm/cm^3	1.7
Insulator Density	gm/cm^3	1.7
Cable Jacket Density	gm/cm^3	1.7
Insulation Dielectric Strength Safety Factor		2
Contingency Parameters		
Backpack Contingency Energy Storage Specific Energy	W-hr/kg	220
Backpack Contingency Energy Storage Load Level	W	25
Backpack Contingency Energy Storage Load Duration	min	30
Component Specific Powers		
DCDC Converter Specific Power	W/kg	380
Power Distribution Unit Specific Power	W/kg	50
Charge/discharge Regulator Unit Specific Power	W/kg	50
Thermal System Specific Power	W/kg	100
Nondistribution Cable Specific Power	W/kg	1000
Component Efficiencies		
DCDC Converter Efficiency	percent	90
Power Distribution Unit Efficiency	percent	99
Charge/discharge Regulator Unit Efficiency	percent	90
Mass Estimation Parameters		
Connector Mass (Percentage of Cable Mass)	percent	10
Energy Storage Structure (Percentage of Energy Storage Mass)	percent	10
Other Power System Structural Mass (Percentage of the DCDC and cable masses)	percent	10

The thermal energy system specific power (for its mass sizing) was based on the maximum power level encountered during the mission timeline. Cable masses internal to the power systems (e.g., between the distribution assembly and charge/discharge unit and between the charge/discharge regulator unit and the energy storage unit) which were not primary power distribution cables were assumed to have a non-optimized mass based on a fixed specific power. The only emergency energy storage was for the suit back load location.

Table 2 shows the power level and cable distance for each of the load sites.

These sites were divided into the following regional locations: left hand, right hand, left foot, right foot, helmet (top), suit front (chest) and backpack. Thus, for a centralized power system, the power distribution cables would extend only to these particular locations. Loads (sensors, heaters, computers and lights) nearest a region were assumed to be powered by the same primary power distribution cable. However, the cables that go from the power system/energy source to each separate load were not considered since it is not clear at this time how many of these loads there are, what their exact power needs are and even if they may be powered without cables. This was assumed to have a negligible effect on a relative comparison because both centralized and localized power subsystems would be required to carry the same mass for powering these loads. Table 2 lists the assumed distances between the regional loads where the distance is from the center of the backpack to the furthest point for each load site. Also shown are the “maximally-common” and “reduced-commonality” power assumptions for each load site.

The power values were selected based on estimated low and high values (the medium value is derived from these extremes).

TABLE 2.—POWER LEVEL AND CABLE DISTANCE FOR EACH OF THE LOAD SITES

	Cable distance (m)	Maximally Common Energy Storage Units						Reduced Commonality Energy Storage Units					
Total Power Level (W)		100	100	100	200	200	200	100	100	100	200	200	200
Distribution Level		Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Load Location													
Left hand	1	5	10	15	10	20	30	5	10	15	10	20	30
Right hand	1	5	10	15	10	20	30	5	10	15	10	20	30
Left foot	1.5	5	10	15	10	20	30	3.5	7.75	12	7	15.5	24
Right foot	1.5	5	10	15	10	20	30	3.5	7.75	12	7	15.5	24
Helmet	0.66	5	10	15	10	20	30	1	3.5	6	2	7	12
Back	0.33	80	55	30	160	110	60	80	55	30	160	110	60
Chest	0.5	5	10	15	10	20	30	2	6	10	4	12	20

For "maximally common" remote energy storage/load sites, it was assumed that all sites other than the backpack had to have the same energy storage size/capacity (since they were likely to be similar anyway). Thus, only two unique energy storage sizes need to be inventoried. On the downside, the effect of this commonality is to oversize the local energy sources compared to what they require if "exactly" sized. For the nominal 100 W system, commonality forces the total power level to go to 110 to 120 W depending on the level of energy required at each regional site. For a nominal 200 W system, the range is 220 to 240 W.

The "reduced commonality" values were based on the assumption that the only common local power system sizes were both hand sites and both feet sites. Besides those common elements, each load site was assumed to have different and unique power requirements. Thus, this results in five unique hardware types, with the back power level highest, then the hand, foot, chest and helmet. Although it is possible that the larger energy storage/power systems (backpack) can be composed of smaller sub-elements, this aspect was considered irrelevant to this trade study.

2.4 Commonality Assessment

The concept behind commonality is that common hardware unit types enable the reduction of spares quantities. For example, for low failure rates (<1 per "tour" or "stay" or logistics supply interval or deployment), it is still required that whole replacement units for each unique hardware type be carried (not by the astronaut, but in the outpost or vehicle). For common hardware units, the fractional number of spares can be combined to whole numbers. If a power source hardware unit has a 5 percent failure rate per tour, but there is only one such unit, a whole spare must be still be carried at the base. If there are 20 **different** units with this failure rate, then 20 separate spares must be carried. However, if the 20 units are **common** rather than different, then only one spare (or perhaps up to three depending on probability models and failure distribution modes) needs to be carried at the exploration logistics supply base. Thus, launch mass and spares cost is minimized.

For the nominal centralized energy storage with distribution cable approach, there is only one nominal energy storage system (although it could possibly be subdivided in some manner for lower level repairs, this is not considered here). However, two approaches for the power distribution cables must be considered. One approach has fixed length cables for going to the hand sites, other different fixed length cables to the foot sites and other separate unique length cables for the chest, helmet and back. This means one power system type and five unique cable types must be accommodated for spares (a total of 6 unique "items" where "items" are the highest level replacement unit).

Alternatively, a higher commonality approach would be to select a fixed cable segment length which can be connected to other lengths to fit all these applications (except perhaps the backpack power cable). Thus, three .5 m cable segments could be connected to form the entire cable to a foot site, two .5 m cable segments could be connected to form the entire cable to the hand site and the remaining load sites could simply use one .5 m cable segments. This means one power system type and one unique cable type must be accommodated for spares (a total of two unique "items"). The drawback is that the "non-unique" power cables are not mass optimized for their intended application (power level) and also may have some cumbersome "slack" due to the standardized segment lengths. The former issue seems to be a minimal concern since cable mass did not vary significantly from low to high power distribution levels (<10 percent of the cable mass). The later may be a concern for total power system mass because the slack is really unneeded mass, besides being an unnecessary volume burden to deal with.

For the localized energy storage/power system sites, the reduced commonality option has five unique types (sizes) of power units and one backpack power distribution power is counted for this comparison (a total of 6 unique "items").

The maximally common option has two unique types of units and one backpack power distribution power is counted for this comparison (a total of three unique "items").

Assessing these commonality issues at a very preliminary level suggests that the two options, from a logistics point of view, which are unfavorable would be the centralized power system with unique power distribution cables (six "items") or the reduced commonality localized power system option (six "items"). The two options with good logistics characteristics are the centralized power system with segmented power distribution cables (two "items") and the maximally common localized power system (three "items").

2.5 Analysis Results

Examination of results for the nominal centralized energy storage with power distribution cables option showed that the mass of the distribution cable (external to the backpack unit) make up for between 1 to 10 percent of the total power system mass, depending upon the energy storage specific energy, power level, and load durations. Given this initial observation, it was highly unlikely that significant total power system mass savings were possible with the localized power system option (in which no such distribution cables were used).

Figure 1 shows the relative total mass of the localized energy storage units/power systems compared to the centralized energy storage/cable power distribution system. Several generic energy storage systems with assumed specific energies are shown. It is apparent that some level of mass improvement was possible by eliminating the distribution cables if the localized energy sources are not driven to be as common as possible. As much as 9 percent total mass savings was possible for low total power level and duration. Higher power levels and durations have less total mass savings (<5 percent). The greatest savings occurs for higher energy storage specific energies (because the cable mass becomes a higher proportion of the total power system mass since the energy storage mass is reduced). Total savings of less than 20 percent indicate that it is likely that the benefit of attempting to localize the energy storage is not worth the development effort of localized power sources.

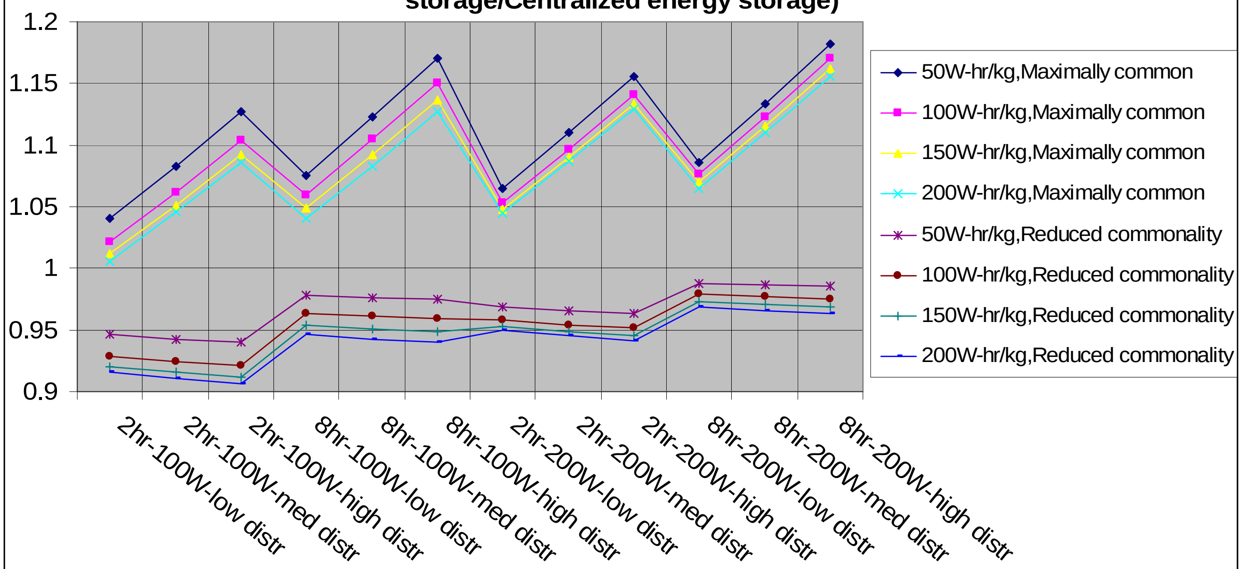
If one considers the commonality aspect, then the localized option total mass savings disappear and actually become worse than the centralized approach. Because the localized energy units would need to be made the same size to enhance the commonality (reduce logistics mass), then clearly the mass of the total power system must be greater than if the exact power requirements are used for energy storage sizing. The lower power levels and durations are least affected by variations in the energy storage units sizing. Also, the higher the specific energy of the energy storage units the lower the adverse mass penalty. Still, the unavoidable result is a higher mass of from 1 to 18 percent from the nominal centralized/power cable distribution option. This definitely indicates that it is not "advanced EVA suit mass beneficial" to have the "maximally common" localized energy approach.

Figures 2, 3 and 4, respectively, show the total power system mass at the hand, foot and helmet locations for the remotely located energy storage options. These values are preliminary estimates of mass based on many assumptions. Only the reduced commonality cases are presented because they provide the lowest mass levels (most beneficial for the advanced EVA suit mass). It is apparent that higher power levels and durations at the hand or foot sites increase the mass burden for the astronaut to carry significantly.

Excessively cumbersome masses per hand or foot are assumed to be >3 kg for lunar operation (3kg*2.2lb_earth/kg*1.0lb_moon/6.0lb_earth=1.1lb_moon) and >1.5 kg for Mars operation (1.5*2.2lb_earth/kg*1.0lb_mars/3.0lb_earth=1.1lb_mars). Based on this, a 50 W-hr/kg energy storage generally is not feasible for remotely located energy storage units unless low durations and power levels are considered (for Mars or Moon). For the more likely available 100 W-hr/kg energy storage, it is not feasible for 8 hr duration and high site power level. For Mars operation, all high site power levels exceed the desirable site masses; only lower site power levels will meet the assumed mass limit.

Figures 5 and 6, respectively, show the length of one side of a cube in centimeters of a theoretical power system at the hand and foot locations for the remotely located energy storage options. The various energy storage units (with specific energies of 50, 100, 150 and 200 W-hr/kg) have assumed specific volumes (100, 200, 300 and 300 W-hr/liter, respectively). Only the reduced commonality cases are presented because they provide the lowest mass levels and lower volume levels. The idea of the figures is to obtain a conceptual idea of the amount of movement impact of having the remotely located power units at the hand and foot sites. It is assumed that the exact shape of the units may be more conformal or thinner (if possible), a cube is the worst case shape for such a device attached to the hand or foot. The size of the power source is seen to get rather large for higher power levels and longer durations. A practical limit seems to be a volume of (9 cm^3) with rectangular or conformal shape (a cube would be infeasible due to clearances).

Figure 1: Total Power System Mass Ratio (Remotely located energy storage/Centralized energy storage)



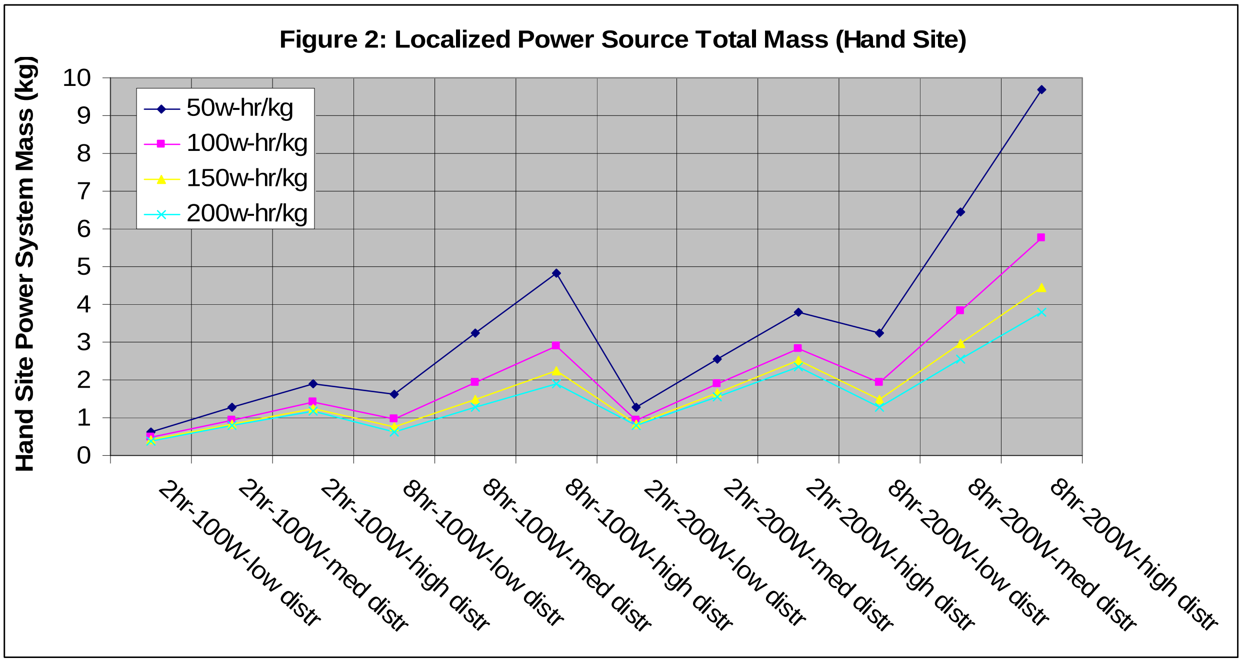


Figure 2: Localized Power Source Total Mass (Hand Site)
Hand Site Power System Mass (kg)
50w-hr/kg
100w-hr/kg
150w-hr/kg
200w-hr/kg
0
1
2
3
4
5
6
7
8
9
10
2hr-100W-low distr
2hr-100W-med distr
2hr-100W-high distr
8hr-100W-low distr
8hr-100W-med distr
8hr-100W-high distr
2hr-200W-low distr
2hr-200W-med distr
2hr-200W-high distr
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8hr-200W-high distr

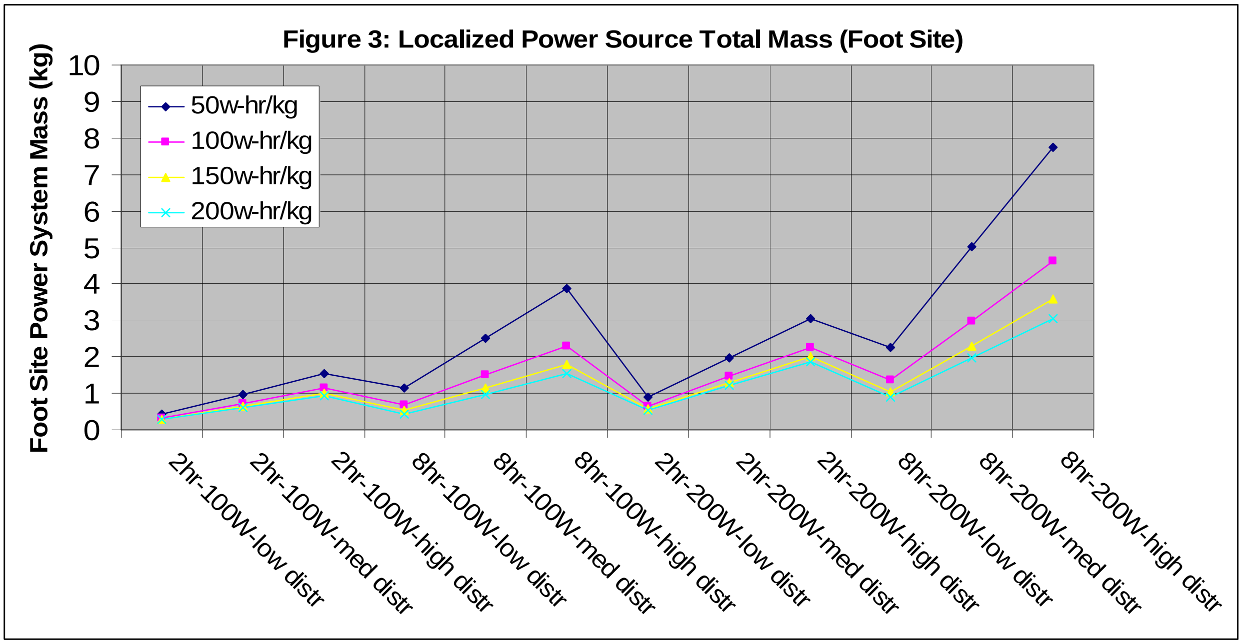
Figure 3: Localized Power Source Total Mass (Foot Site)
Foot Site Power System Mass (kg)
50w-hr/kg
100w-hr/kg
150w-hr/kg
200w-hr/kg
0
1
2
3
4
5
6
7
8
9
10
2hr-100W-low distr
2hr-100W-med distr
2hr-100W-high distr
8hr-100W-low distr
8hr-100W-med distr
8hr-100W-high distr
2hr-200W-low distr
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8hr-200W-high distr

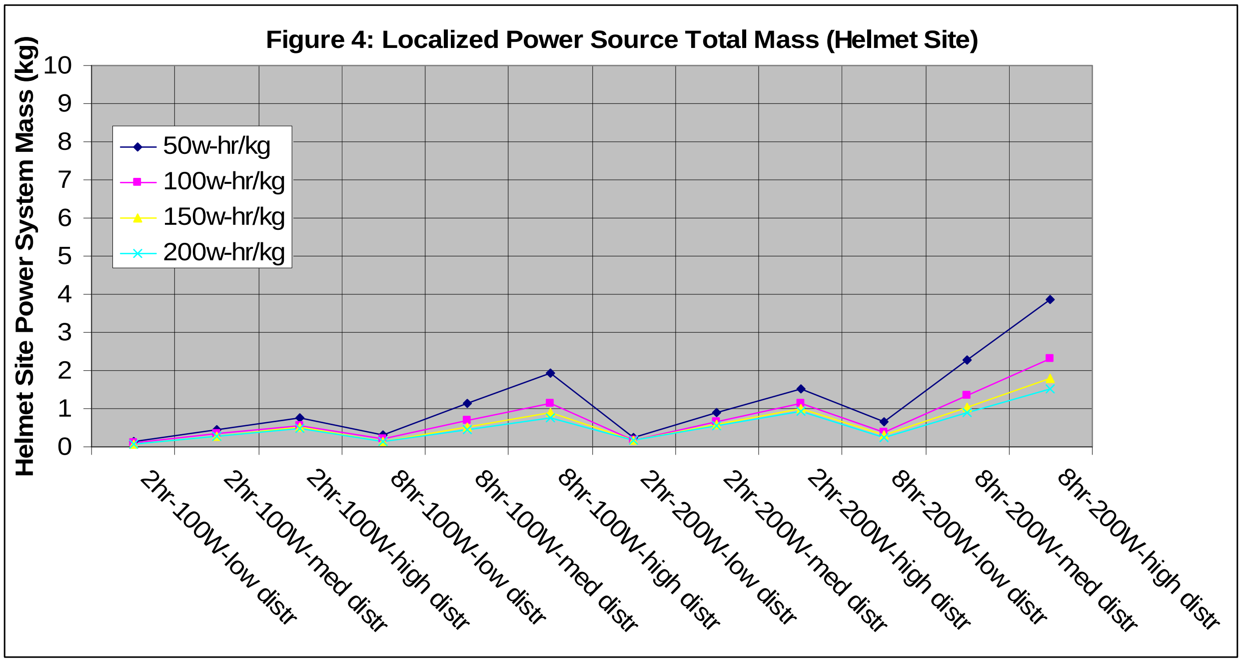
Figure 4: Localized Power Source Total Mass (Helmet Site)
Helmet Site Power System Mass (kg)
10
9
8
7
6
5
4
3
2
1
0
50w-hr/kg
100w-hr/kg
150w-hr/kg
200w-hr/kg
2hr-100W-low distr
2hr-100W-med distr
2hr-100W-high distr
8hr-100W-low distr
8hr-100W-med distr
8hr-100W-high distr
2hr-200W-low distr
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8hr-200W-high distr

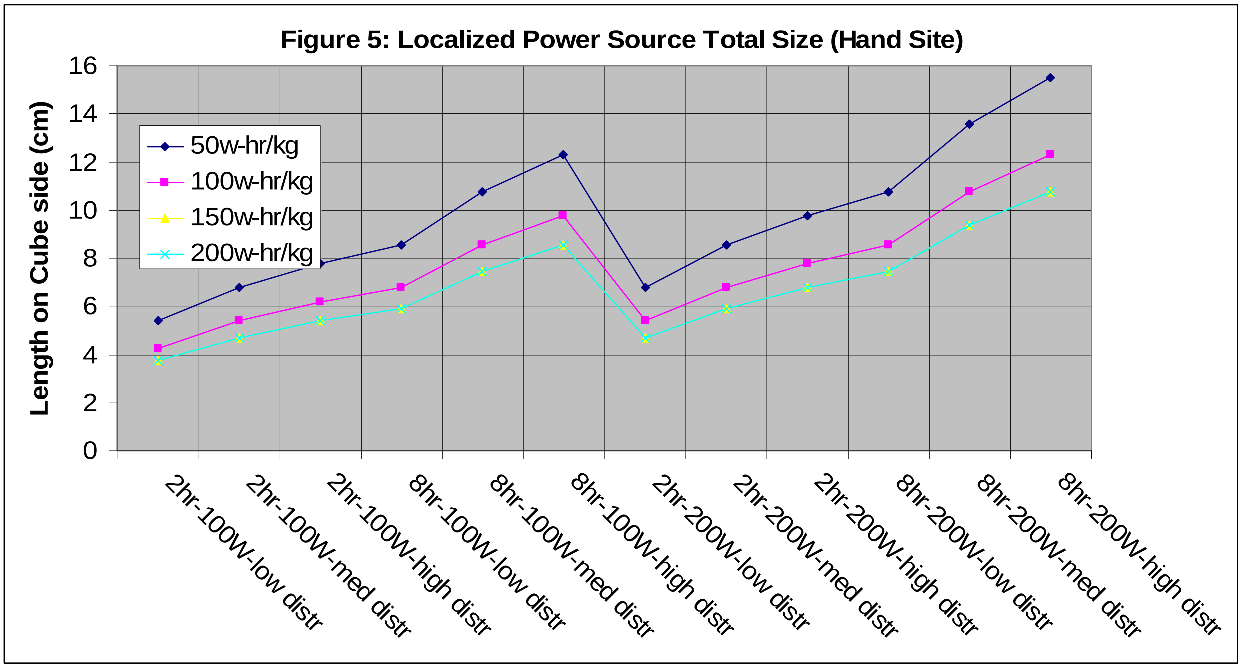
Figure 5: Localized Power Source Total Size (Hand Site)
Length on Cube side (cm)
16
14
12
10
8
6
4
2
0
50w-hr/kg
100w-hr/kg
150w-hr/kg
200w-hr/kg
2hr-100W-low distr
2hr-100W-med distr
2hr-100W-high distr
8hr-100W-low distr
8hr-100W-med distr
8hr-100W-high distr
2hr-200W-low distr
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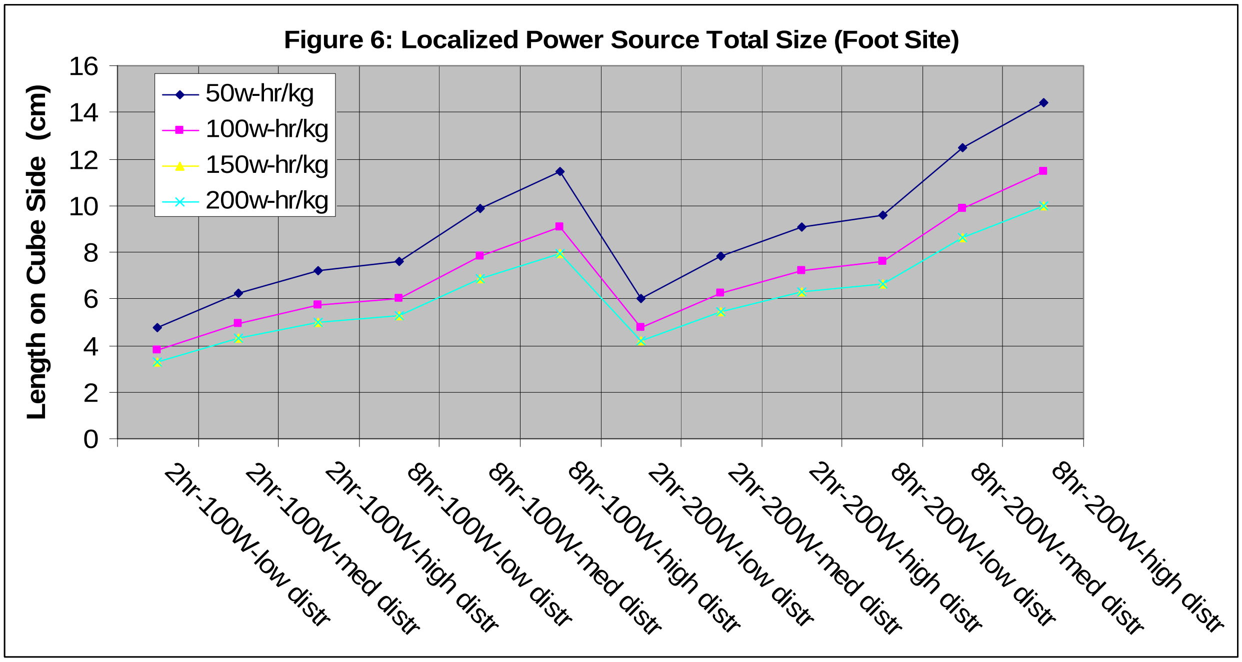
8hr-200W-high distr



Figures 7, 8 and 9 shows a 3D model with three sizes of cube: 3, 9 and 16 cm. Clearly the size becomes cumbersome above (9 cm^3). Figure 9 is indicative of the volume for long duration, high power and low specific energy storage/specific volume.

Examination of the sensitivity of the total power transmission cable mass to various power cable safety factors (i.e., oversizing the wire for much higher loads than planned on) showed that increasing the factor from 2 to 3 increased the total cable mass by about 10 percent. A power cable safety factor of 2 was felt to be justified given the current knowledge of the site load levels.

During power distribution cable mass optimization, the wire gauge was allowed to be as small as AWG 38 (0.010 cm diameter wire) for very low power loads to AWG 19 (.091 cm diameter) for the higher power loads (typically the backpack). The average wire gauge for the power distribution cables to the hand and foot sites was AWG 30 (0.025 cm diameter). The wire mass optimizer can be set to have a minimum allowable wire gauge. When the limit to the wire diameter was set to AWG 22 (.0643 cm diameter), the total mass of the centralized power system with distribution cables increased 0.1 to 2.5 percent (depending on the case). Figure 10 shows the total power system mass comparison when the wire diameter was limited (compare with Fig. 1). The primary difference is that it is clear that fixing the wire radius to AWG 22 causes a plateau of cable mass, thus the exact power level at the distribution site no longer affects the result (as long as the total power level is the same). Also, for the lowest distribution power/duration and high specific energy storage units (case 2-hr-100 W-low distributed power level), the high commonality remotely located option is lower than the centralized option. This indicates that larger minimum wire radius limits may make the remotely distributed energy option lower mass than the centralized energy option, although it will likely never save the groundruled amount of 20 percent of total power system mass (to make the approach worth the effort and risk). Even for the reduced commonality remote distributed energy option, which already are lower in mass than the centralized energy option, although there is a slight improvement in the total power system mass, the 20 percent total power system mass savings groundrule is not met (a maximum reduction of 11 percent is seen for low duration/power level options).

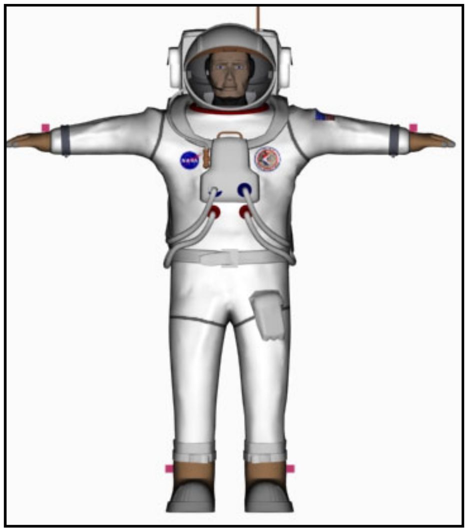


Figure 7.—3 cm cube

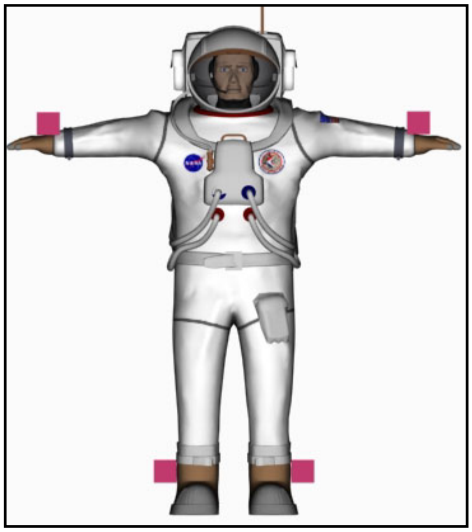


Figure 8.—9 cm cube

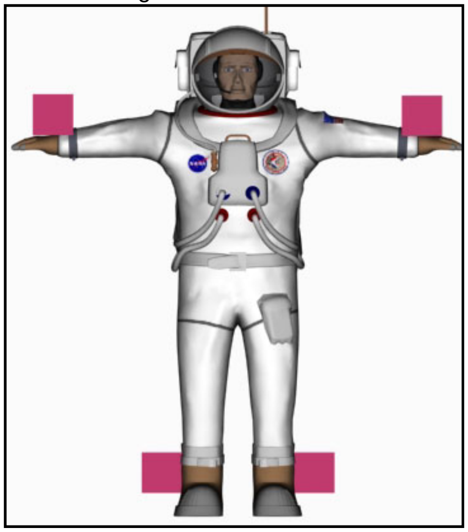
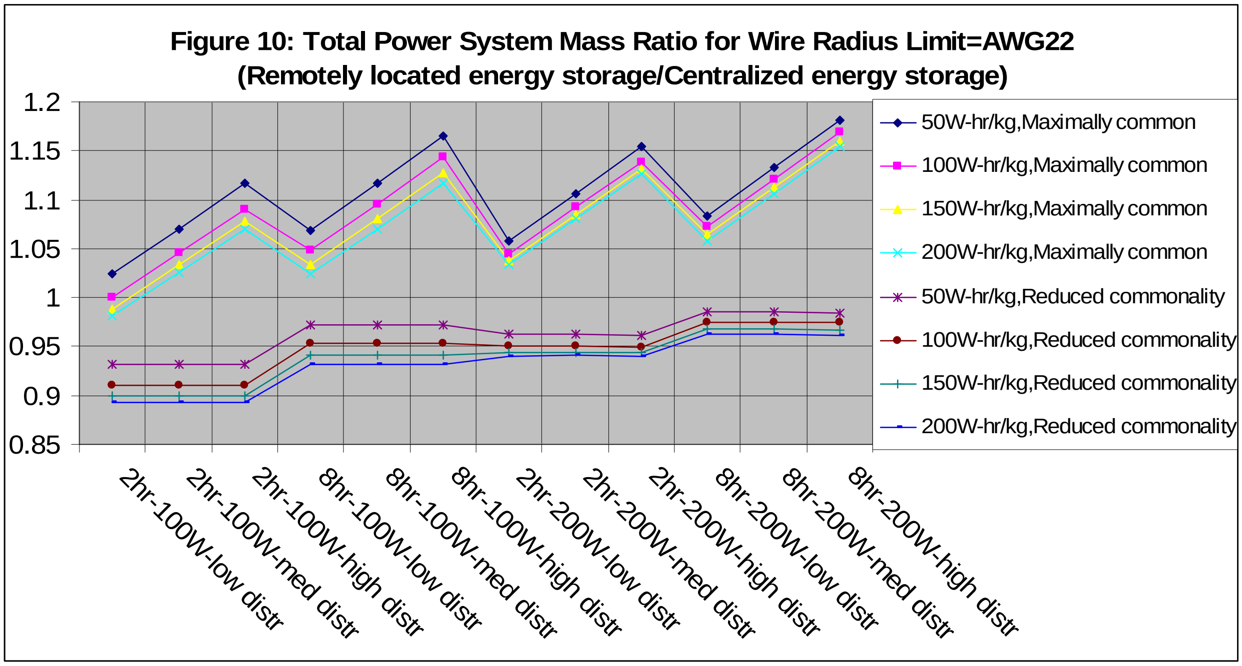


Figure 9.—16 cm cube



2.6 Conclusion

A centralized power system with power distribution cables is the best option of those considered. This option modified to enhance commonality in the distribution cables may have somewhat higher mass and volume but would have lower spares requirements. Localized power sources with reduced commonality may provide somewhat lower mass, but this benefit is outweighed by considering 1) commonality (spares/logistics), 2) power source volume/clearance issues, 3) localized appendage power source mass, 4) recharge or swap out complexity of multiple units and 5) development cost of multiple power source types. Localized power source with maximal commonality lose the total mass benefits while retaining the other negative attributes (except for commonality and logistic considerations).

The aspect that cannot be assessed by this trade study is the difficulty in integrating the cable into the suit. Cables are not exposed (outside the suit protective garment) so they must be fed within that layer in some manner. Qualitatively, it seems that feeding one cable from backpack to each hand and foot is not a complex matter; it is wiring the entire suit to each sensor that is complex. It is unlikely that any future suits would have woven “main” power cables since the desire to make these kinds of cables a replacement unit is high (rather than replace an entire “woven” garment or “woven” power thread).

Power cables are likely to remain the only method of distributing power levels above 1 W. There may be some possibility to distribute power below that level using other methods (e.g., radio frequency, induction), but these must be addressed in detail based on the power needs of the sensors. However, if a power cable is used for hand and feet, then perhaps the same cable (and added RF/other power emitting methods/electronics) can be used to provide power to miscellaneous very low power sensors using these other methods without the complexity of individual wiring to them.

3.0 Trade Study 3: Umbilical-Only Power Versus Suit-Mounted Power for the Advanced EVA Suit

Date: September 23, 2005

3.1 Results Summary

Based on the Crew Exploration Vehicle design, umbilical lengths of up to 20 m can be expected. The maximum mass savings of a suit-mounted energy storage power system versus an umbilical-only power system (for a 20 m umbilical) is about 4 kg for one suit (includes power cable in umbilical and any suit-related power system). The most favorable suit-mounted energy storage options are for low power <50 W and short duration (<1 hr) with recharging. The primary energy (non-rechargeable) storage system has the most mass savings although it is limited by being a onetime use (this may be acceptable depending upon the number of planned/groundruled EVAs per mission). If other umbilical resources are considered (O_2, cooling, power, etc), the launch mass savings (based on a Shuttle EMU suit) increase to at least 40 kg for one suit (mass due to umbilical infrastructure/ mechanisms and O_2/cooling fluids inside the umbilical are omitted here, but would increase the savings considerably). Suit-mounted energy storage has enhanced mobility and reduced encumberness as compared to umbilical-only power options. Umbilical-only power is the best selection for in-space pressurized (in-cabin) suits. Surface suits favor suit-mounted energy storage with short umbilicals for recharge (longer umbilicals are not favored for surface suits because of dust, wear, abrasion and severing concerns, as well as reduced mobility and increased encumberness).

3.2 Purpose

The purpose of this trade study is to evaluate the benefits of using suit-mounted energy storage systems for the advanced EVA suit as opposed to connecting the suit to a power source via an umbilical.

3.3 Past/Current Umbilical Data

Umbilicals can be used for in-space EVA suits as well as surface suits. Table 1 displays the typical uses and characteristics of past/current EVA suits with umbilicals. Tether data is also included. Umbilicals can provide various resources to an EVA suit including cooling, oxygen, communications/sensor linkups, mechanical linkage/support and power. Umbilicals may either provide nominal power to the suit during a sortie or be used to recharge a suit attached nominal power system.

In designing a power umbilical, the maximum length is important to know. This is dependent upon the application. Which resources are carried in the umbilical is important since this affects size, flexibility and mass. Past anecdotes illustrate that very long (>18 m) umbilicals (which carry O_2 and cooling) were too cumbersome. The Skylab umbilical designs were theoretically able to extend to 36 m (Skylab data is incomplete thus it is not clear what was the implemented umbilical length/characteristics). Such long umbilicals require that one astronaut is dedicated to perform the EVA and the other to handle (deploy or retract) the umbilical. One version of the Orlan suit had a power/communications-only umbilical of as much as 25 m. The Gemini suit had a 15 m umbilical which carried O_2 and cooling primarily, but was considered very bulky and was difficult to return to the airlock.

It is assumed that the umbilical is connected near one point (nominally the egress point or airlock) and the length of the umbilical is the limit to the astronaut travel. It is possible that multiple EVA umbilical external connection sites could be included in the CEV design (assuming a small EVA power system to handle movement between EVA sites and a moderate length umbilical to handle most of the sortie activity), but this is considered unlikely due to the added complexity and launch mass balanced against the infrequent use of such ports. For in-space, pressurized application, it is connected to one of possibly many ports on the inside. For surface operation, it is either connected to a port near the airlock or recharge station, or to a rover port.

TABLE 1.—PAST UMBILICAL/TETHER DATA

Program	Type	Location	Purpose	Length, m	Note
Voskhod	Umbilical	In-Space	Comm/O_2	5	Berkut suit
Gemini	Umbilical	In-Space	Comm/O_2/cooling/sensors	8 to 15	Tangling problems at 15 m length, bounced off Agena
Apollo surface	Umbilical	In-Space	Cooling	3	Used to share resources between suits in an emergency
Apollo surface	Umbilical	In-Space	Power?	?	Connection with Rover?
Apollo	Umbilical	In-Space	Comm/O_2/cooling/sensors/mech	2.5	Apollo 15
Skylab	Umbilical	In-Space	Comm/O_2/cooling/sensors/mech	18, 36 two in series	Apollo pressure suit and astronaut life support assembly (emergency, O_2, pressure control unit, life support umbilical)
Skylab	Umbilical	In-Space	?	14	In-pressurized cabin use
Shuttle EMU (IEU)	Umbilical	In-Space	Comm/O_2/cooling/sensors/power/fluids	7	Used in unpressurized
Shuttle EMU (SCU)	Umbilical	In-Space	Comm/O_2/cooling/sensors/power/fluids	3.3	Used in airlock (pressurized)
Shuttle (not suit)	Umbilical	In-Space	Power/comm.	3, 10	To power satellites
Orlan	Umbilical	In-Space	Power/comm.	25	
Orlan	Umbilical	In-Space	O_2/fluids/cooling	3	
Gemini	Tether	In-Space	Mechanical	8, 33, 47	
Apollo	Tether	In-Space	Mechanical	9	
Shuttle EMU	Tether	In-Space	Mechanical	1 to 18	

3.3.1 Emergency Backup Power

Another consideration is whether the EVA suit has emergency backup power or not. Generally, in past and current EVA suits, if umbilicals are used, the EVA suit has an emergency backup O_2 system to enable the astronaut to return a pressurized environment. However, only the most recent in-space suits such as the Orlan and Shuttle EMU have emergency backup power. The reason for this is that past suits seem to require less electronics and be more mechanical. It is not clear whether this can be considered true for future suits since communications at least is a critical function that seems to require some power if the umbilical fails. However, it may be groundruled that, for a specific EVA suit application, emergency backup power is not needed.

3.3.2 Contingency EVA

The in-space, external EVA suit has been previously groundruled (by the AEVA program) for contingency EVAs only (as opposed to assembly and nominal operations). A contingency EVA is performed as an emergency to save the spacecraft and/or its crew. Thus, transfer between orbiting vehicles or transfer between compartments in the same vehicle, emergency repair procedures on equipment (orbiting vehicle external solar array or radiator deployment, antenna deployment, thermal tile inspection/repair) are permitted but nominal assembly or scientific data acquisition/data retrieval are excluded. Table 2 describes typical contingency EVA applications (generic and historical). Duration, power level (i.e., may be lower than nominal EVAs), mobility requirements (e.g., may need to detach umbilical at location different from egress point) of each contingency EVA cover a wide range.

Since contingency EVAs should not happen frequently (given a well designed vehicle), it is possible to consider one time use suit-mounted non-rechargeable energy storage systems. Replacement energy storage units (and other resources) could be carried for a certain threshold quantity of contingency EVAs (to be determined by analysis).

TABLE 2.—EXAMPLES OF CONTINGENCY EVAS

Salyut6	Remove the KRT-10 antenna from Salyut 6's aft docking port
Apollo 9	Demo of contingency EVA transfer between the Apollo Lunar Module and Command Module (in case IVA blocked)
Skylab	Failure of solar panel, loss of power and cooling, released remaining solar array, erected sunshade
STS–6	Demo of payload bay door closure
STS–37	EVA to deploy GRO high gain antenna which could not be deployed after the GRO was raised from the payload bay
STS–57	Secure carrier antennae that would not latch on retraction
Mir 1987	Removed obstruction (most likely a sheet) that was fouling the docking between Mir and Kvant
Mir 1990	Fixed insulation blankets on the Soyuz landing capsule. Indentified the faulty hatch problems/features and forced it closed.
ISS 2001	A contingency EVA was ordered to clear an obstruction in the docking port
Example	Adjust a displaced insulation blanket
Example	Adjust a displaced micrometeoroid shield
Example	Check the mating of a cable connector that might have malfunctioned during operations.

3.3.3 Applications of Umbilicals

The primary reason for a power umbilical is to provide the main power for an in-space, external EVA suit, eliminating the need for a suit-mounted energy storage system.

A power umbilical can also be used to recharge the EVA suit energy storage (either for contingency or nominal operations). This can be used for in-space or surface suits (in pressurized or unpressurized environments). For surface suits, the same method as in-space recharging can be used (in an unpressurized airlock or external location or while in transit on a rover). These likely have short lengths (<3 m).

Use of long umbilicals for powering or recharging surface suits is likely impractical due to dust adhesion, mechanical abrasion/wear, risk of severing/puncture due to sharp rocks, mass and mobility limitations.

In a pressurized in-space cabin use, a powered suit is most likely to be powered via a short umbilical.

3.3.4 Anticipated Sortie Duration and Umbilical Length

Regarding sortie duration, for in-space, exterior use, Skylab assumed a nominal translation rate of about 0.3 ft/sec which means that 20 m can be covered in 1 min. At even 5 times this value, this implies significant time at the work site if the total sortie time is only 1 hr. Longer sortie times than 1 hr (and, especially, unlimited ones) would be favored.

Regarding likely umbilical length, since the release of the Exploration Systems Architecture Study report, it is possible to view the likely maximum in-space distance which must be traversed in a contingency EVA. Assuming only the Crew Exploration Vehicle and Lander elements (i.e., the Departure Stage is jettisoned), the maximum umbilical distance is about 20 m. If the Departure Stage is included, the EVA traverse distance goes to up to as much as 60 m. This later case is considered unlikely in that contingency operations on the Departure Stage would be prohibited due to safety concerns (i.e., a mission abort would most likely occur).

3.4 Analysis Method

The primary goal of the analysis was to quantify the power system mass for both the suit-mounted energy storage option and the umbilical-only power cable option. This would enable a comparison of the suit mass, launch mass and provide data to gauge how encumbered the astronaut would be with each option. The same EVA suit power system model was utilized that was developed for the previous trade studies. This model was modified to include an umbilical (using cable sizing relationships from the suit power system). Various umbilical lengths (1, 5, 10, 15, and 20 m), power levels (25, 50, 100, 150, and 200 W) and power durations (1, 2, and 4 hr) were analyzed. Various energy storage specific energies were considered (50, 100, 150, and 200 W-hr/kg). (Note that primary energy storage for either emergency or nominal usage were assumed to have a 220 W-hr/kg specific energy. Both primary (non-rechargeable) and secondary (rechargeable) energy storage were assessed for the suit-mounted energy storage options. Cases with and without emergency backup energy storage (using primary/non-rechargeable batteries) were considered. The recharge method was designed to be based on electrical recharge only (of batteries), not by recharging fuel cells via pressurized lines (i.e., fuel cells are ground ruled out for near-term AEVA in-space application).

The basic method of generating mass data for the various options was to size the umbilical cables for the various power levels and lengths. Then, the nominal power system was sized for various power levels, durations and specific energies. The emergency energy storage system sized as appropriate. These values were combined to generate all the permutations of cases presented in the analysis results.

3.5 Power System Assumptions

Power system assumptions are listed in Table 3. For the primary/non-rechargeable battery energy storage options, a discharge regulator is used, however for rechargeable battery energy storage options, a charge/discharge regulator is used. Each component has a different efficiency which affects the sizing of the energy storage system.

TABLE 3.—POWER SYSTEM ASSUMPTIONS

Power System Parameters		
Voltage Type		Direct Current
Power System Voltage Level	V	28
Nominal Energy Storage Depth of Discharge	percent	80
Total Site Power Into DCDC Converter	percent	20
Cable Parameters		
Cable Wire Material		Copper
Cable Wire Density	gm/cm^3	8.9
Cable temperature	K	279
Cable Power Safety Factor		2
Number of Redundant Cable Pairs/Transmission Line		1
Cable Jacket Filler Density	gm/cm^3	1.7
Insulator Density	gm/cm^3	1.7
Cable Jacket Density	gm/cm^3	1.7
Insulation Dielectric Strength Safety Factor		2
Contingency Parameters		
Backpack Contingency Energy Storage Specific Energy	W-hr/kg	220
Backpack Contingency Energy Storage Load Level	W	25
Backpack Contingency Energy Storage Load Duration	min	30
Component Specific Powers		
DCDC Converter Specific Power	W/kg	80
Power Distribution Unit Specific Power	W/kg	50
Charge/discharge Regulator Unit Specific Power	W/kg	50
Thermal System Specific Power	W/kg	100
Nondistribution Cable Specific Power	W/kg	1000
Component Efficiencies		
DCDC Converter Efficiency	percent	95
Power Distribution Unit Efficiency	percent	99
Charge/discharge Regulator Unit Efficiency (Secondary)	percent	80
Discharge Regulator Unit Efficiency (Primary/Emergency)	percent	90
Mass Estimation Parameters		
Connector Mass (Percentage of Cable Mass)	percent	10
Energy Storage Structure (Percentage of Energy Storage Mass)	percent	10
Other Power System Structural Mass (Percentage of the DCDC and cable masses)	percent	10

For the umbilical-only sizing, only DC-DC converters, cables and switchgear are sized. Note that the DC-DC converter specific power is based on its output power (i.e., input power divided by 5.0).

The limiting wire gauge of AWG 22 is assumed for the internal electrical system.

For the internal electrical system of the suit, an "average" distribution of power is assumed to size the cables (see Table 4). Local loads for total suit power levels of 25, 50, 100, 150 and 200 W are presented.

TABLE 4.—DISTRIBUTION OF POWER

		Power Level at Each Load Location (W)				
Load location	Cable distance (m)	25	50	100	150	200
Left hand	1	2.5	5	10	15	20
Right hand	1	2.5	5	10	15	20
Left foot	1.5	1.94	3.875	7.75	11.625	15.5
Right foot	1.5	1.94	3.875	7.75	11.625	15.5
Helmet	0.66	0.88	1.75	3.5	5.25	7
Back	0.33	13.74	27.5	55	82.5	110
Chest	0.5	1.5	3	6	9	12

3.5.1 Analysis Limitations

Sizing of the emergency energy storage was fixed to a specific power level and duration for all options. No attempt was made to determine the transfer time of the astronaut from various distances to the airlock. Since the actual need for emergency power is unknown at this time, a fixed assumption is the best approach although it can be modified in the future. This likely has little effect on the results.

Mass and sizing data on past umbilical systems is mostly unavailable. Better data would enhance this analysis.

This analysis did not consider fuel cell recharge (via pressurized lines) or swap-out of hardware. This is anticipated to make little difference to the results.

Enhanced umbilical protection was not included in the umbilical power cable model. It was assumed that the balance of the umbilical mass would have such a mass element (if needed). Charging such mass to the power cable portion would increase the mass benefits of suit-mounted energy storage options by a moderate amount.

3.5.2 Analysis Results

A basic ground rule carried from past analysis is that a total power system mass savings of at least 20 percent is required for any alternative option to be considered viable. This has been done because of modeling uncertainty and the desire to have adequate savings to justify new development and hardware risk.

It is difficult to determine the optimum design methodology for the umbilical power cable because of the many competing metrics. In order to minimize the number of cases presented in this trade study, two specific "typical" power umbilical designs were selected. Generally, these two types were based on minimum mass and minimum thermal load.

Figure 1 shows the effect of sizing the power umbilical based on cable temperature. A thinner power cable provides more resistance and, thus, a higher voltage drop and parasitic power loss. This raises the temperature of the power cable. Conceivably, the cable temperature can be as high as 120 °C, but realistically, this is unacceptable for umbilicals for many obvious reasons. Although the lowest mass can be obtained for the umbilical for high temperatures, the increased temperature of the umbilical places a thermal load on the cooling loop (if present in the umbilical) and on the thermal design of a power only umbilical. In addition, the added required power (i.e., the parasitic power loss in addition to the nominal power) may be a burden to the vehicle (or rover). Since it is unknown what the temperature/thermal requirements are at this stage of EVA suit analysis, the temperature of 25 °C was selected as a typical, "reasonable" value. This was done because it was near the "knee" of the curves (which is near the plateau of cable mass benefit versus operating temperature). This case is considered the "ideal" but is likely to not be “real” since the goal to reduce parasitic power (a burden on any in-space vehicle which may be operating on limited battery storage only during a contingency operations event) and thermal load.

Figure 2 shows the effect of sizing the power umbilical based on cable efficiency. As seen in the previous figure, lower efficiency cables are thinner, lighter, have a higher voltage drop, parasitic power loss and higher operating temperature. Higher efficiency cables are thicker, heavier, have very low voltage drop/parasitic losses/operating temperature. It is difficult to select an “ideal” cable efficiency. The typical method to do this is to examine the curves and select a point near the “knee” of the curve (which represents the plateau of cable mass benefits versus efficiency. This resulted in 95 percent efficiency being selected for the comparisons. This case, even though it is heavier than the previous one, is more likely to be closer to an actual implemented power cable for the umbilical because reduced power loads on the in-space vehicle are very important.

Figure 3 shows the total power system mass (including power system umbilical) for various assumed power levels and durations. The emergency power system is included. This figure enables one to understand the relative magnitudes of the masses being compared. Masses range from 3.3 to 45 kg. Subsequent figures will provide a better method to compare the merits of umbilical only mass versus the on-suit energy storage options.

Figure 4 shows the total power system mass (including power system umbilical) for various assumed power levels and durations. The emergency power system is not included. Some minor mass savings occur by excluding emergency power (which may be viable depending on the EVA suit design). Masses range from 2.2 to 38 kg. Subsequent figures enable a better relative comparison of the options.

Figures 5 through 9 show the total power system mass including any suit mounted power system (including emergency energy storage) and power umbilical. These figures are designed to show the relative benefit of the various power system configurations relative to a baseline (proposed) alternative.

Figure 5 has a suit mounted, primary (non-rechargeable) energy storage system as the baseline alternative. Using the 20 percent improvement in mass metric, then it can be seen that using the primary/non-rechargeable energy storage option is superior to a number of umbilical length, power level and power duration cases. The first observation is that the primary/non-rechargeable energy storage is superior in terms of mass as compared to other secondary energy storage options. The obvious drawback of the primary/non-rechargeable storage is that it is a onetime use only. If used for contingency EVA operation, the number of contingencies that must be planned for affects the logic of using such a system. Comparison with the umbilical power–only options show, in general, that lower power levels and durations enable the primary/non-rechargeable energy storage option to have superior mass. Primary/non-rechargeable energy storage provides at least 20 percent mass savings over the umbilical only power option with load durations of 1 hr and power level <50 W over umbilicals 10 m and longer (for the “realistic” 95 percent efficiency umbilical design case). For 2 hr and <50 W, the savings occur over umbilicals of about 12 m (visual interpolation) and longer. For 4 hr and <50 W, the savings occur over umbilicals of about 17 m (visual interpolation) and longer. For 1 hr and >100 W, the savings occur over umbilical of about 16 m (visual interpolation) and longer. For 2 hr and >100 W, the savings occur over umbilical of about 20 m and longer. For 4 hr and >100 W, there are no savings of >20 percent in mass over the umbilical.

Figure 6 has a suit mounted, 50 W-hr/kg secondary energy storage system as the baseline alternative. This is typical of a near-term (NiMH battery). This option has only one application that is superior in terms of mass. This is the 1 hr load duration, 25 W power level case. Here, the secondary energy storage system saves at least 20 percent mass over umbilical-only power longer than 17 m (visual interpolation). Because of the limited applicability in terms of load level and duration, it seems that such an alternative is not viable. However, duration is not critical in that the 1 hr could be the EVA time between recharging.

Figure 1: Minimum Mass Umbilical Power Cable Option (power rich/voltage flexible vehicle)

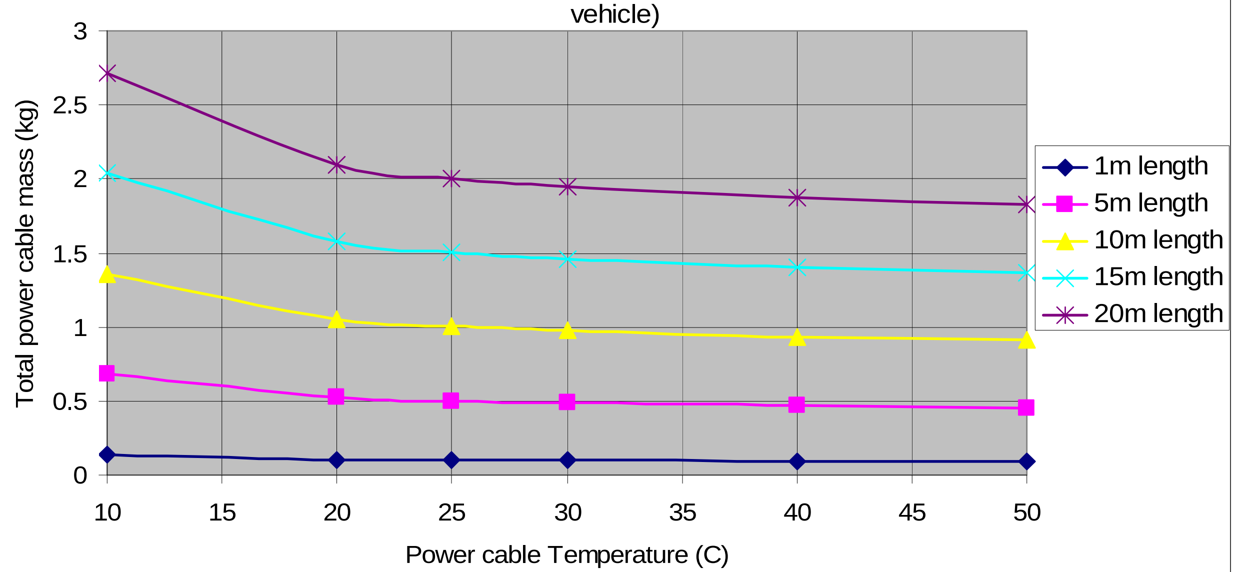
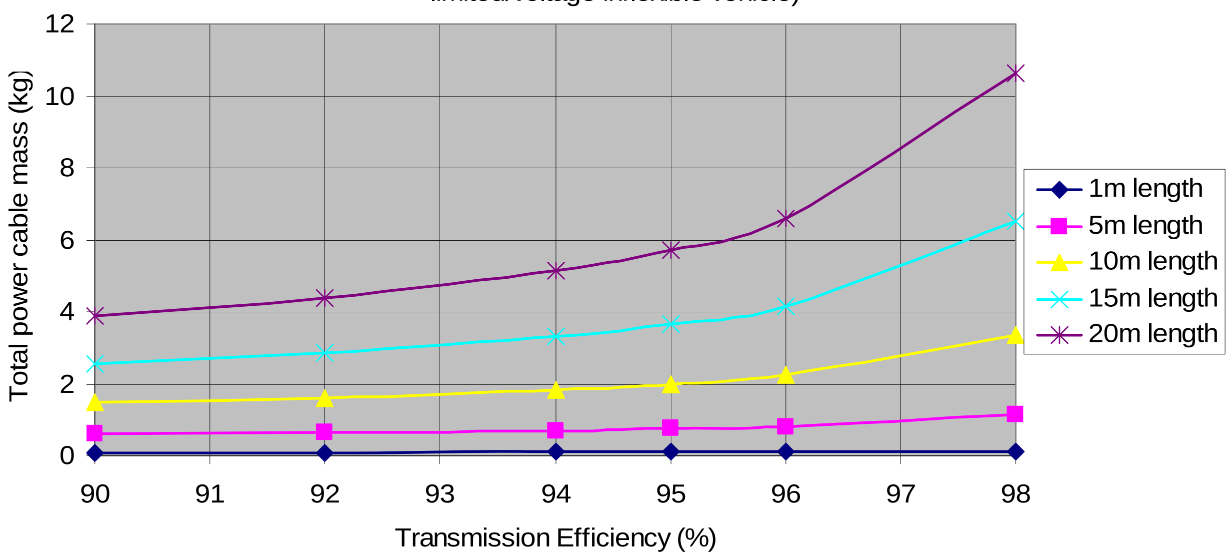


Figure 2: Low Thermal Load Umbilical Power Cable Mass Option (power limited/voltage inflexible vehicle)



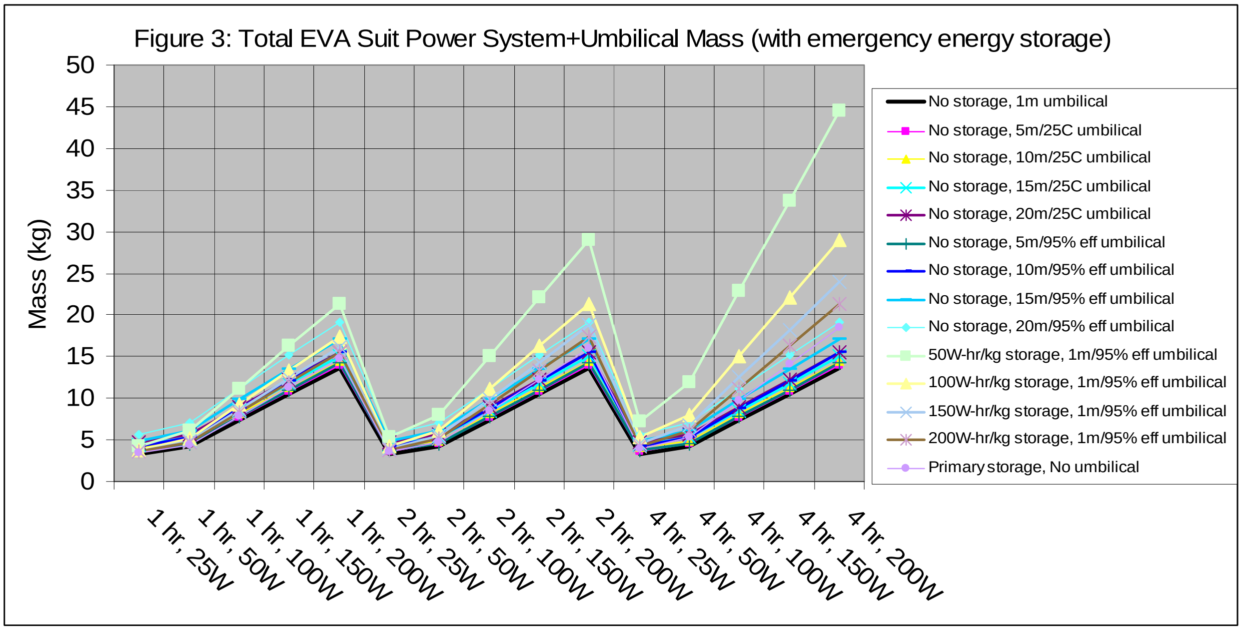


Figure 3: Total EVA Suit Power System+Umbilical Mass (with emergency energy storage)
Mass (kg)
50
45
40
35
30
25
20
15
10
5
0
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

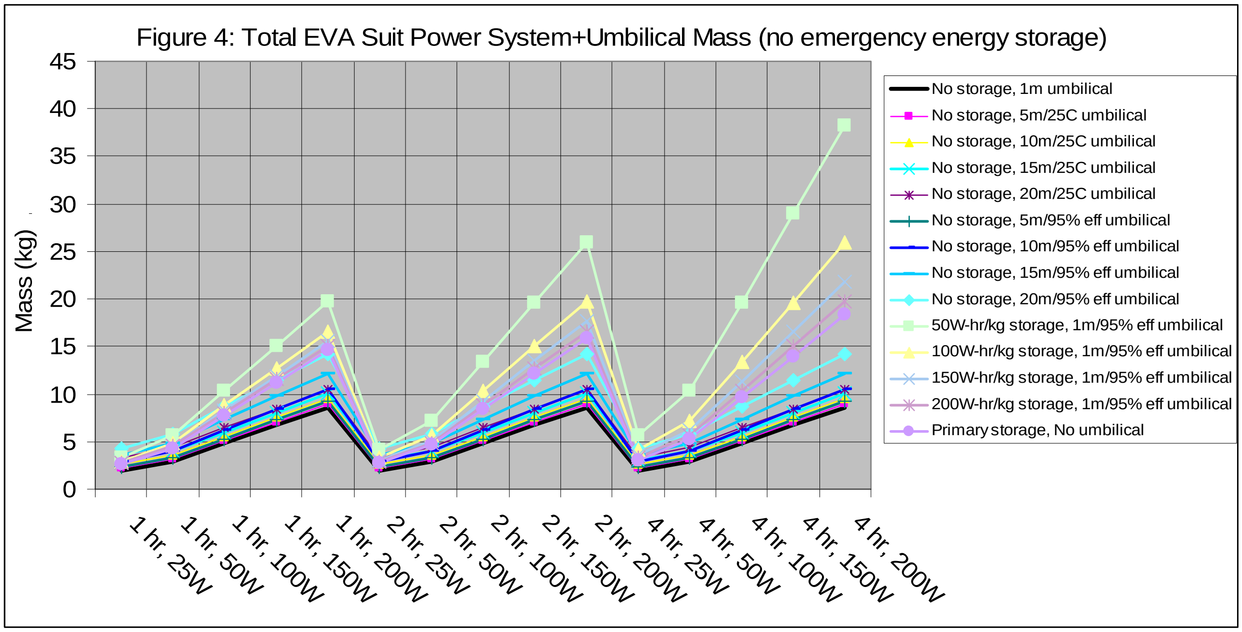


Figure 4: Total EVA Suit Power System+Umbilical Mass (no emergency energy storage)
Mass (kg)
45
40
35
30
25
20
15
10
5
0
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

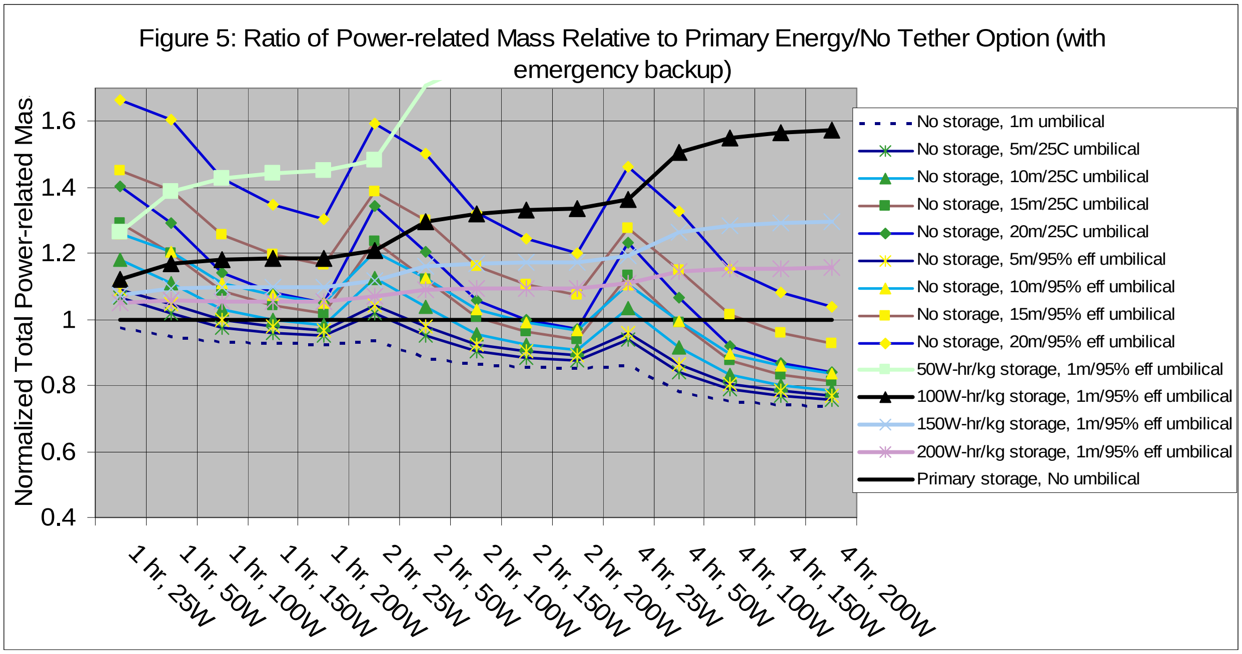


Figure 5: Ratio of Power-related Mass Relative to Primary Energy/No Tether Option (with emergency backup)
Normalized Total Power-related Mas
1.6
1.4
1.2
1
0.8
0.6
0.4
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

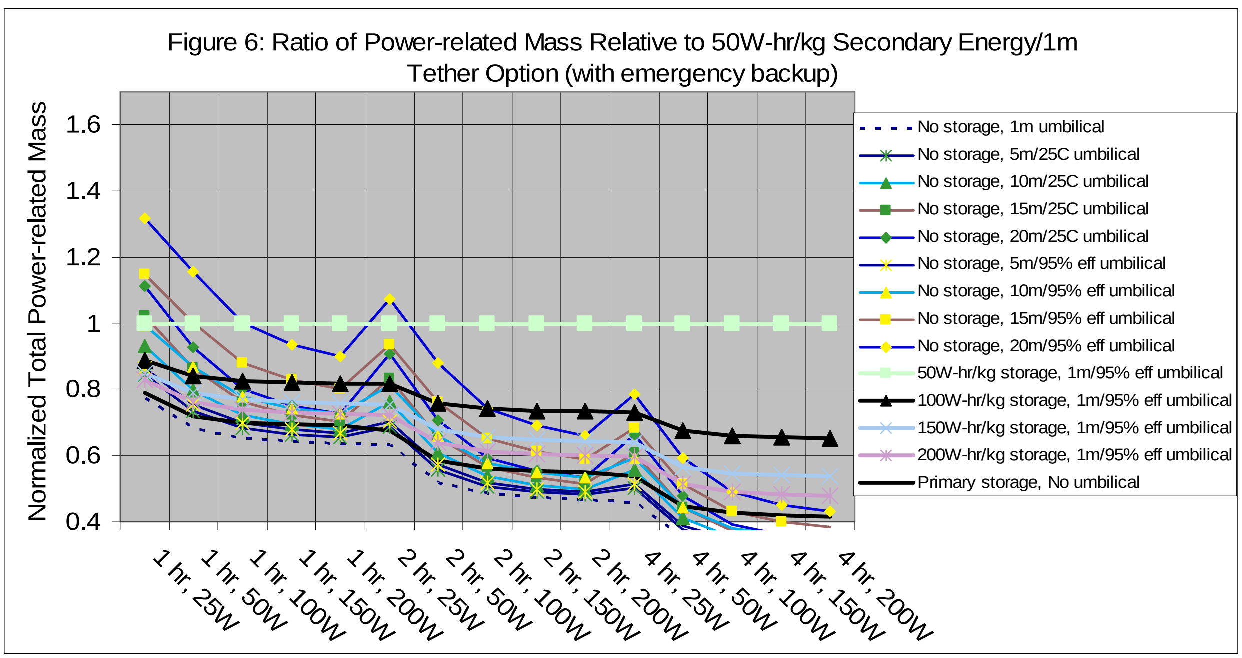
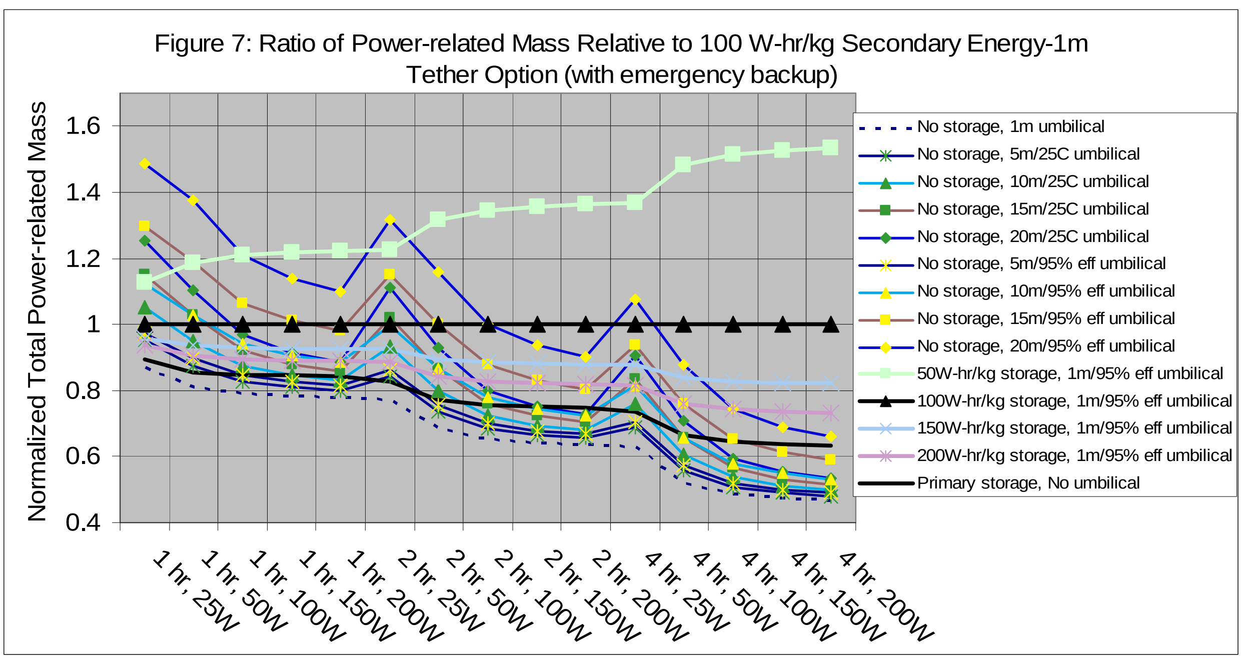


Figure 6: Ratio of Power-related Mass Relative to 50W-hr/kg Secondary Energy/1m Tether Option (with emergency backup)
Normalized Total Power-related Mass
1.6
1.4
1.2
1
0.8
0.6
0.4
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

Figure 7 has a suit mounted, 100 W-hr/kg secondary energy storage system as the baseline alternative. This option can be considered equivalent to a near-term Li polymer battery. For load durations of 1 hr and power levels <50 W, the 100 W-hr/kg energy storage options has at least 20 percent less mass than umbilical-only power options with lengths 15 m and longer. Even load durations of 2 hr and power levels <50 W have savings for umbilical lengths of 21 m (visual interpolation) and longer. Load durations of 4 hr have mass savings below the accepted limit. Therefore, there is some potential for this option to be feasible, as long as recharging occurs every 1 to 2 hr.

Figure 8 has a suit mounted, 150 W-hr/kg secondary energy storage system as the baseline alternative. This energy storage system can be considered representative of a more advanced Li polymer type battery. For load durations of 1 hr and power levels of <50 W, this option saves at least 20 percent mass of umbilical-only cases of lengths from 13 m (visual interpolation) and longer. For 2 hr and <50 W, the savings occur for lengths from 17 m and longer. Load durations of 4 hr do not meet the mass savings criteria. For 1 hr and >100 W, savings occur for lengths >20 m. Therefore, for recharging intervals of about 1 hr and lower power levels, this option is feasible. Even for higher power levels, as long as the recharge interval is about 1 hr, it is feasible.

Figure 9 has a suit mounted, 200 W-hr/kg secondary energy storage system as the baseline. This energy storage is representative of an advanced far-term Li polymer battery. This case is fairly similar to the primary/non-rechargeable energy storage option since they have similar W-hr/kg. The main difference is that the primary system is non-rechargeable and the electronics have different efficiencies. For 1 hr and <50 W, the (at least) 20 percent savings occur for umbilical lengths of 12 m (visual interpolation) and longer. For 2 hr and <50 W, the savings occur for 15 m and longer. For 4 hr and <50 W, the savings occur for 21 m (visual interpolation) and longer. For 1 hr and >100 W, the savings occur for 19 m (visual interpolation) and longer. Therefore, for low power levels, recharging at various intervals (1 to 4 hr) seems to make this option feasible. Even 1 hr recharge for higher power levels makes this option feasible. It is clearly more feasible than the primary battery (non-rechargeable) option from the standpoint of EVA duration due to the ability to recharge. Although this option seems viable, its drawback is the technology unavailability for the near and midterm.



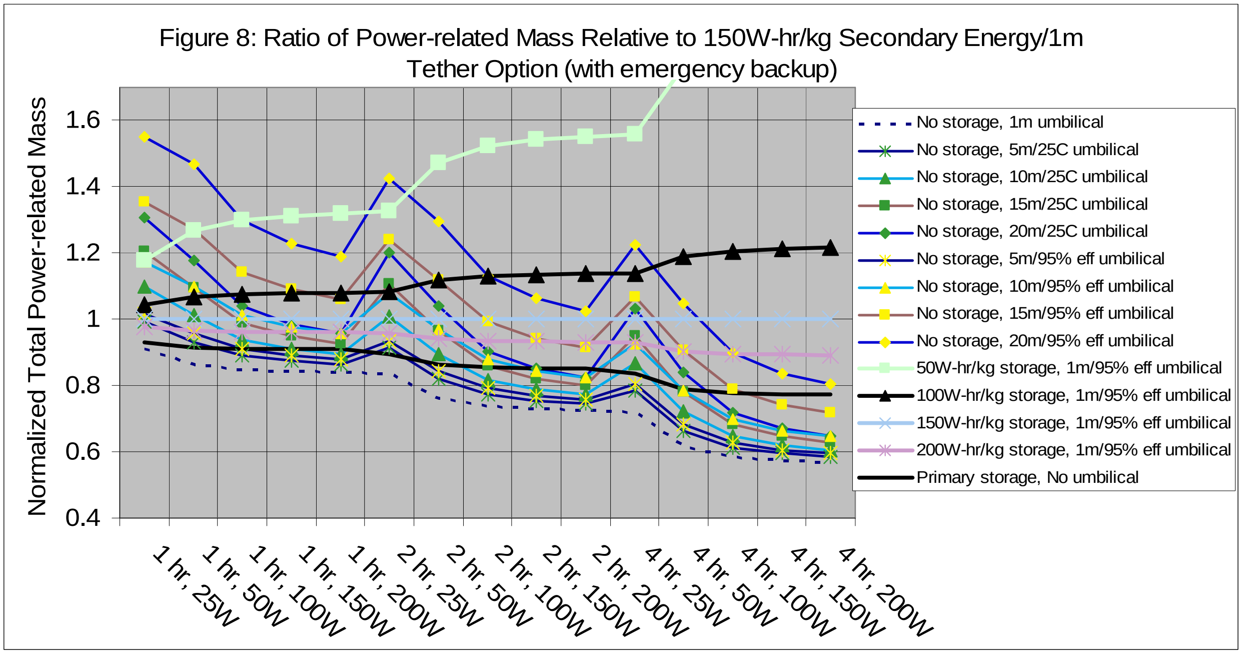


Figure 8: Ratio of Power-related Mass Relative to 150W-hr/kg Secondary Energy/1m Tether Option (with emergency backup)
Normalized Total Power-related Mass
0.4
0.6
0.8
1
1.2
1.4
1.6
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

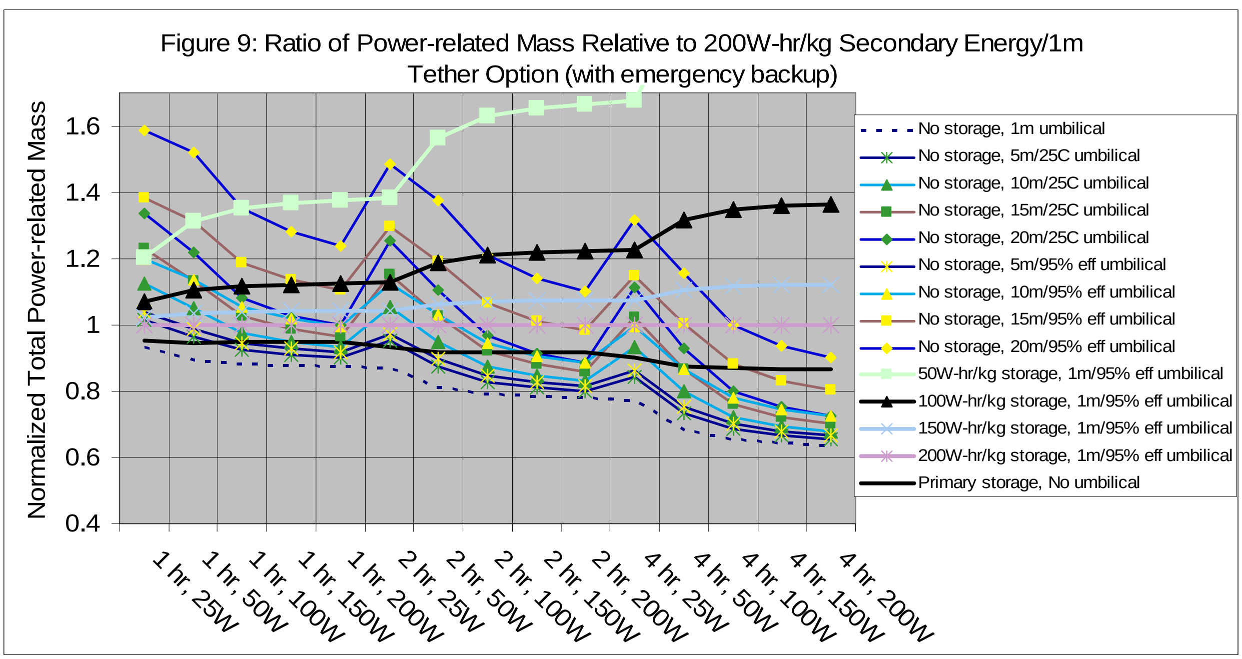


Figure 9: Ratio of Power-related Mass Relative to 200W-hr/kg Secondary Energy/1m Tether Option (with emergency backup)
Normalized Total Power-related Mass
0.4
0.6
0.8
1
1.2
1.4
1.6
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

Figures 10 through 14 show the total power system mass including any suit mounted power system (emergency power is not considered) and power umbilical.

Figure 10 has a suit mounted, primary (non-rechargeable) energy storage system as the baseline alternative. Omitting the emergency storage worsens the mass savings of this option over the umbilical only cases. The reason for this is that an umbilical-only power system that must have extra mass on the EVA suit for emergency storage must add an entire power system mass, while for an existing EVA suit energy storage system with its related electronics/electrical system, some of which can be used by an emergency energy storage system. This means that using a nominal suit attached energy storage/power system provides some synergies and dual use hardware that the umbilical system would not have. Removing the emergency energy storage from both systems removes the advantage of the synergies and makes the umbilical power option lower in mass. Primary (non-rechargeable) energy storage provides at least 20 percent mass savings over the umbilical only power option with load durations of 1 hr and power level <50 W over umbilicals 18 m and longer. For 2 hr and <50 W, the savings occur over umbilicals of about 19 m (visual interpolation) and longer. For 4 hr and <50 W, the savings occur over umbilicals of about 23 m (visual interpolation) and longer. High power levels (>100 W) are not feasible from a mass savings perspective compared to the umbilical option (unless much longer umbilicals are considered). Low power levels may be feasible depending upon the travel distance requirements (to compare with the umbilical mass).

Figure 11 has a suit mounted, 50 W-hr/kg secondary energy storage system as the baseline alternative. This is typical of a near-term (NiMH battery). No emergency energy storage is included. This option has only one application that is superior in terms of mass. This is the 1 hr load duration, 25 W power level case. Here, the secondary energy storage system saves at least 20 percent mass over umbilical-only power longer than 18 m (visual interpolation). Because of the limited applicability in terms of load level and duration, it seems that such an alternative is not viable. However, duration is not critical in that the 1 hr could be the EVA time between recharging.

Figure 12 has a suit mounted, 100 W-hr/kg secondary energy storage system as the baseline alternative. This option can be considered equivalent to a near-term Li polymer battery. No emergency energy storage is included. For load durations of 1 hr and power levels <50 W, the 100 W-hr/kg energy storage options has at least 20 percent less mass than umbilical-only power options with lengths 20 m and longer. For 2 hr and power levels <25 W, savings exist for umbilical lengths of 18 m (visual interpolation) and longer. Load durations of 4 hr have no mass savings. Therefore, there is some potential for this option to be feasible, as long as recharging occurs every 1 to 2 hr for low power levels.

Figure 13 has a suit mounted, 150 W-hr/kg secondary energy storage system as the baseline alternative. No emergency energy storage is included. This energy storage system can be considered representative of a more advanced Li polymer type battery. For load durations of 1 hr and power levels of <50 W, this option saves at least 20 percent mass of umbilical-only cases of lengths from 19 m (visual interpolation) and longer. For 2 hr and <50 W, the savings occur for lengths from 23 m (visual interpolation) and longer. Load durations of 4 hr do not meet the mass savings criteria. For 1 hr and >100 W, savings occur for lengths much greater than 20 m. Therefore, for recharging intervals of about 1 hr and lower power levels, this option is feasible. Even for some higher power levels, as long as the recharge interval is about 1 hr, it is may be feasible from a mass savings perspective.

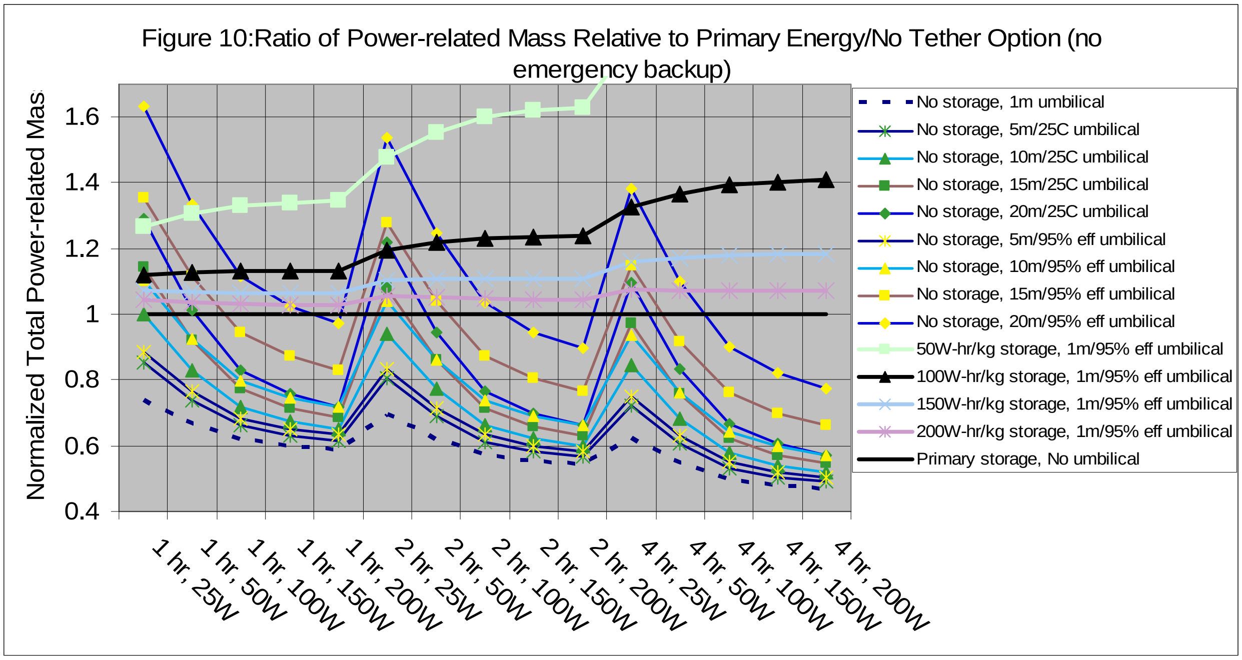


Figure 10:Ratio of Power-related Mass Relative to Primary Energy/No Tether Option (no emergency backup)
Normalized Total Power-related Mas
1.6
1.4
1.2
1
0.8
0.6
0.4
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

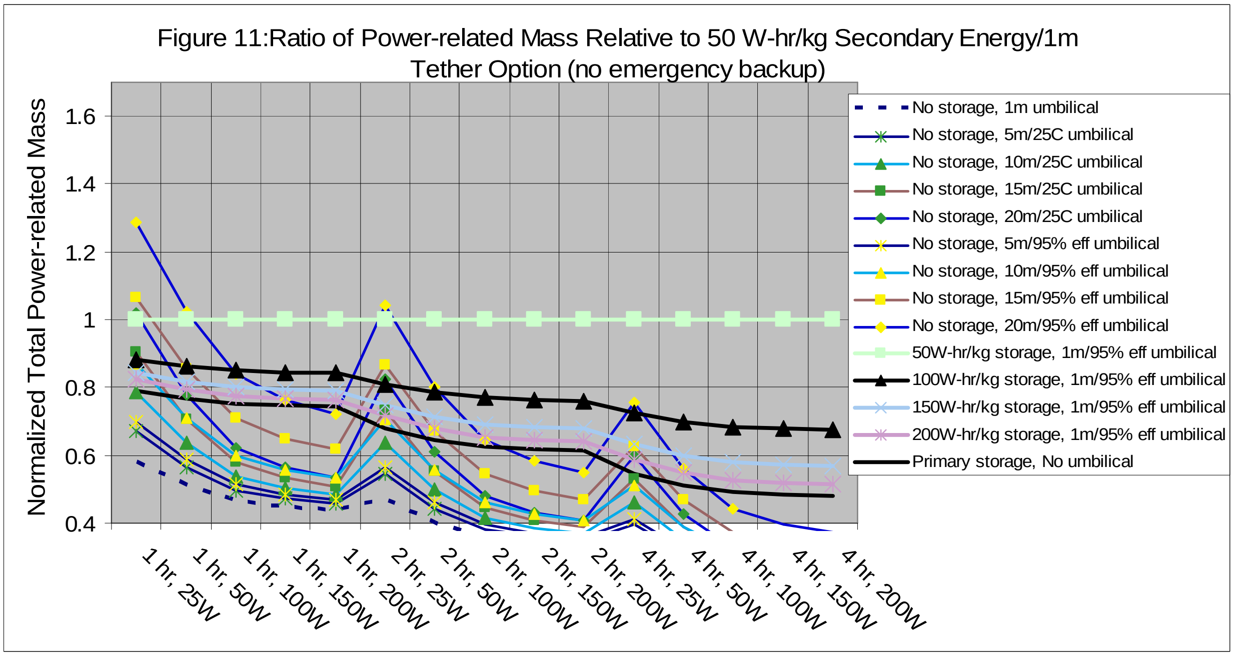


Figure 11:Ratio of Power-related Mass Relative to 50 W-hr/kg Secondary Energy/1m Tether Option (no emergency backup)
Normalized Total Power-related Mass
1.6
1.4
1.2
1
0.8
0.6
0.4
1 hr, 25W
1 hr, 50W
1 hr, 100W
1 hr, 150W
1 hr, 200W
2 hr, 25W
2 hr, 50W
2 hr, 100W
2 hr, 150W
2 hr, 200W
4 hr, 25W
4 hr, 50W
4 hr, 100W
4 hr, 150W
4 hr, 200W
No storage, 1m umbilical
No storage, 5m/25C umbilical
No storage, 10m/25C umbilical
No storage, 15m/25C umbilical
No storage, 20m/25C umbilical
No storage, 5m/95% eff umbilical
No storage, 10m/95% eff umbilical
No storage, 15m/95% eff umbilical
No storage, 20m/95% eff umbilical
50W-hr/kg storage, 1m/95% eff umbilical
100W-hr/kg storage, 1m/95% eff umbilical
150W-hr/kg storage, 1m/95% eff umbilical
200W-hr/kg storage, 1m/95% eff umbilical
Primary storage, No umbilical

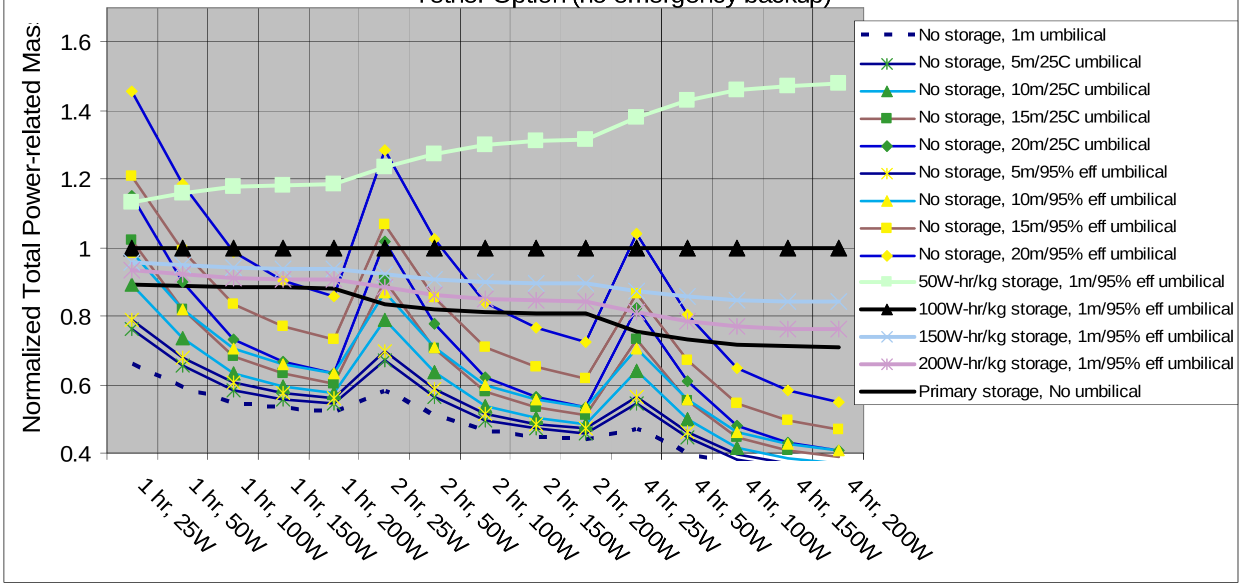


Figure 12:Ratio of Power-related Mass Relative to 100 W-hr/kg Secondary Energy/1m Tether Option (no emergency backup)

Figure 14 has a suit mounted, 200 W-hr/kg secondary energy storage system as the baseline. No emergency energy storage is included. This energy storage is representative of an advanced far-term Li polymer battery. This case is fairly similar to the primary (non-rechargeable) energy storage option since they have similar W-hr/kg. The main difference is that the primary system is non-rechargeable and the electronics have different efficiencies. For 1 hr and <50 W, the savings of at least 20 percent occur for umbilical lengths of 18 m (visual interpolation) and longer. For 2 hr and <50 W, the savings occur for 20 m and longer. For 4 hr and <25 W, the savings occur for 18 m (visual interpolation) and longer. No high power (>100 W) options seem feasible for the umbilical lengths considered (much longer than 20 m may be feasible). Therefore, for low to very low power levels, recharging at various intervals (1 to 4 hr) seems to make this option feasible. It is clearly more feasible than the primary battery option from the standpoint of EVA duration due to the ability to recharge. A drawback is the technology unavailability for the near and midterm.

In the previous figures, only mass directly related to the power system was considered. Relatively speaking, the absolute magnitude of the mass savings is rather low. This analysis would be specifically applicable to a case where only a power umbilical was used (without other resources such as O_2 and cooling). Detailed mass breakdowns of umbilicals are not available. However, some mass data is available for the Shuttle EMU and umbilical.

Figure 15 was created to illustrate effect of the “balance of mass” contributors for the umbilical. On the left is the current Shuttle EMU suit mass. This would be representative of the suit-mounted energy storage cases described earlier in this report. On the right are cases for an umbilical only (power, cooling, O_2 and communication) option. The masses are the sums of the space suit assembly (SSA), umbilical interface block/gauges/regulators, emergency O_2 pack and the ISS EMU Umbilical-IEU (scaled for various lengths). The interface block is an estimate of the needed connections to connect solely with the suit (without the PLSS). The IEU is 3.3 m long and 13.6 kg (excluding the cooling fluid and O_2 mass), thus 4 kg/m was derived for estimating longer umbilical lengths. The umbilical interface was estimated to be ¼ of the PLSS mass. The figure illustrates that for umbilicals longer than 15 m, the non-umbilical options becomes competitive on a mass basis. The mass savings is 40 kg. Note that the figure does not include the umbilical cooling fluid or O_2 mass which may increase the mass savings significantly (i.e., one must add 20 to 40 kg to the 40 kg savings). For two astronaut EVAs, then two such umbilicals would be required, doubling the mass savings if the non-umbilical were used instead. Another aspect excluded from mass estimation is the required umbilical support/deployment/retraction hardware which is likely of considerable mass.

Figure 13:Ratio of Power-related Mass Relative to 150 W-hr/kg Secondary Energy/1m Tether Option (no emergency backup)

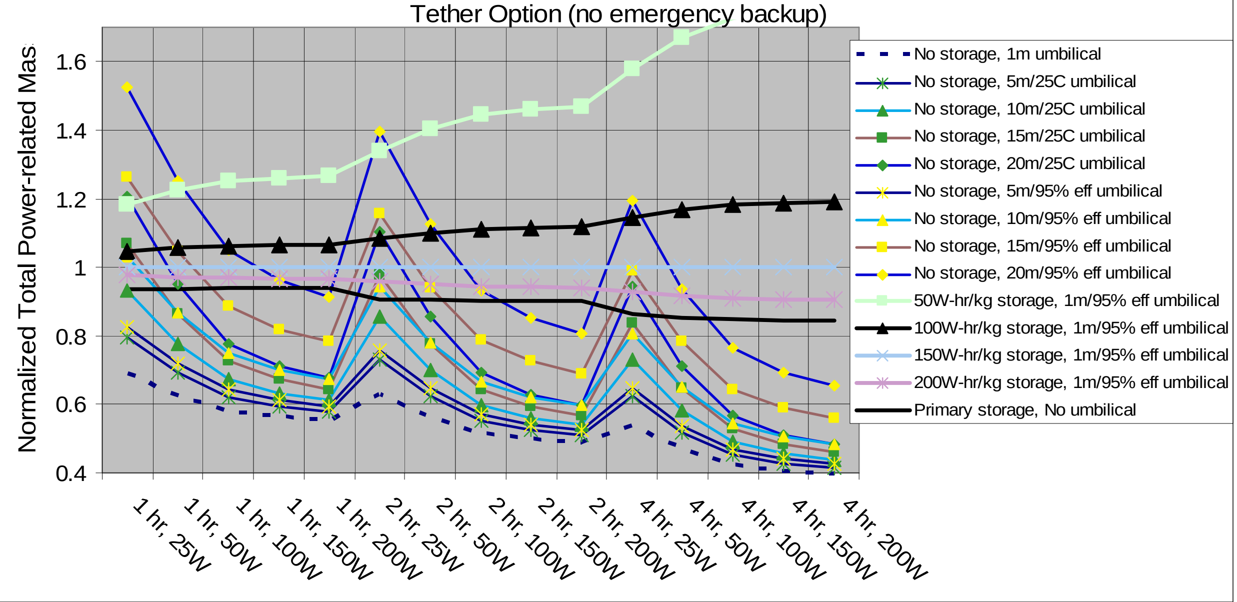
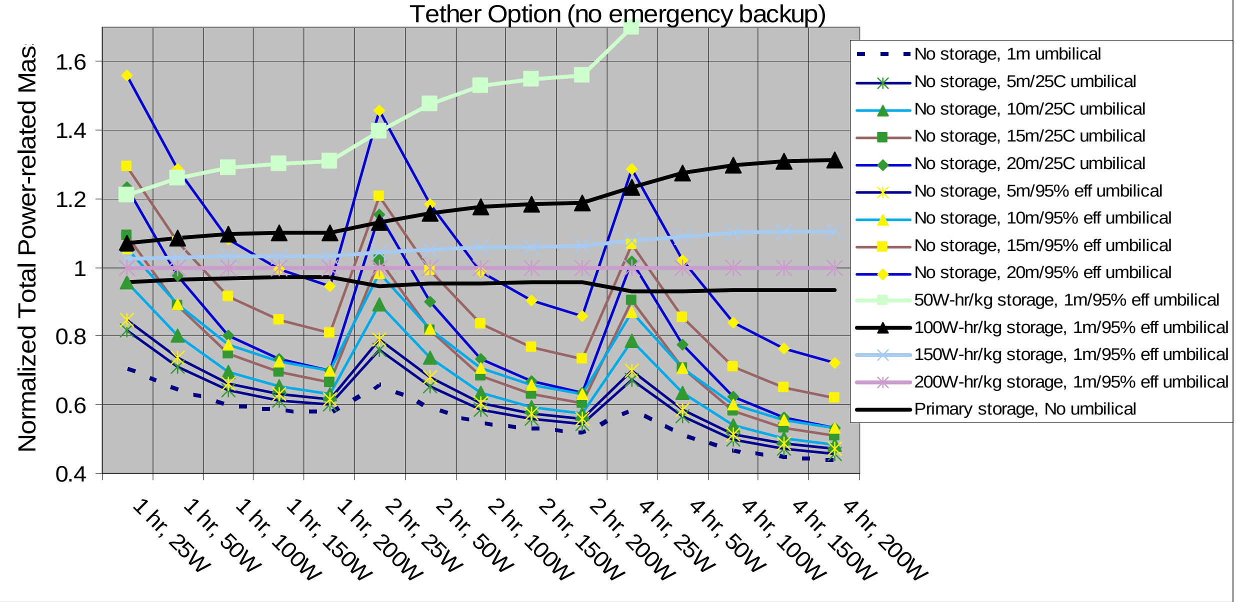
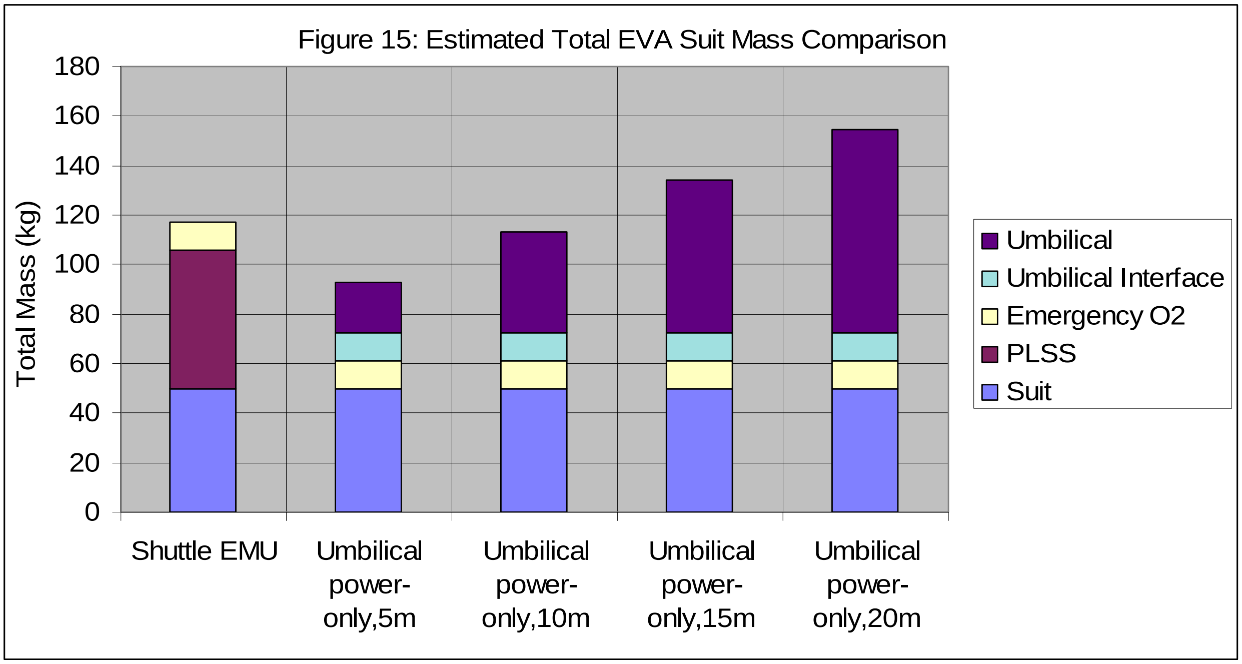


Figure 14:Ratio of Power-related Mass Relative to 200 W-hr/kg Secondary Energy/1m Tether Option (no emergency backup)





For reference purposes, results from a past report are presented here. In April 1973, Hamilton Standard published a report called "Space Shuttle EVA/IVA Support Equipment Requirements Study". It included a section comparing self-contained versus umbilical systems. Various options were considered including closed, semi-closed, semi-open and open loop for both types of systems. Various suit operating pressures were examined. The pressure suit by itself weighed from 29.5 kg (for 4 psi) to 34 kg (for 10 psi). Umbilical length of 30 m was reported. The mass of the umbilical was estimated at between 10 to 13 kg. Thus the mass per unit length was .3 kg/m, much smaller than a value based on the existing Shuttle IEU. This report seemed to consider only the aspects affected by pressure level, thus the cooling lines/communications lines/sensors and power cables were excluded. Cooling was done by sublimation and thus no cooling lines are assumed in the umbilical. The water weight, tankage and portion of the thermal control system required for humidity control and equipment loads was included in the basic PLSS weights. Although it is interesting to consider the options other than closed, the problem with those options is that total system mass (including consumables) becomes too high. The report deletes from consideration the closed loop umbilical on the grounds that "The closed loop umbilical system is slightly larger and heavier than the self-contained closed loop system and also has the disadvantage of umbilical management." Figures show that the closed loop umbilical system is ***twice*** as heavy as the self-contained closed loop system. For a 10 psi/closed loop umbilical system, the PLSS and Umbilical mass was estimated at 8.8 kg but for the self-contained closed loop system it was estimated to be 4.9kg (note that the pressurized suit mass of 32 kg and ECLSS mass of 6kg were the same for both systems). No mobility or "management" data was included in the report. The stowed volume for a 30 m umbilical was estimated at 0.2 m^3.

3.6 Other Aspects

The mobility that is provided by eliminating the use of an umbilical is difficult to quantify. A fixed length umbilical almost always implies a maximum distance the astronaut may travel from the airlock (or umbilical connection site). Given that the absolute distance requirement for any possible use is unknown, it is desirable to make this distance as long as possible to account for all uses. Qualitatively, the suit-attached energy storage options offer the maximum mobility while umbilical options offer least mobility.

Another quantitative problem regards "encumberness". This metric is a measure of how difficult it is to move around or operate for a specific suit configuration. For in-space suits, the mass of either the suit or umbilical should not be a concern for the astronaut. However, suit volume, inertia and accelerations are affected by having an energy storage system on the suit. Umbilicals have a problem in that the longer they are (and long ones are usually needed for unknown EVA situations) the more difficult they are to accommodate, manipulate, deploy, situate, retract and stow. They must be routed to minimize damage risk to the spacecraft or to the umbilical. This encumberness metric is some combination of mass and these other aspects. Qualitatively, the encumberness of umbilicals is greater than the self-contained energy system options.

Risk is another measure that must be qualitatively addressed. Long umbilicals have the risk of puncture or severing. However, since such risks can be addressed with emergency backups (for either umbilical-only or suit-mounted power options), it is not necessary to be concerned with such measures at this time.

3.7 Conclusions

Depending upon the requirements of the EVA suit, there are specific mass beneficial niches for the suit-mounted nominal energy storage (either primary/non-rechargeable or secondary/rechargeable) over the umbilical-only power option. These niches are typically low power (<50 W) and low duration (<1 hr). Groundruling that suit-mounted emergency energy storage be used enhances the mass benefits of using nominal suit mounted energy storage. While the total mass benefits are relatively modest (<4 kg for one suit) for typical likely lengths (20 m), the combination of mass benefits with enhanced mobility and reduced encumberness indicates that suit-mounted energy storage options should be considered for contingency in-space EVA use.

Although suit-mounted primary battery energy storage has the best mass benefit, a secondary energy storage is beneficial because it is rechargeable (thus providing multiple uses) and more forwardly compatible to future uses (surface suit). Any use of secondary energy storage would require limited duration sorties to enable recharge of the batteries (and other resources). Even the relatively poor specific energy option (50 W-hr/kg) is superior to some umbilical power-only options.

These power system mass savings are relatively modest, especially in terms of an in-space suit, since zero gravity makes mass somewhat less important (except as it contributes to inertia and acceleration effects). If launch mass is a concern, these savings are negligible. However, if the remaining umbilical mass elements are considered, sizable launch mass savings are created by using a suit-mounted system. Including these other umbilical mass elements (cooling, O_2, etc) shows that umbilicals with a length of 20 m may weigh as much as 40kg more (and likely much more due to mass of umbilical infrastructure/mechanisms and O_2/cooling fluids inside the umbilical) per suit than suit-mounted energy options.

Umbilical-only power is the best selection for in-space (pressurized/in-cabin) suits. There is no justification to use suit-mounted energy storage for such suit. Surface suits favor suit-mounted energy storage with short umbilicals for recharge (longer umbilicals are not favored for surface suits because of dust, wear, abrasion and severing concerns, as well as reduced mobility and increased encumberness).

Non-rechargeable energy options have the benefit of maximum mobility (because they are not tied to a power recharge port but other resources may still need an umbilical) although the EVA duration has a relatively short "hard" time limit which requires swap out of the energy storage to accommodate.

Umbilical power-only options (with our without emergency backup) have "unlimited" EVA duration and are fairly reusable (potential for numerous separate EVAs are possible with same hardware) although the mobility (range of travel and encumberness) is limited and mass is likely a problem for longer lengths.

3.8 Future Modifications:

1) Adjust the minimum wire gauge from AWG 22 (which may be excessive) to 24 to 26 AWG for power levels below 50 W. Base gauge selections on standards such as "JSC-49894 Electronic Part Selection and Design Guidelines for Low Criticality Space Flight Payloads" and "NASA-STD-8739.4 Requirements for Interconnecting Cables, Harnesses and Wiring, Crimping, Interconnecting Cables, Harnesses and Wiring".

2) Include reliability and availability analysis on power system design topology (e.g., number of redundant wire pairs, battery cell connectivity).

3) Consider zinc-oxygen primary batteries. The 1973 Hamilton Standard report mentioned that although these zinc-air (oxygen) primary batteries had the highest specific energy, they were ground ruled out for the self contained EVA suit because of an only 7 day activation life and it requires an oxygen flow of at least 48 cc/min to meet the requirements and thus poses an interface within the PLSS not otherwise present. Assuming a pure O_2 instead of air feed into the battery could address the activation life issue. Assuming a clean sheet PLSS, the O_2 interface should be permissible. The O_2 mass needed to supply the system must be accounted (which it is not clear that they did in the trade study) and added interconnects/pressure lines for the oxygen must be considered. Currently, a company called Electric Fuel has zinc-air batteries rated at 350 W-hr/kg and a 800 W-hr battery pack based on 30 A-hr cells (12 to 24 V). Such batteries have even been proposed to be "rechargeable" on the anode level via "anode cassettes"

4) Examine effects of multiple recharge/umbilical attach points on CEV (assuming small suit-mounted translation power system)

4.0 Trade Study 4: Lunar Surface EVA Suit Power Subsystem Rapid Recharge Versus Replace

Date: May 26, 2006

4.1 Results Summary

This trade study assessed both the PLSS and Rapid Recharge System (RRS) Station power subsystem masses for supporting lunar surface EVA operations. Options considered included 8 hr PLSS and 4 hr PLSS with recharging, refilling or replacing of the energy storage subsystem. The results of the trade study showed that primary fuel cell and battery (with specific energy >=200 W-hr/kg) energy storage options provide the lowest PLSS power subsystem mass. Given the low PLSS mass savings involved (<3 kg for >=100 W PLSS options), PLSS power subsystem rapid replacement, refilling or recharging is not justifiable. However, if low PLSS mass savings are desired, PLSS energy storage replacement or refilling can be performed with a low to moderate RRS Station mass (5 to 42 kg for a 100 W PLSS). For >=265 W-hr/kg battery PLSS options, recharge can be performed with 'heavy' RRS Stations (>160 kg for a 100 W PLSS). Solar energy reduces RRS Station mass modestly, but inductive charging increases both the PLSS and RRS Station mass. Recharging both suits simultaneously during 15 min has large thermal and electronics impacts thus either sequential recharging or longer recharge times should be considered.

4.2 Introduction

The goal of this trade study is to identify power subsystem options which minimize the mass of the lunar surface EVA suit PLSS and EVA PLSS support equipment (called the RRS Station). This report is divided into sections that 1) describe the options considered and their assumptions, 2) size the PLSS power subsystem options, 3) use the PLSS sizing results to help size the RRS Station options, 4) combine the PLSS and RRS Station power subsystem masses for a 'net' mass metric and 4) generate a ranking table to compare the relative benefits of all options.

4.3 PLSS Power Subsystem Options

Table 1 lists the various PLSS power subsystem options considered for this trade study.

TABLE 1.—PLSS POWER SYSTEM OPTIONS

Energy Storage Option				Energy Storage type	Battery Specific Energy, W-hr/kg	Max charge rate	15 min recharge from this depth of discharge, percent	Vendor/ comment
8 hr	4 hr Replace	4 hr Refill	4 hr Recharge					
X	X		X	Li ion battery	100	1C	25	Note 1
X	X		X	Li ion battery	150	1C	25	Note 1
X	X		X	Li polymer battery	200	1C	25	Note 1
X	X		X	Li sulfur battery	265	3C	75	Sion claimed present capability
X	X		X	Li sulfur battery	318	6C	80	Sion claimed present capability
X	X	X		Primary fuel cell (H_2/O_2)	-----	---	---	Note 1
			X	Nickel metal hydride	65	7C	80	Electroenergy claimed present capability
			X	Li ion battery	85	7C	80	A123 claimed present capability
			X	Li ion battery	100	2C	50	Note 1
			X	Li ion battery	150	2C	50	Note 1
			X	Li polymer battery	200	2C	50	Note 1

The left four columns indicate whether the particular battery or fuel cell option (as defined by the right four columns) was considered for the various 'Energy Storage Options'.

The ‘8 hr’ energy storage option has the energy storage sized for a full 8 hr EVA, thus, has no in situ recharge/replacement/refilling and no RRS Station is needed (at least for the power subsystem).

The ‘4 hr Replace/Refill’ energy storage options have the PLSS power subsystem sized for a 4 hr EVA. The PLSS is designed with replaceable battery modules or fuel cell tank modules (PLSS $H_2/O_2/H_2O$ tanks clustered together for simultaneous removal). Such replacements add to the design complexity and increase risk. Replacement requires either two astronauts (since the energy storage has traditionally been on the back of the astronaut) or the energy storage be located more forwardly accessible. For primary fuel cell refilling, high pressure recharge of the PLSS fuel cell tanks via a hose connection to the RRS Station is required. The pressurization level is based on safe flow rates to accommodate 15 min refilling in a non-optimum (dusty) environment. The RRS Station is designed to store and maintain either module type (or the high pressure refilling equipment and tanks) for a 7 day period prior to the EVA activity. After this 7 day period, a single, 4 hr EVA replace/refill capability for each of two astronauts is needed at the RRS Station.

The ‘4 hr Recharge’ energy storage option has the PLSS power subsystem sized for a 4 hr EVA but has the PLSS power subsystem recharged within 15 min by the RRS Station. The electrical recharge can be either done conductively or inductively. The RRS Station must simultaneously recharge two astronaut’s PLSS power subsystems within 15 min to provide the ability to perform another 4 hr EVA.

The column ‘Energy Storage Type’ lists those energy storage types considered to be most likely to be used in the lunar surface EVA application. Section 4.8 describes the various battery options in more detail including references to literature in which the characteristics are discussed. Primary (non-rechargeable) batteries were not considered due to their nonrenewable nature. Supercapacitors were not considered due to their very low specific energy. Also, it was assumed that EVA suit-mounted regenerative fuel cells would be impractical for this time frame. Supercritical and cryogenic storage of fuel for primary fuel cell subsystems were not considered at this time due to the added hardware complexities.

The column ‘Battery Specific Energy W-hr/kg’ is the assumed value for this battery type.

The column ‘Max Charge Rate’ is the assumed maximum rate at which the battery can safely be recharged. ‘1C’ indicates the battery may be recharged (from a completely discharged state) in 1 hr. The ‘8 hr’ options may be assumed to be ‘slowly’ recharged/refilled at the base (not at the EVA sortie site). ‘Slow’ (traditional) battery charge methods (=<1C) are battery life/safety friendly. Section 4.8 discusses rapid charging batteries in more detail.

The column ‘15 Minute Recharge From This Depth of Discharge’ is the maximum amount that the battery can be discharged in order to be recharged at the maximum charge rate within 15 min. Thus, for a 1C battery which can be fully recharged from a completely discharge state in 1 hr, it may only be discharged 25 percent in order to recharge the battery completely at 1C within 15 min. The effect of this partial discharging to accommodate the charge rate limitation is that the battery must be oversized to provide the energy requirement within 15 min. For all battery options with less than 4C charge rate, the battery must be oversized. For safety and life reasons, the maximum allowable battery depth of discharge is 80 percent.

Under ‘Vendor/Comment’, some details relating to type of energy storage characteristics are listed. Vendors provide current test data as well as projected capabilities for their products. 'Note 1' indicates that the listed set of metrics were based on a possible range of capabilities for TRL6 by 2010. The methodology of how all of these battery metrics were determined is discussed in detail in Section 4.8.

Note that the battery ‘roundtrip’ efficiency (used in the determination of the amount of energy the RRS Station must provide the PLSS for recharging) was assumed to be 80 percent for NiMH battery types and 90 percent for Li battery types.

4.4 PLSS Power Level Assumptions

Examination of the schematic study results (NASA Crew Robotics And Vehicle Equipment Contract Delivery Order #1–DO-CRAVE-EC5-001) for one EVA suit for a 4 hr EVA showed the required user energy to be 251 W-hr to 2490 W-hr (for a cold environment) and 133 W-hr to 1920 W-hr (for a moderate environment). Assuming only Schematics 3 (the minimum mass option) and 4 (low power in a moderate environment option), the required user energy is ~135 W-hr (for a moderate environment) and ~282 W-hr (for a cold environment). The derived power levels are, thus, ~34 W (for a moderate environment) and ~70 W (for a cold environment). This trade study assumed a range of power levels (25, 50, 100, 150, and 200 W) (as measured at the user electrical load after PLSS power subsystem losses).

4.4.1 PLSS Primary Fuel Cell Assumptions

Three primary fuel cell options were considered: size the primary fuel cell for 8 hr, size it for 4 hr and replace the fuel cell tank cluster and size it for 4 hr and refill the tank cluster using high pressure lines. Refilling the fuel cell tank cluster at the RSS site has some risk due to the required fluid connection in a dusty environment. However, since recharging of the EVA suit breathing tanks is likely to be required, then similar technologies can be assumed to be used for oxygen connections and recharging. This applicability does not exist for hydrogen recharging, therefore operational and technology development is needed for this gas. For the fuel cell tank cluster replacement option, only the oxygen, hydrogen and water tanks were assumed to be replaced at the RRS Station. The astronaut must be able to access the tanks (by placing them on the front/side or another astronaut must perform the replacement) in a dusty environment. Any quick disconnect/connect valves and attachments must be resistant to dust. It is difficult to estimate replacement times but a 15 min replacement seems feasible. One tank cluster would be used to power during the replacement period of the other cluster.

A model for the primary fuel cell based power subsystem was created based on the data and algorithms listed in the report entitled ‘Small Portable PEM Fuel Cell Systems for NASA Exploration Missions’ (Kenneth A. Burke, NASA/TM—2005-213994, December 2005, AIAA–2005–5680). The key assumptions used in this trade study were mostly derived from this reference. These include the following assumptions. The fuel cell energy conversion efficiency was assumed to be a conservative 60 percent. The fuel cell active area per unit mass was assumed to be 2000 cm^2/kg. The fuel cell discharge current density was assumed to be 0.398 A/cm^2. The cell voltage was assumed to be .8V. The high pressure H_2/O_2 tanks burst pressure was assumed to be 573 atm (this limit is based on 15 min fill rate). A fuel cell stack multiplier (number of independent full power stacks for redundancy in case something should go wrong with one stack) was assumed to be 3.0. A tank cluster multiplier (number of tanks to split the fuel into for redundancy in case something should go wrong with one tank cluster) was assumed to be 2.0. Ancillary Equipment specific power was assumed to be 0.002 kg/ W. The other fuel cell packaging/insulation mass fraction was assumed to be 25 percent of all the other fuel cell mass.

4.4.2 Recharge Methods

There are two methods to provide electricity from the RRS Station to the PLSS power subsystem. Section 4.9 goes into more detail on these and includes various references to technical literature. These methods are summarized here.

4.4.2.1 Conductive

This method relies upon a traditional direct electrical connection (wires/cable harness) from RRS Station to PLSS. In order to reduce the mass carried on the EVA suit, this method assumes that any high power charge electronics (i.e., battery charge regulator, DC-DC converter) are located in the RRS Station.

4.4.2.2 Inductive

This method uses a noncontact method to transfer the electricity from the RRS Station to the PLSS power subsystem. DC power is converted at the RRS Station to high frequency AC power. The power is then transferred over a narrow gap (which depends upon the design) via separate halves of a transformer (one on RRS Station side and one on PLSS side). The AC power is converted back to DC in the PLSS using electronics which then charge the batteries. This method has been used in underwater vehicles and electric cars and the main reason it is considered for lunar operational use is because of the potential reduced impact of dust on power connections (i.e., enhanced power/current safety).

Sizing characteristics of inductive chargers include the inductor specific power (one ‘half’ only) of 370 W/kg with an inductor efficiency of 90 percent. Also, high power PLSS-side recharge electronics must be accounted for (i.e., AC-DC converter, battery charge regulator). Transfer of data is possible inductively (done with underwater vehicles) and may be needed to control the battery charging.

4.4.3 Other PLSS Power Subsystem Sizing Assumptions

Numerous other assumptions must be made in order to size the PLSS power subsystem.

For thermal sizing, the mass of the power-related thermal subsystem is based on specific power where the power level considered is the load power. For the 8-hr battery and 4-hr battery replacement options, the thermal loads are ‘nominal’ and a specific power of 0.01kg/ W was assumed to estimate the mass. However, higher thermal loads are assumed for all primary fuel cell options (due to primary fuel cell 60 percent efficiency) and all recharge options (15 min recharge effect and battery efficiency impact). For these the thermal subsystem specific power was assumed to be double the nominal value (0.02 kg/W). All thermal mass estimates are very rough and require more detailed analysis.

For structure sizing, the mass is estimated as a fraction of the mass the structure must hold or contain. Two classes of structures are energy storage structure and electronics structure. The ‘nominal’ level of structure (all energy storage options except replacement options) assume that the energy storage structure mass is 10 percent of the energy storage mass. All replacement options (batteries or primary fuel cells) require extra structure for mechanisms that can be used in a dusty environment by gloved astronauts, thus, the energy storage structure mass is assumed to be 20 percent of energy storage mass. Also, for replacement, an extra 10 percent is added to the nominal mass of power cables/interconnects to account for enhanced dust resistance and astronaut handling/durability/aids.

For electronics sizing, it was assumed that the power was delivered to the user at 28 Vdc. Electronics components were sized based on specific powers derived from spacecraft historical data. The battery regulator was assumed to be 0.02 kg/ W with an efficiency of 90 percent. The power distribution unit was assumed to be 0.02 kg/ W with an efficiency of 99 percent. And the DC-DC converters were assumed to be 0.0125 kg/ W with 95 percent efficiency.

In order to size the distribution cables connecting the centralized PLSS power subsystem to the loads throughout the EVA suit, a distribution of the user power to various sites had to be assumed (Table 2). Because of the low power levels for distribution, cable sizing is based on minimum mass down to the minimum wire radius (.032cm). At these wire radii, the efficiencies are very high and losses low.

TABLE 2.—USER POWER DISTRIBUTION

Load Location	Cable distance (m)	Local	Load	Power	Level	(W)
Left hand	1	2.5	5.0	10.0	15.0	20.0
Right hand	1	2.5	5.0	10.0	15.0	20.0
Left foot	1.5	1.9	3.9	7.7	11.6	15.5
Right foot	1.5	1.9	3.9	7.7	11.6	15.5
Helmet	0.66	0.9	1.7	3.5	5.2	7.0
Back	0.33	13.7	27.5	55.0	82.5	110.0
Chest	0.5	1.5	3.0	6.0	9.0	12.0
Total user power level, W		25	50	100	150	200

DC-DC converters were assumed to be needed at each load site to converter power for computer electronics. It was assumed that 20 percent of the allocated electrical load at each load site would be converted for this use.

Some power cables (between the battery modules and discharge regulator, between the discharge regulator and power distribution unit, and between the power distribution unit and a DC-DC converter) were sized using a simplified method (e.g., 99.9 percent efficiency and .001 kg/W_net_suit power).

High current charging cables for the various recharge options had to be sized using cable design algorithms. PLSS side recharging cable mass had to be sized to not exceed a temperature of 293 K while being able to handle the high currents that occur for 15 min recharging. In order to generate a minimum PLSS-side mass as well as reduce electrical losses/thermal loads, the PLSS-side electrical recharging cables are assumed to be the shortest practical length. For this trade study, the length was assumed to be 0.15 m from the connector (into which external power is input into the PLSS) to the battery (e.g., if the battery is on the backpack, then the connector is on the back). The implication of this approach is that either two astronauts are needed to connect the RRS Station recharging line to the back of the PLSS, or the PLSS energy storage components are front or side EVA-suit mounted, or a specialized 'backup-into' self-connection assembly is utilized at the RRS Station. Li batteries, because they have smaller amp-hour sizes, require more, separate cables if the charge regulation unit is assumed to be on the RRS Station. The mass of such charge cables for Li batteries are about three times the mass of NiMH battery charge cables (1 A-hr versus 6 A-hr). Note that the charging power cables require two backup power cable pairs to assure that the batteries can be charged even with two faults in the cables. For NiMH battery types, the recharge cable mass ranges from 0.03 kg (1 cable for 25 W PLSS/excluding redundancy) to 0.24 kg (six cables for 200 W PLSS). For Li battery types, the recharge cable mass is from 0.13kg (5 cables for 25 W PLSS) to 0.89kg (35 cables for 200 W PLSS).

For the PLSS-side refill high pressure lines, it was assumed that they were the shortest practical length in order to minimum mass and enhance safety. The implication of this approach is that either two astronauts are needed to connect the RRS Station refilling line to the back of the PLSS, or the PLSS energy storage components are front or side EVA-suit-mounted, or a specialized 'backup-into' self-connection assembly is utilized at the RRS Station.

It was assumed that reliable, safe and practical designs operated by a suited astronaut in a dusty lunar environment can be implemented for low and high power/current electrical connections (for data and power), high pressure H_2/O_2 connections, low pressure H_2O connections and mechanisms/hinges.

4.4.4 PLSS Power Subsystem Redundancy Assumptions

The PLSS power subsystem must include consideration of redundancy to enhance reliability and astronaut safety. Each energy storage options as well as other aspects of the power subsystem must address redundancy.

For the various battery energy storage options, it was assumed that it would be designed such that no extra mass would be required to achieve redundancy (i.e., no extra battery modules or extra cells within each battery). This was felt to be feasible since the quantity of battery modules were likely greater than two and each module likely composed of multiple cells. Thus, in case of a module level failure, the PLSS could operate at reduced power levels with the remaining battery module until the failed battery module is replaced. It is groundruled that the design would have more than one battery module and that they are operated to permit safe return to a replacement station.

For the primary fuel cell option, the fuel cell stack was assumed to have three full power backups. It was assumed the fuel and storage was separated into two separate fuel cell tank clusters. In the unlikely event that there are two total failures of the fuel cell stack, the fuel cell can still provide the full nominal power level. In case one fuel cell tank cluster fails for any reason, the remaining tank cluster can be used to provide the nominal power level for a reduced time (or a reduced power level for a longer time).

For all PLSS power subsystem options, it was assumed that power cables for nonessential loads (i.e., all loads except those on the back of the EVA suit) had one backup cable pair and that power cables for essential loads (i.e., only one assumed to be located on the back of EVA suit) had two backup cable pairs. All electronics are assumed to have internal redundancy. In general, all power subsystem components were assumed to have inherent 'high' (yet currently undefined) reliability.

Despite these considerations and assumptions for redundancy, the mass required for the contingency power subsystem was also included within the total PLSS power subsystem mass. This was assumed because of historical safety considerations on Shuttle suits and because assurance of astronaut safety is of paramount importance. It is assumed that powered hardware is an absolute requirement for safe suit operation, thus a backup power system is needed in case of an emergency condition. Such a contingency power subsystem may be used instead of relying on redundancy or in addition to redundancy but is nevertheless a groundruled requirement. The depth of discharge for the contingency primary battery is assumed to be 90 percent.

Other PLSS power subsystem sizing assumptions are included in Table 3.

TABLE 3.—PLSS POWER SUBSYSTEM SIZING ASSUMPTIONS

Power Subsystem Parameters		
Voltage Type		Direct Current
Voltage Level	V	28
Total Site Power Into DCDC Converter	percent	20
Total Load Levels Considered	W	25, 50,100,150,200
Cable Parameters		
Cable Wire Material		Copper
Cable Wire Density	gm/cm^3	8.9
Cable temperature	K	279
Cable Power Safety Factor		2
Number of Redundant Cable Pairs/Transmission Line		1
Cable Jacket Filler Density	gm/cm^3	1.7
Insulator Density	gm/cm^3	1.7
Cable Jacket Density	gm/cm^3	1.7
Insulation Dielectric Strength Safety Factor		2
Contingency Parameters		
Contingency Energy Storage Specific Energy	W-hr/kg	220
Contingency Energy Storage Load Level	W	25
Contingency Energy Storage Load Duration	min	30
Component Specific Powers		
DCDC Converter Specific Power	kg/W	0.0125
Power Distribution Unit Specific Power	kg/W	0.02
Discharge Regulator Unit Specific Power	kg/W	0.02
Nondistribution Cable Specific Power	kg/W	1000
Component Efficiencies		
DCDC Converter Efficiency	percent	95
Power Distribution Unit Efficiency	percent	99
Discharge Regulator Unit Efficiency	percent	90
Mass Estimation Parameters		
Connector Mass (Percentage of Cable Mass)	percent	10
Other Power System Structural Mass (Percentage of the DCDC and cable masses)	percent	10

4.4.5 PLSS Power Subsystem Sizing Results

Figures 1 through 8 depict the PLSS power subsystem sizing results. The first three figures show the PLSS power subsystem mass for each of the options for user power levels of 25, 50 and 100 W. The 8 hr Li battery (>=150 W-hr/kg) options, fuel cell (replace and refill) options, replace options and Li battery conductive recharge options (with >=2C charge rate excluding 100 W-hr/kg Li ion) all have competitively low mass. However, rapid charge (e.g., 7C charge rate), NiMH/Li ion options, 100 W-hr/kg Li ion option, all 1C recharge options and inductive charging options have higher masses.

The net mass savings between replacing, recharging and 8 hr PLSS are small enough (i.e., comparing cases A.3/A.4/A.5 with C.3/C.4/C.5 show <3kg savings for 100 W PLSS) to indicate that the added complexities of replacement and recharging are not justified.

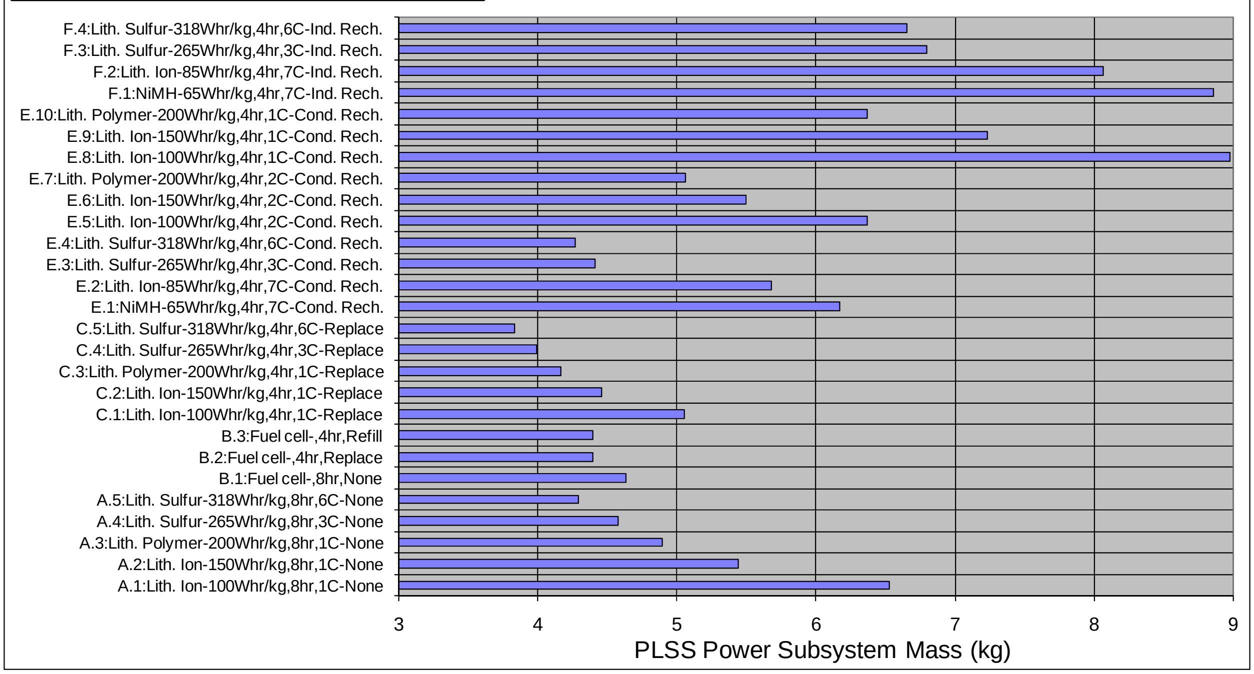


Figure 1: 25W PLSS Power Requirement

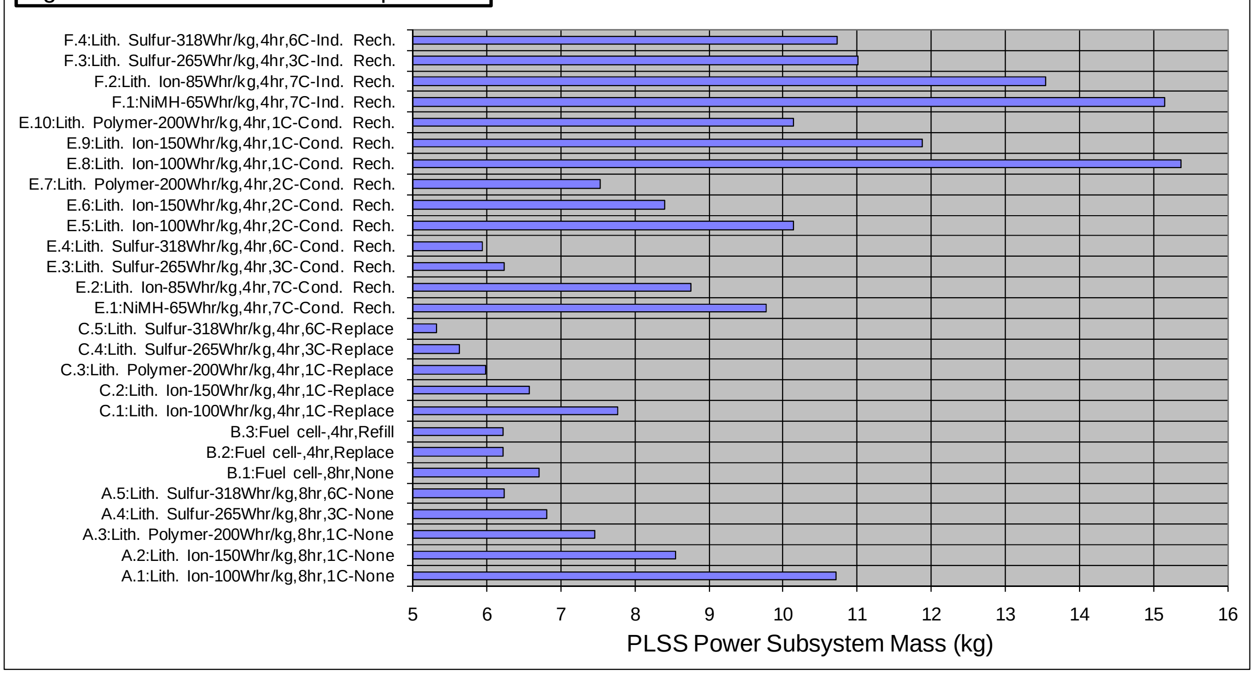


Figure 2: 50W PLSS Power Requirement

Figure 4 depicts the same data as the previous 3 figures except now it is possible for the reader to select user power levels up to 200 W different from the discrete values of 25, 50 and 100 W. To assist in selecting the correct PLSS power subsystem options (which is complicated due to the number of lines/symbols), the legend has been ranked from highest line (top) to lowest line (bottom).

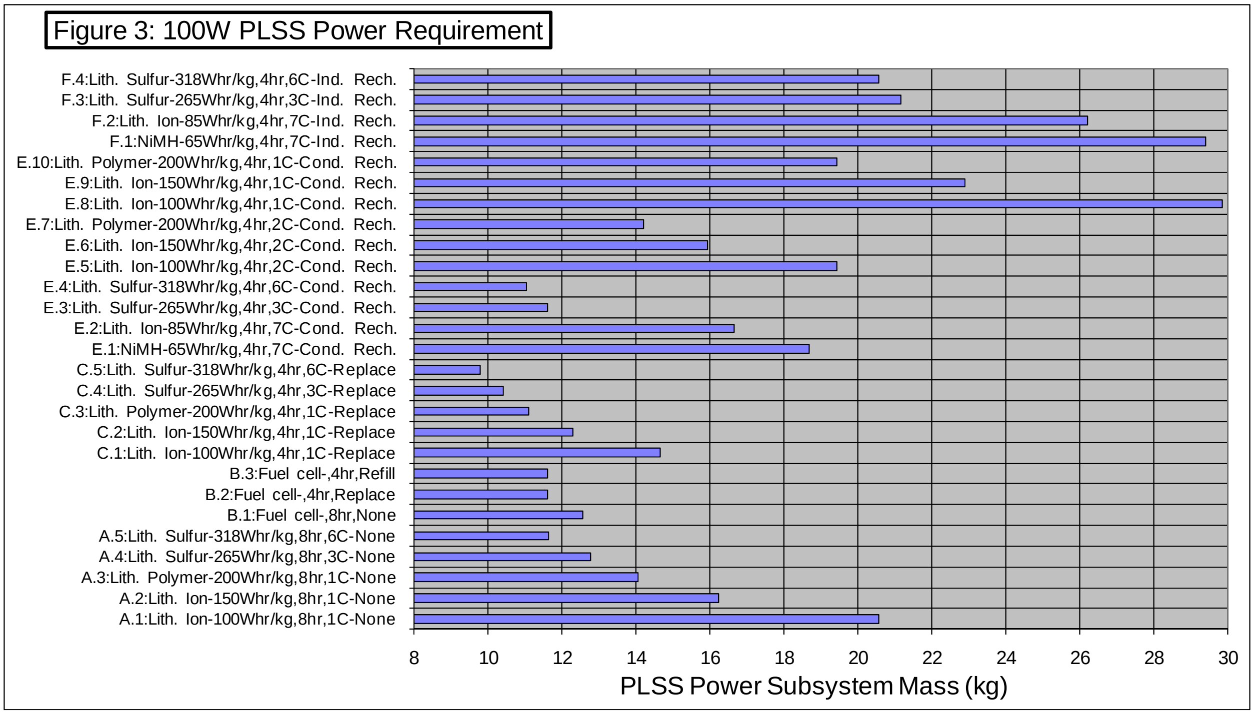


Figure 3: 100W PLSS Power Requirement

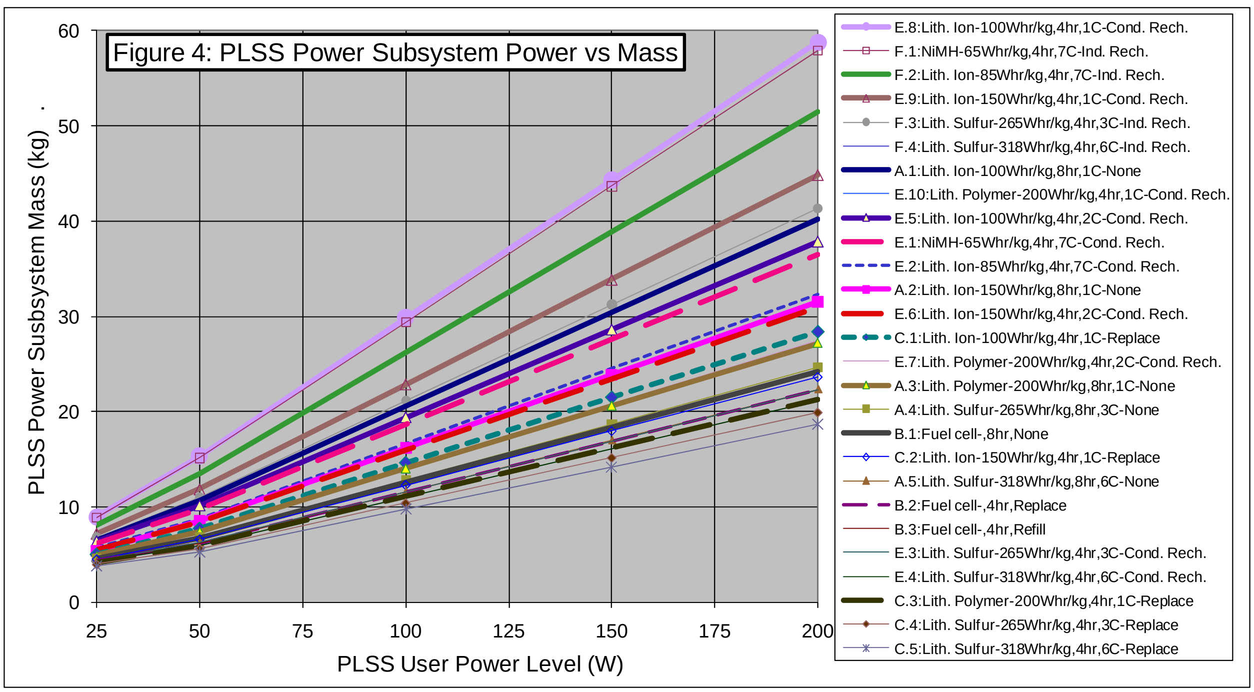


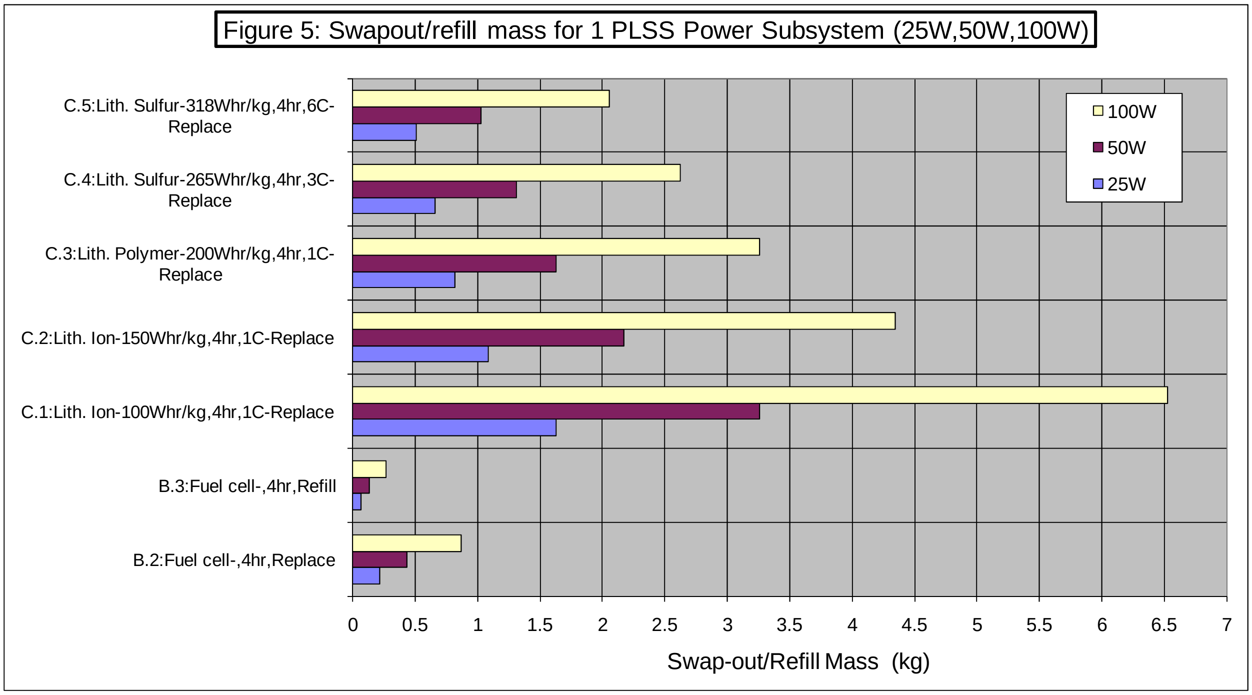
Figure 4: PLSS Power Subsystem Power vs Mass

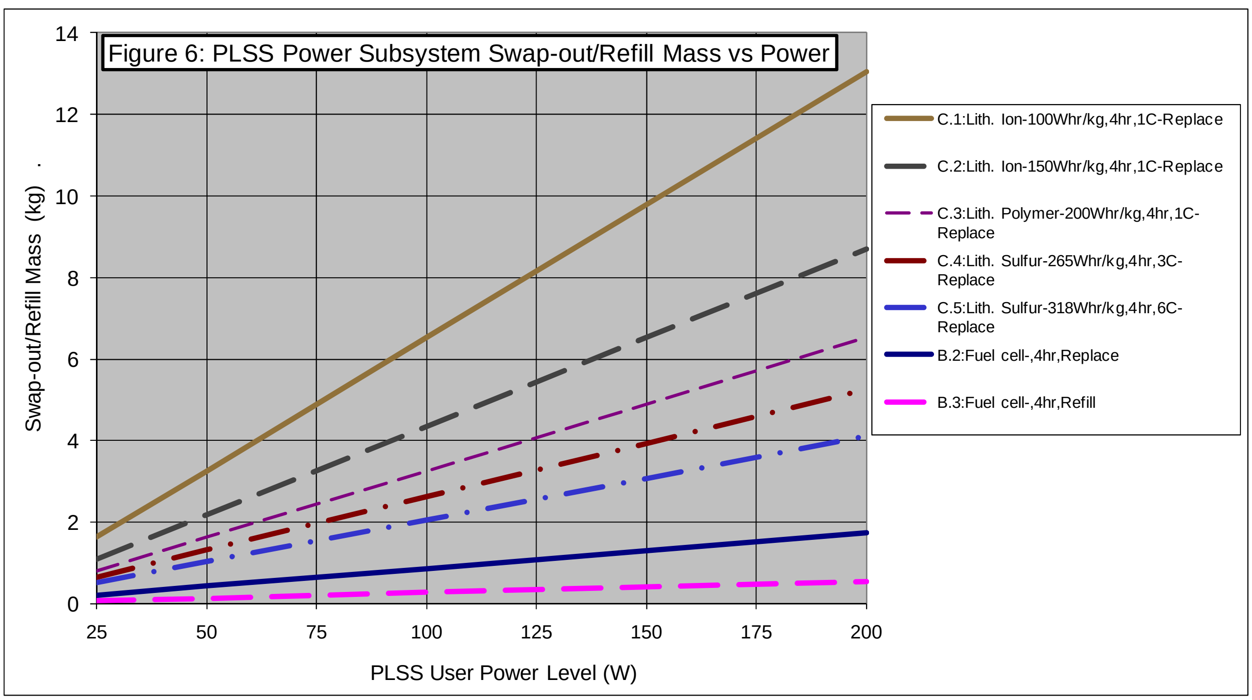
Figure 5 summaries the replacement mass for battery module or fuel cell tank clusters and the fuel cell tank refilling mass for 25, 50 and 100 W PLSS user power levels. For user power levels <=50 W, the replace/refill masses are low. Fuel cell tank replace/refill masses have the lowest required mass.

Figure 6 depicts the data in Figure 5 such that the reader may derive the PLSS power subsystem replace/refill mass for subsystems with user power levels other than 25, 50 and 100 W.

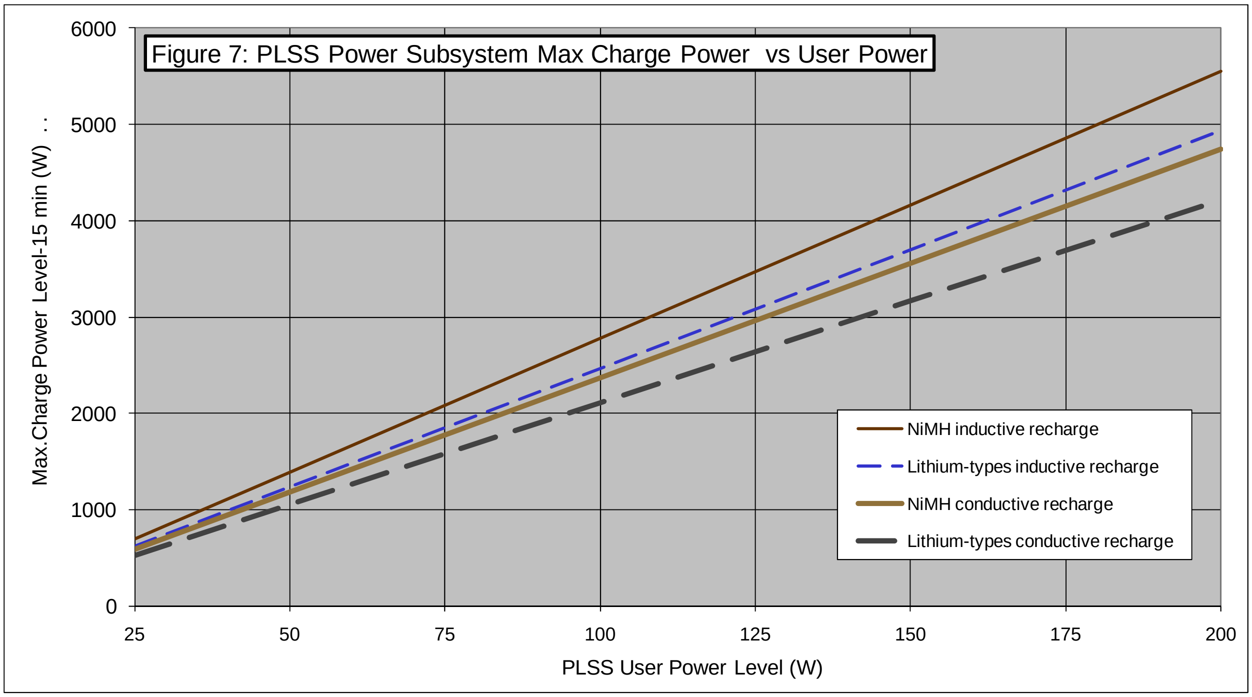
Figure 7 shows the maximum charging power required to recharge the PLSS power subsystem batteries in 15 min. This data is used to size charging cables, charging related electronics and thermal subsystem and affects the RRS Station sizing. In addition to affecting mass, high power levels (and currents) may affect safety.

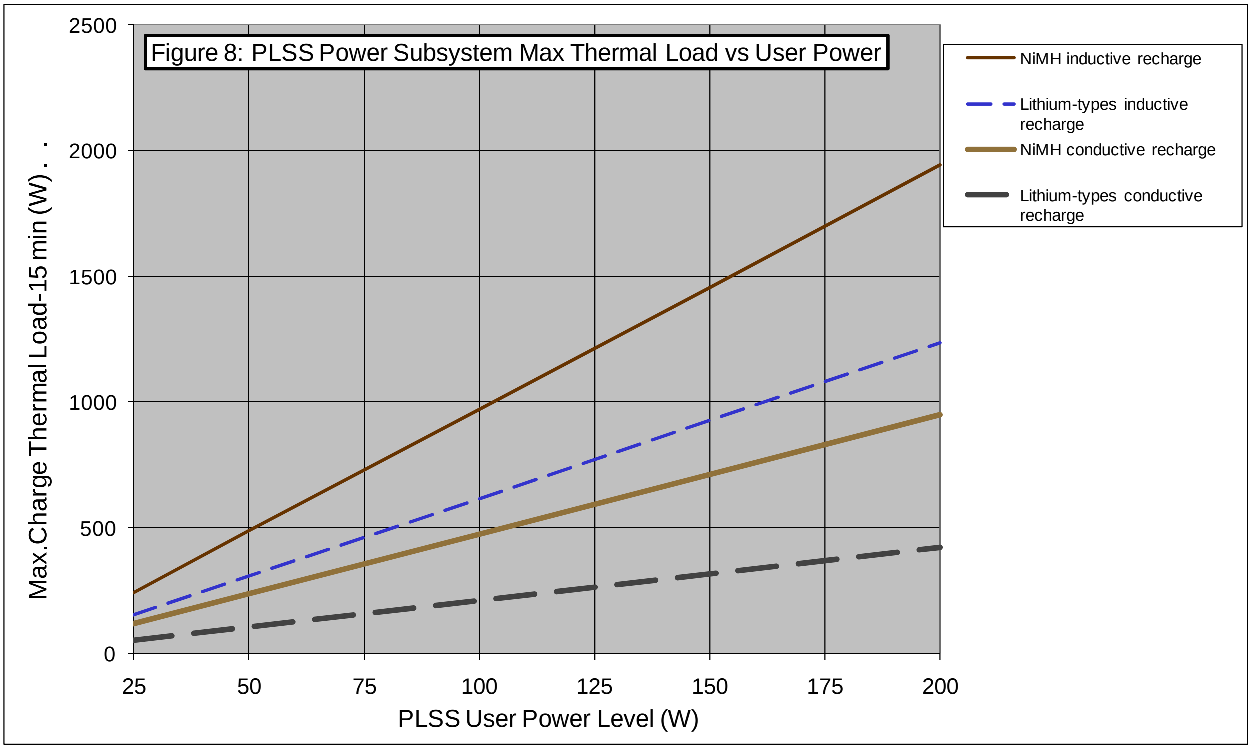
Figure 8 shows the derived thermal load for conductive and inductive recharging of NiMH and Li energy storage types. These thermal loads are due to electronics, battery and charge cable efficiencies. High power/current charging (mandatory for a 15 min recharge) result in high thermal loads which require thermal management to keep the PLSS cool during this period. Such transient loads are likely beyond the capability of the PLSS thermal subsystem unless the user power levels are low or Li conductive recharging PLSS options selected. To address the recharging thermal issues, design options





require: 1) larger PLSS thermal control system mass, 2) coolant loop connection to PLSS from RRS Station or 3) a 'cold plate' attachment from RRS Station onto PLSS thermal system. Each of these options add mass and complexity to the PLSS. Due to the sizing method used, thermal effects/mass must be analyzed in more detail.





4.4.6 RRS Station Power Subsystem Requirements

The RRS Station is used to supply recharging, replacement or refilling resources (in addition to power) for one 4 hr EVA for two astronauts. For PLSS options in which the power subsystem is sized for a full 8 hr EVA, then the RRS Station must still be sized for power to support the recharge/replacing/refilling of other PLSS subsystems. The baseline approach to the RRS Station activity is to assume both astronauts can perform the activity simultaneously and within 15 min. The RRS Station is assumed to be deployed prior to an EVA and the Station maintains the recharging or replacement capabilities both thermally and electrically until needed. Since the Station may be deployed 7 days prior to an EVA activity, the Station must provide its capabilities at the end of the 7 day period. Deployment and operation in either illuminated or shadowed lunar conditions must be considered. The continuous RRS Station housekeeping power is assumed to be an average of 20 W total during the entire 7 day period. This power level is for sensors, electronics and heaters. Power for communications and other power needs have not been considered at this time. Very low power levels are needed for thermal maintenance and/or battery trickle/top off charging.

4.5 RRS Station Power Options

A number of different options were considered for the RRS Station power subsystem. Table 4 lists these options. Separate power sources were considered for both the continuous 'housekeeping' power and for the 'rapid recharge' power. 'Replace/refill' (and also 8 hr PLSS power subsystem) options require only the RRS Station to provide housekeeping power.

TABLE 4.—OPTIONS CONSIDERED

Option type	Housekeeping power source	Rapid recharge power source
Replace/refill	None	None
Replace/refill	Battery (200 W-hr/kg) Li polymer	None
Replace/refill	Battery (318 W-hr/kg) Li sulfur	None
Replace/refill	Solar	None
Replace/refill	Primary fuel cell	None
Replace/refill	Radioisotope (Stirling)	None
Recharge	Solar	Battery (200 W-hr/kg) Li polymer
Recharge	Solar	Battery (318 W-hr/kg) Li sulfur
Recharge	Solar	Primary fuel cell
Recharge	Solar	Solar
Recharge	Radioisotope (Stirling)	Flywheel

Battery and primary fuel cell RRS Station components and their assumptions are similar to those discussed in the PLSS power subsystem sizing section and are not duplicated here.

The ***RRS Station solar power subsystem*** option was assumed to be used when the Station was deployed in illuminated locations. It was assumed to be a one sided, non-tracking solar panel composed of 27 percent efficiency/3-junction gallium arsenide solar cells. The solar panel was assumed to be fixed by the astronaut to the optimum solar pointing for the particular 7 day deployment. This resulted in a pointing factor of 91 percent (100 percent=perfect continuous pointing, 50 percent= pointed perfectly at the Sun half the time and away from the Sun the other half). The solar panel was sized including 7 percent albedo energy reflected from the surrounding lunar surface and the solar panel was assumed to operate at 100C. The solar array regulator efficiency was assumed to have 95 percent efficiency and a specific power of 50 W/kg. Typical solar RRS Station sizing results show that the solar array by itself has a specific power of ~170 W/kg but when all other power subsystem masses are included (electronics, thermal, structure, harness/cables), this value goes down to ~10 W/kg. The total surface area of the solar panel to provide a continuous 20 W 'housekeeping' power is 0.13 m^2. For the total surface area of the 'rapid recharge' solar panel, the areal power is ~200 W/m^2 where the power used is the peak charge power. For a 15 min conductive recharge of two 25 W PLSS power subsystems, the total area needed is

~5 m^2 and this goes to ~11 m^2 for two 50 W PLSS units. Values above 10 m^2 seem unrealistic for this application.

The ***RRS Station Radioisotope power subsystem*** (RPS) option was considered because of its usefulness during continuous non-illuminated (lunar night/shadowed) operations. The two primary methods of converting thermal heat to electricity are advanced Stirling conversion (37 percent converter efficiency and 30 percent system efficiency) and thermoelectric (6 percent system efficiency). Because of the scarcity and expense of the radioisotope fuel, advanced Stirling, whose high conversion efficiency reduces the amount of fuel, was baselined (e.g., for every Stirling 1 fuel unit, 5 thermoelectric fuel units are needed). Although Stirling power subsystems have a limiting external operational temperature of 100 °C (lunar max. is 120 °C), this limitation may be mitigated through judicious thermal orientation/management. RPS was not considered for high power recharge due to large amount of fuel required. Also, since the smallest RPS size is sized for 1 fuel unit, the minimum power level provided by Stirling is 65 We while for thermoelectric the 20 W required power is feasible using 2 fuel units. Although new development efforts could be performed to design smaller Stirling units, this may not be an issue since it is likely that the RRS Station power needs will exceed 20 W in any event.

The ***RRS Station Flywheel energy storage subsystem*** was considered due to its capability for fast charge and discharge and relatively high energy density. Such subsystems are typically designed for 60 min charge and 30 min discharge and are used commercially for uninterruptible power supplies. The concept for using this kind of energy storage would be to pre-deploy the RRS station with the flywheel not spinning. Then, either the solar or RPS power subsystem would be used to spin up the flywheel unit over a period of about 1 day. At that point the energy may be discharged according to the required power level. Note that technology development is required for this kind of flywheel charge/discharge cycle due to modifications needed to the motor/generator. Sizing assumptions based on projected capabilities for the flywheel subsystem show a specific energy of 50 W-hr/kg (with no specialized containment) and 33 W-hr/kg (with containment, i.e., 50 percent of flywheel mass) is possible with adequate funding to TRL6 by 2010. Included in this projection are low power flywheel electronics (10 W startup/operating power per flywheel).

4.6 RRS Station Redundancy Assumptions

Despite the fact that the power subsystem is inherently designed for high reliability, since the RSS Station power subsystem is a critical system, redundancy is included. For the replacement options, it is assumed that one extra module (i.e., PLSS battery module and fuel cell tank cluster) is stored in RRS Station. For the refill (PLSS fuel cell tanks) options, it is assumed that 50 percent more fuel is stored in the RRS Station (only one tank cluster needed on the RRS Station to store the fuel). For the RRS Station battery options, 25 percent more mass is added to account for backup battery modules, cables, and electronics. The lower redundancy percentage is because it is a distributed system (i.e., has numerous battery modules) and the loss of a few would not affect the mission. For the RRS Station solar options, 25 percent more mass is added to account for backup solar cells, interconnects, electronics, and cables. The lower redundancy percentage is because it is a distributed system (with numerous cells). For the RRS Station primary fuel cells option, there are 3 separate stacks and 3 separate tank clusters, each sized for full power/energy. For the RRS Station flywheel option, 3 separate flywheel assemblies (each at full power/energy) were assumed. Flywheels are inherently designed for safety and reliability by way of operation at lower speeds. For the RRS Station radioisotope power option, 3 separate converters/electronics units were assumed (each converter was oversized for this application at 60 W).

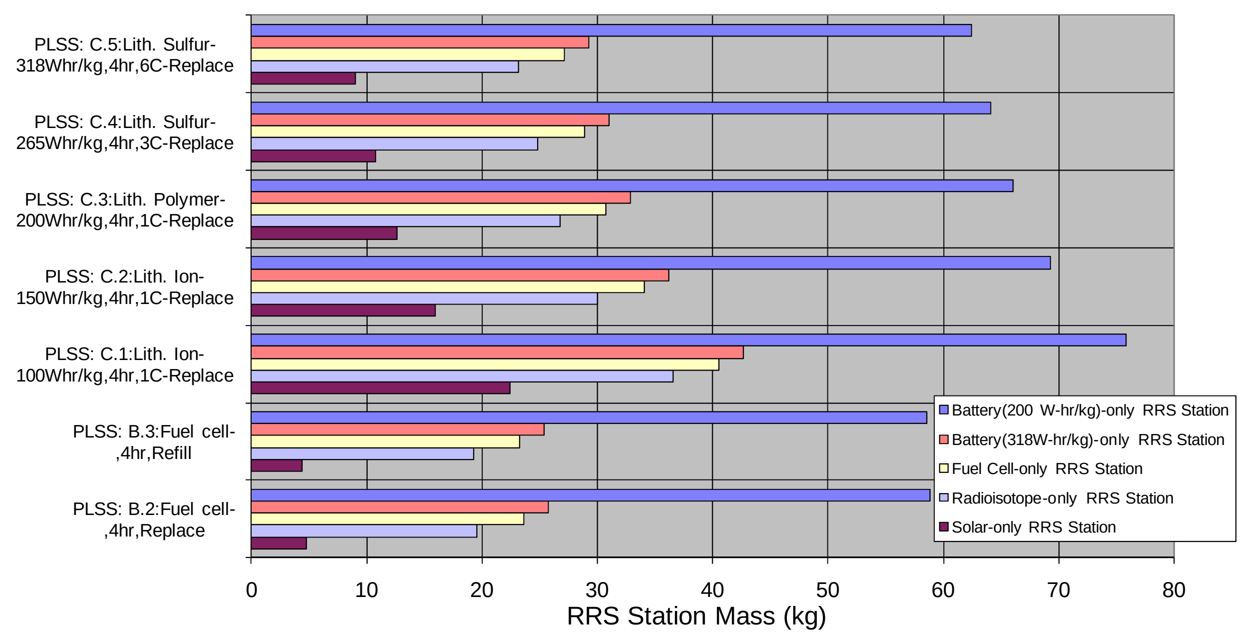
4.6.1 RRS Station Power Subsystem Mass Results

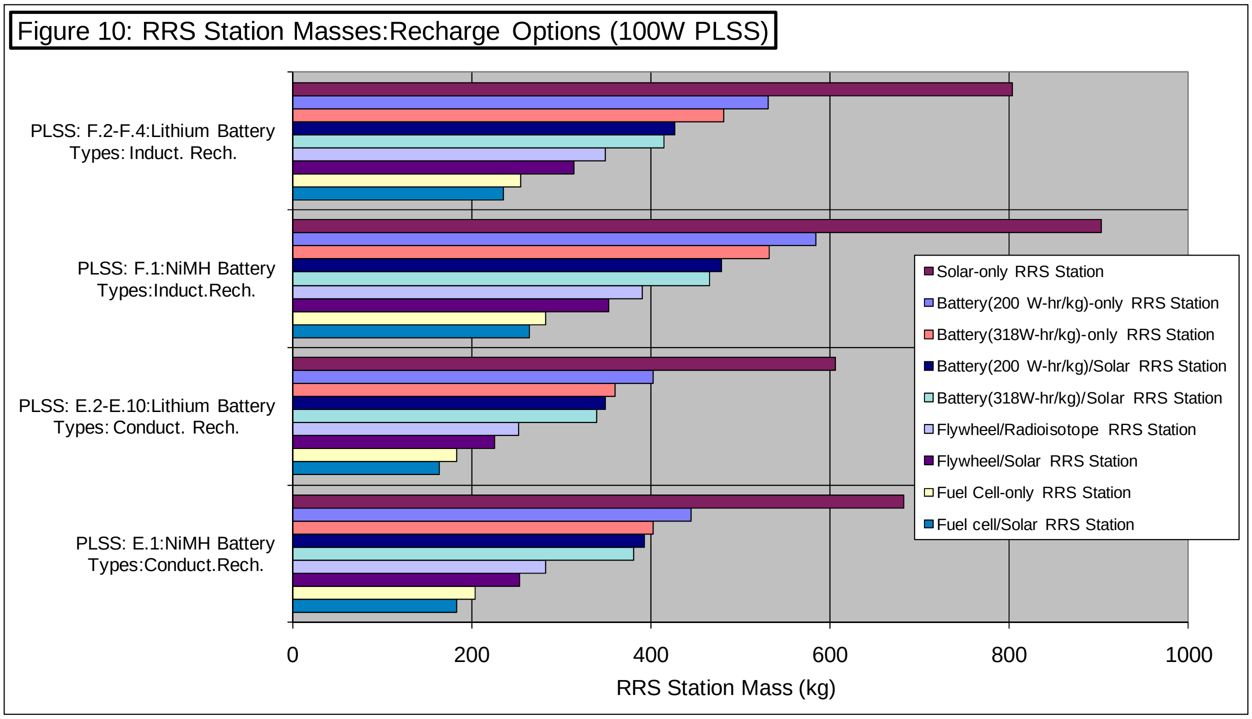
Figures 9 through 19 show the mass for each RRS Station option with each of the PLSS power subsystem recharge/replace options. Figure 9 shows the RRS Station mass for the replace/refill PLSS power subsystem options for a 100 W PLSS user power.

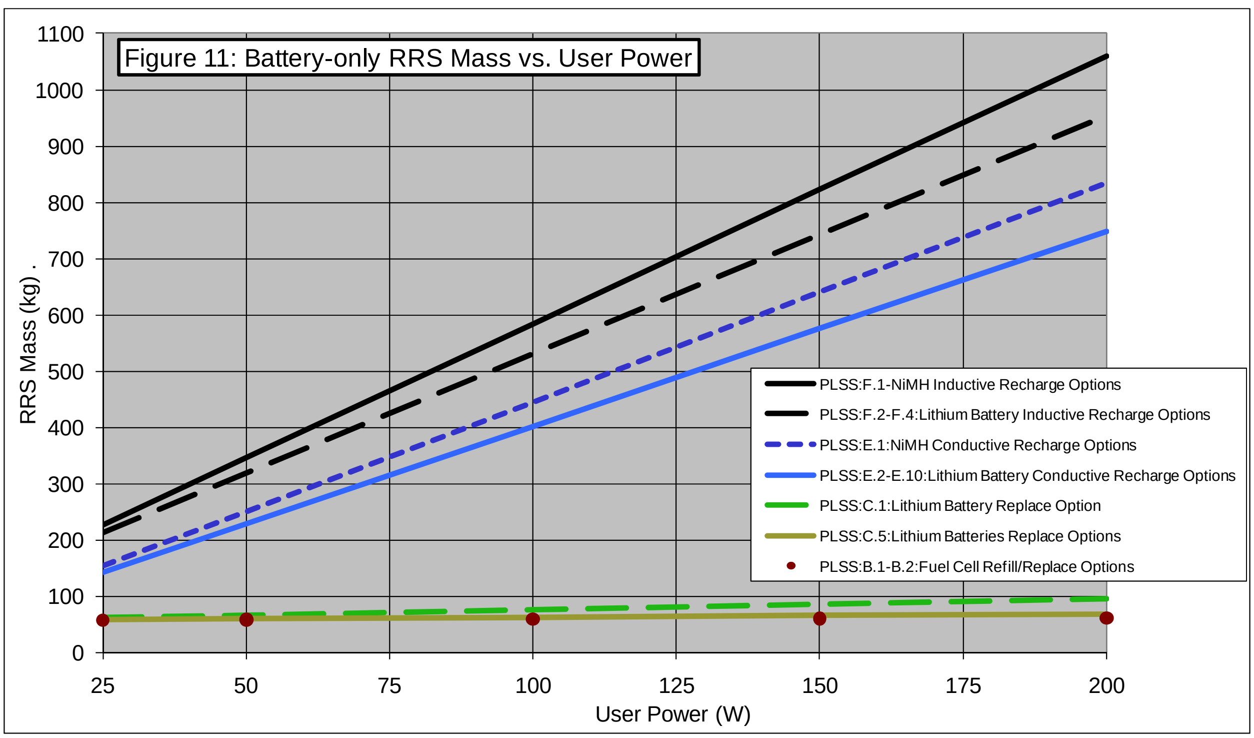
In general, RRS Station options which are used to replace/refill PLSS power subsystems rather than perform a PLSS power subsystem recharge have the lowest mass. This is mainly due to the peak recharging power sizing effects on electronics and thermal subsystems. Solar replace/refill RRS Stations have the lowest mass but are limited to illuminated operation. Radioisotope, fuel cell and 318 W-hr/kg battery RRS Station options are moderate mass options which can operate in non-illuminated conditions. The 200 W-hr/kg battery-only RRS Station option has a relatively high mass. Fuel cell replace/refill PLSS options have the lowest mass RRS Station mass with 318, 265 and 200 W-hr/kg battery replace PLSS options having next lowest mass RRS Stations. For these RRS Station options, < 40 kg RRS Station (for the power subsystem only) seems feasible.

Figure 10 shows the RRS Station mass for the recharge PLSS power subsystem options for a 100 W PLSS user power. The fuel cell and flywheel RRS Station options have the lowest mass. Combining solar for housekeeping power with other energy storage types for recharging provides modest mass savings. Battery-only RRS Station options have close to the highest masses. The solar-only RRS Station option has the largest mass due to the requirement of sizing for the peak charging power. The solar-only option has the potential to have a large area (based on 200 peak_chargingpowerwatts/m^2). Also, inductive charging increases the mass of the RRS Station by 60-200 kg due to inefficiencies of the method.

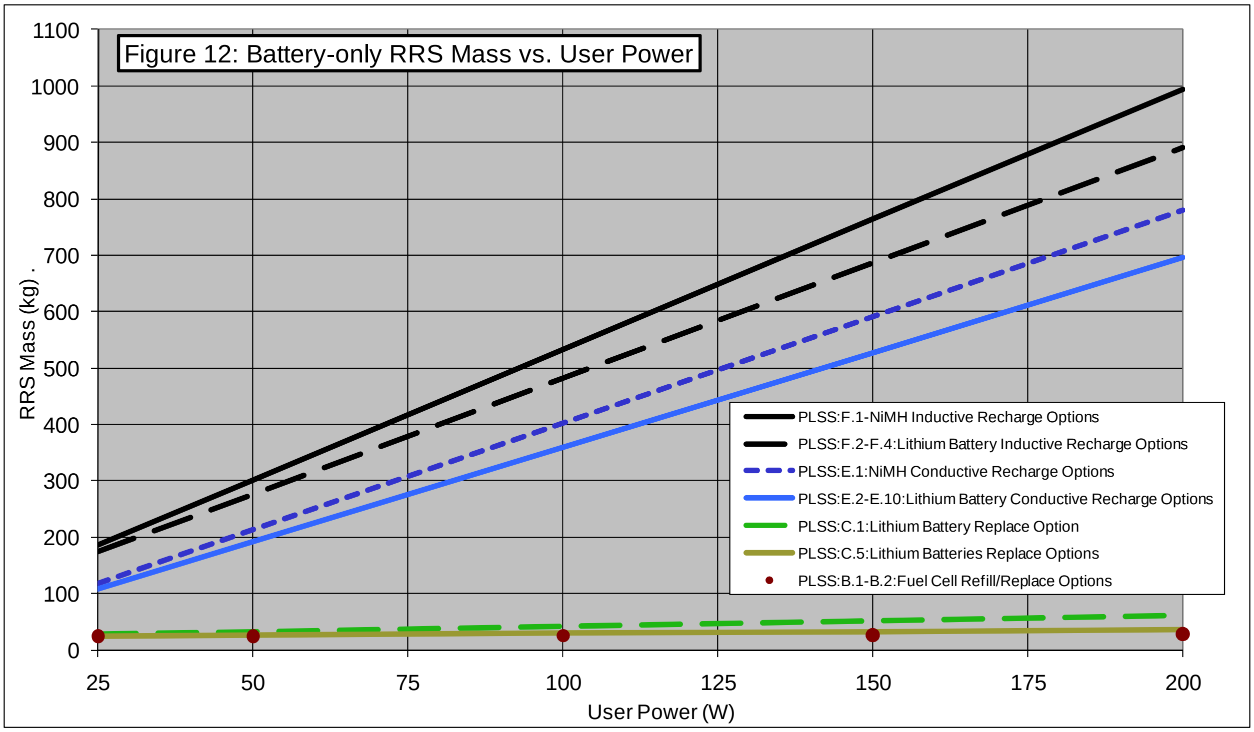
Figure 9: RRS Station Masses:Replace/Refill Options (100W PLSS)

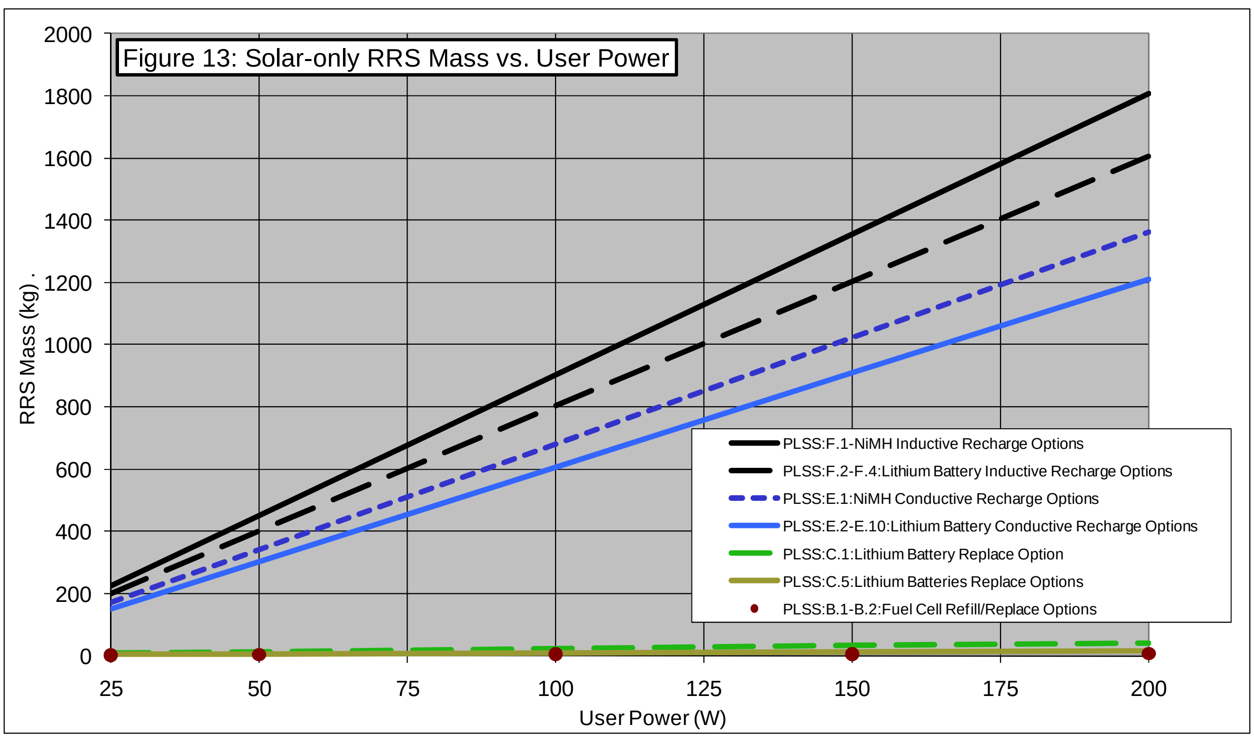






Figures 11 through 19 show the RRS Station mass from the previous figures in a different format to permit the reader to select different PLSS user powers from the 25 W, 50 W and 100 W values. Each figure represents a different RRS Station power subsystem options as reflected in its title. The legend for each figure lists the various PLSS power subsystem options. The order of the items in the legend is based on the magnitude of the line in the figure. Recharge RRS Station options have much steeper slopes and relatively higher magnitudes compared to replace/refill RRS Station options.





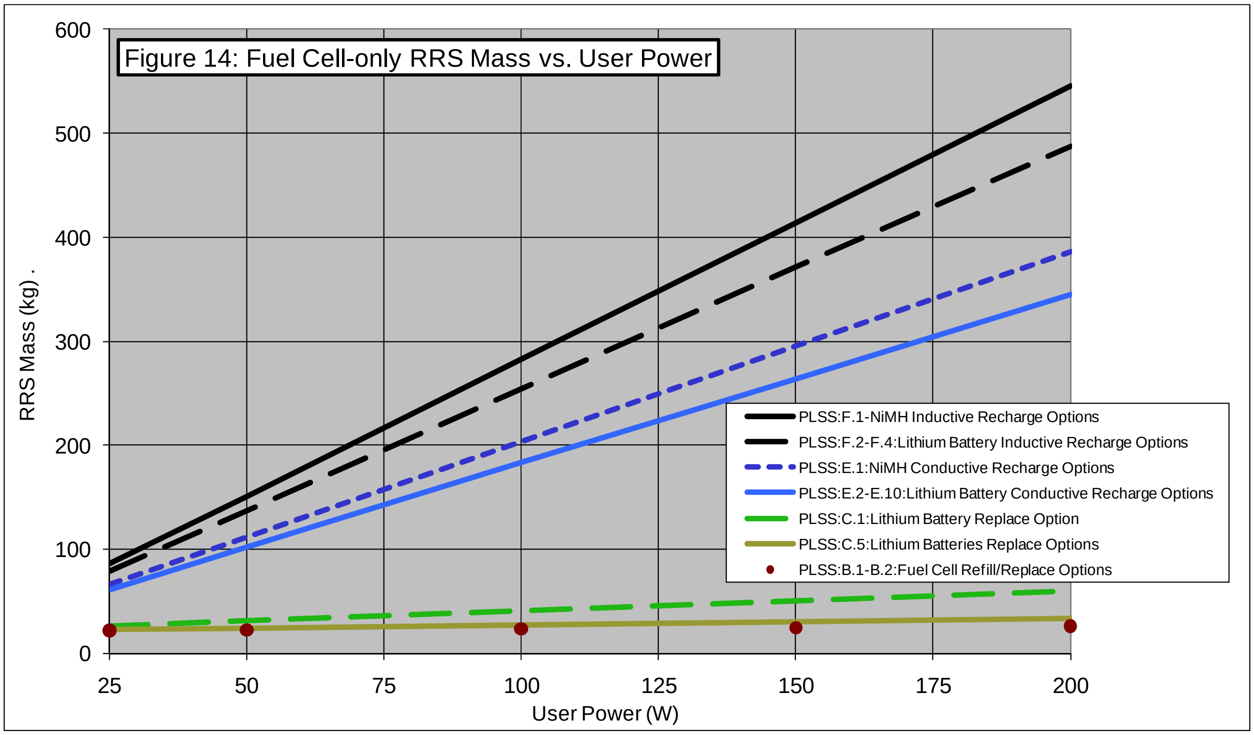


Figure 14: Fuel Cell-only RRS Mass vs. User Power
RRS Mass (kg)
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
User Power (W)
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

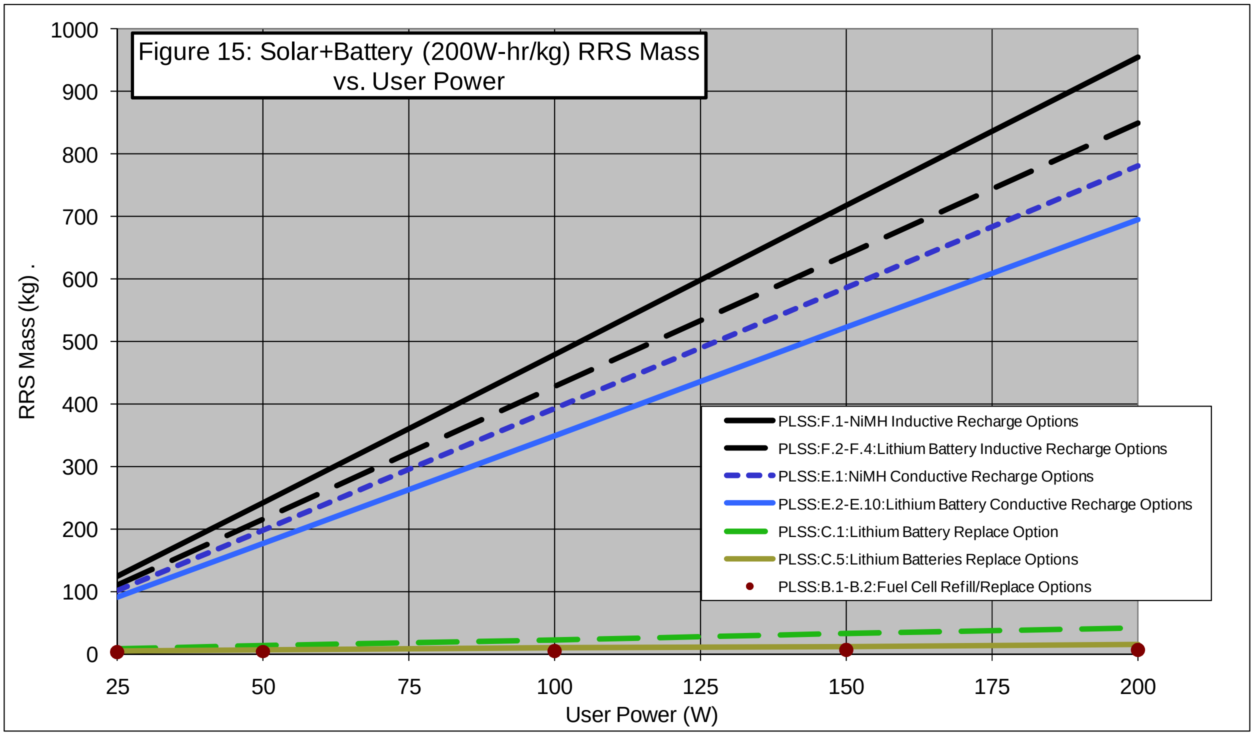


Figure 15: Solar+Battery (200W-hr/kg) RRS Mass vs. User Power
RRS Mass (kg)
1000
900
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
User Power (W)
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

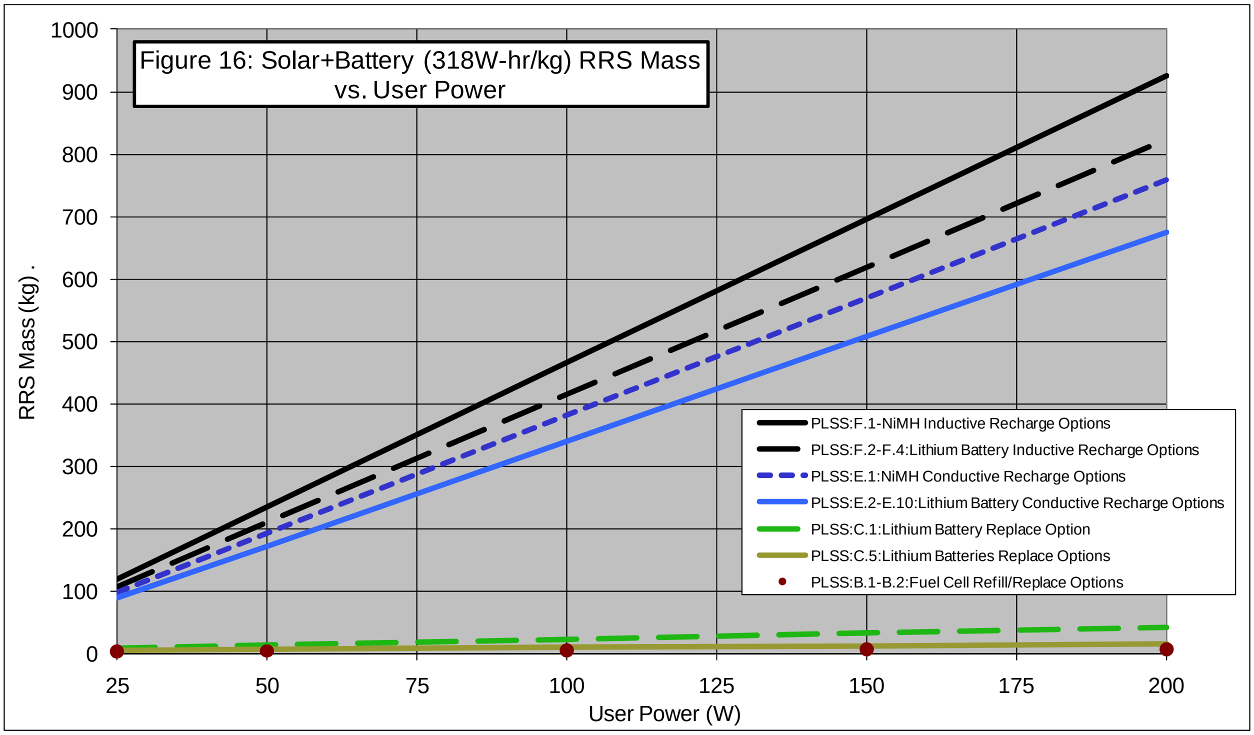


Figure 16: Solar+Battery (318W-hr/kg) RRS Mass vs. User Power
RRS Mass (kg)
User Power (W)
1000
900
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

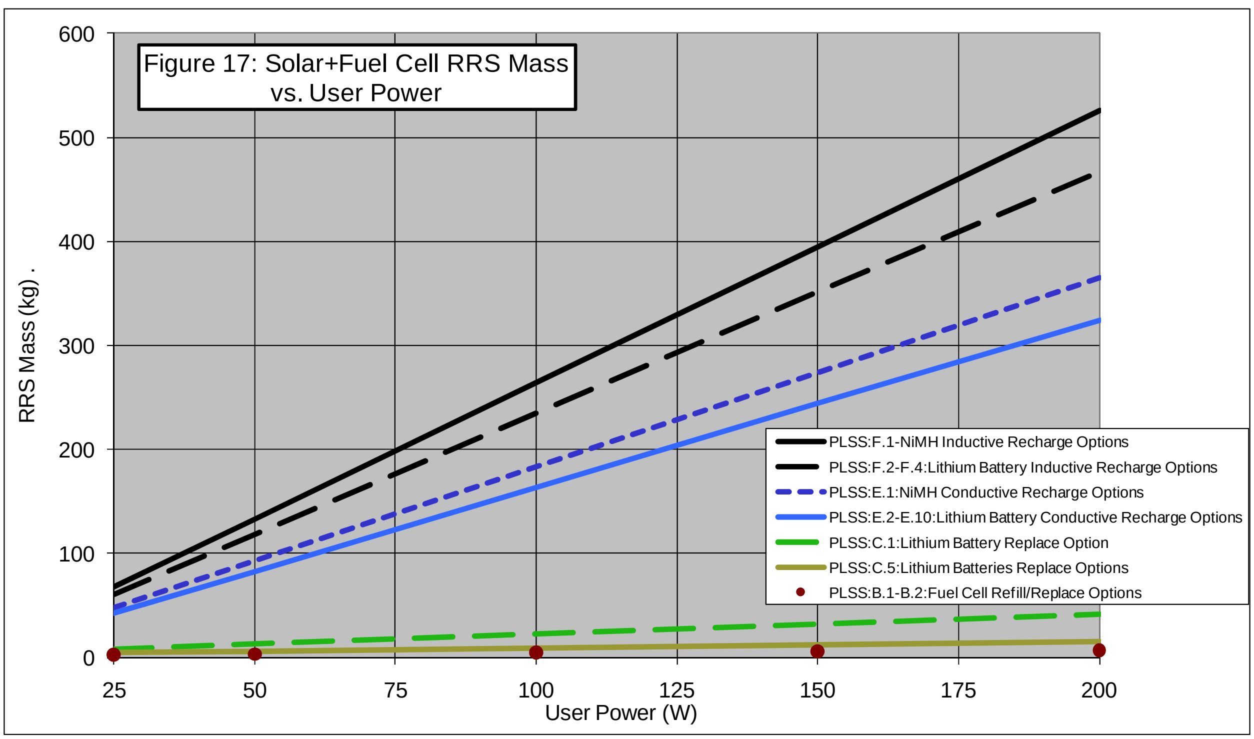


Figure 17: Solar+Fuel Cell RRS Mass vs. User Power
RRS Mass (kg)
User Power (W)
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

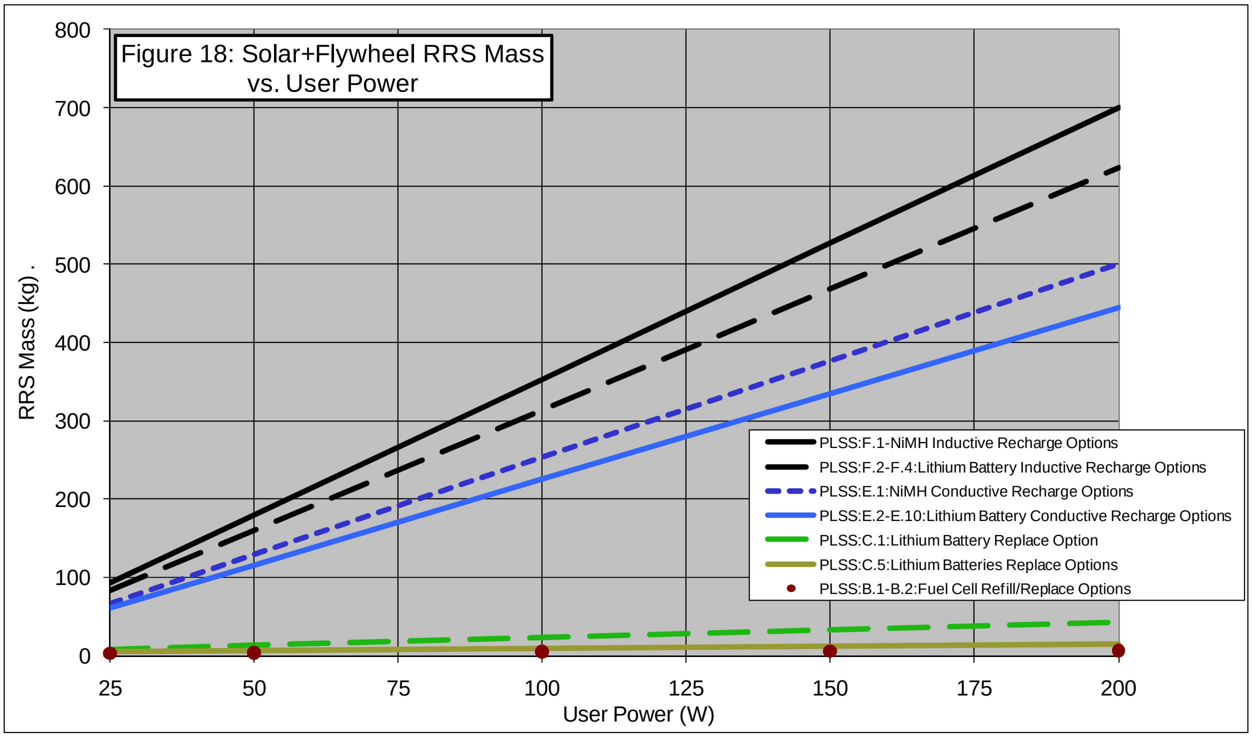


Figure 18: Solar+Flywheel RRS Mass
vs. User Power
RRS Mass (kg)
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
User Power (W)
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

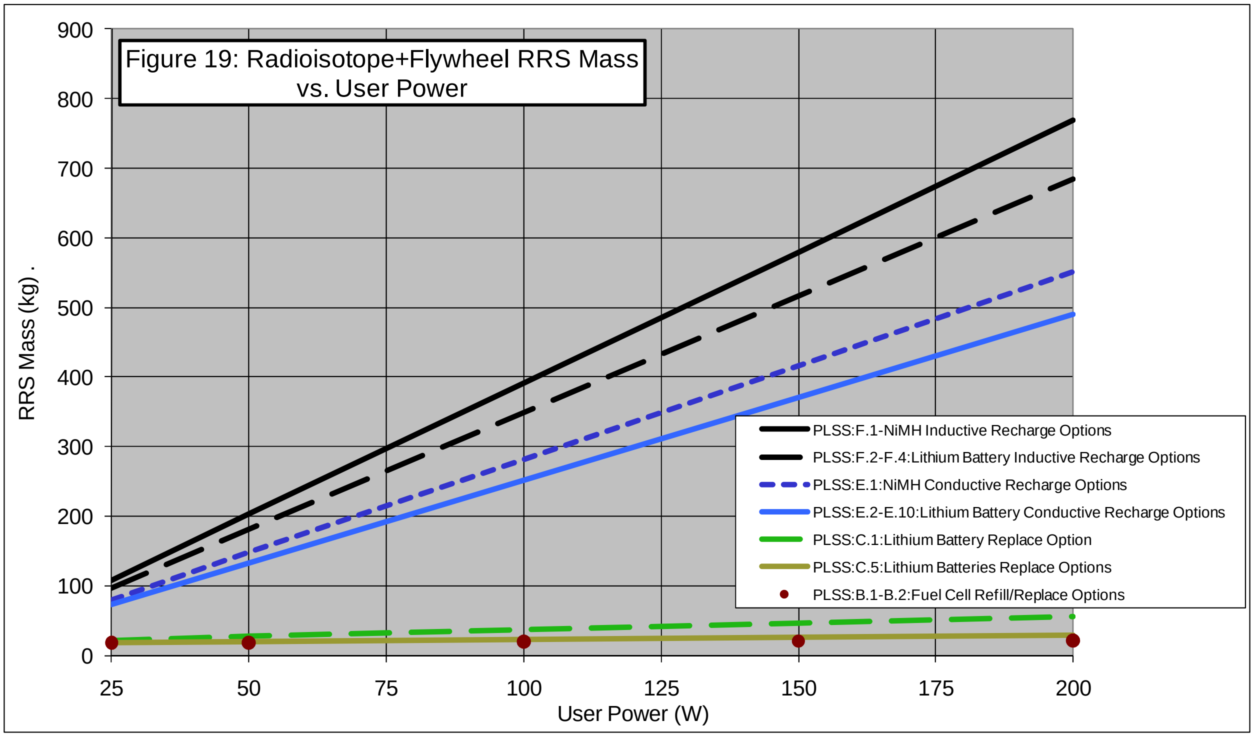
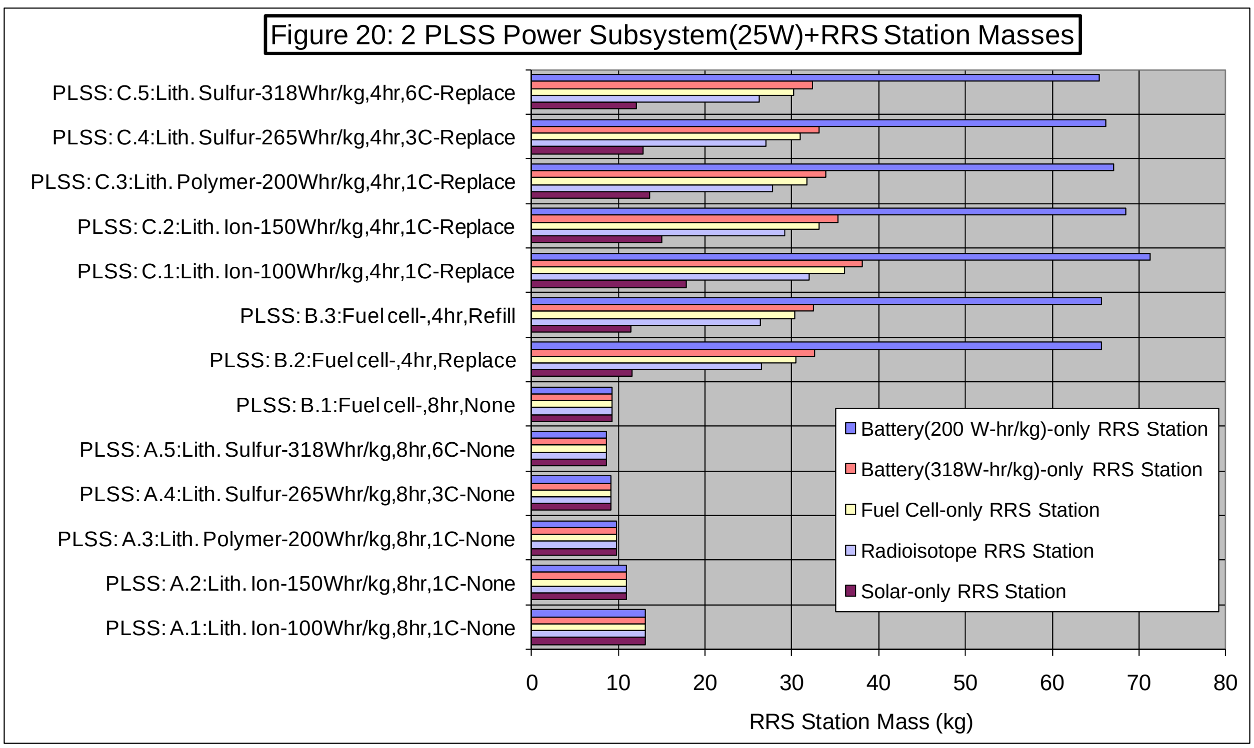


Figure 19: Radioisotope+Flywheel RRS Mass
vs. User Power
RRS Mass (kg)
900
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
User Power (W)
PLSS:F.1-NiMH Inductive Recharge Options
PLSS:F.2-F.4:Lithium Battery Inductive Recharge Options
PLSS:E.1:NiMH Conductive Recharge Options
PLSS:E.2-E.10:Lithium Battery Conductive Recharge Options
PLSS:C.1:Lithium Battery Replace Option
PLSS:C.5:Lithium Batteries Replace Options
PLSS:B.1-B.2:Fuel Cell Refill/Replace Options

4.6.2 Combined RRS and 2 PLSS Power Subsystems Mass Results

Figures 20 through 34 show the combined masses for each RRS Station option with each of the PLSS power subsystem recharge/replace/refill options. Two PLSS recharges/replacements/refillings (plus redundancy) are included in the RRS Station mass and two PLSS power subsystem masses are included in the combined mass. The results are similar to the previous sections with PLSS power subsystem mass only and RRS Station mass only. Figures 20 through 22 show the combined replace/refill/8 hr option PLSS power subsystem mass and RRS Station mass for three PLSS user power levels. Figures 23 through 25 show the combined recharge option PLSS power subsystem mass and RRS Station mass for three PLSS user power levels.

In general these figures show that the 8 hr PLSS power subsystem option (except for 8 hr PLSS 100 W-hr/kg battery option) has the lowest combined mass. Replace, refill and 8 hr PLSS power subsystem options have moderate combined mass. For these PLSS options, the solar-only RRS Station has the lowest mass in the group but is limited to illuminated operation. Other methods (except RRS Station 200 W-hr/kg battery-only option) are next lowest in overall mass, are fairly competitive with each other and are not limited to in-Sun operation. The rechargeable PLSS power subsystem options have much higher mass compared to replace/refill/8hr options. For rechargeable PLSS options, fuel cell and flywheel RRS Station options result in lower combined mass whereas battery with solar options have moderate mass and solar-only and battery-only options have generally the highest combined mass.



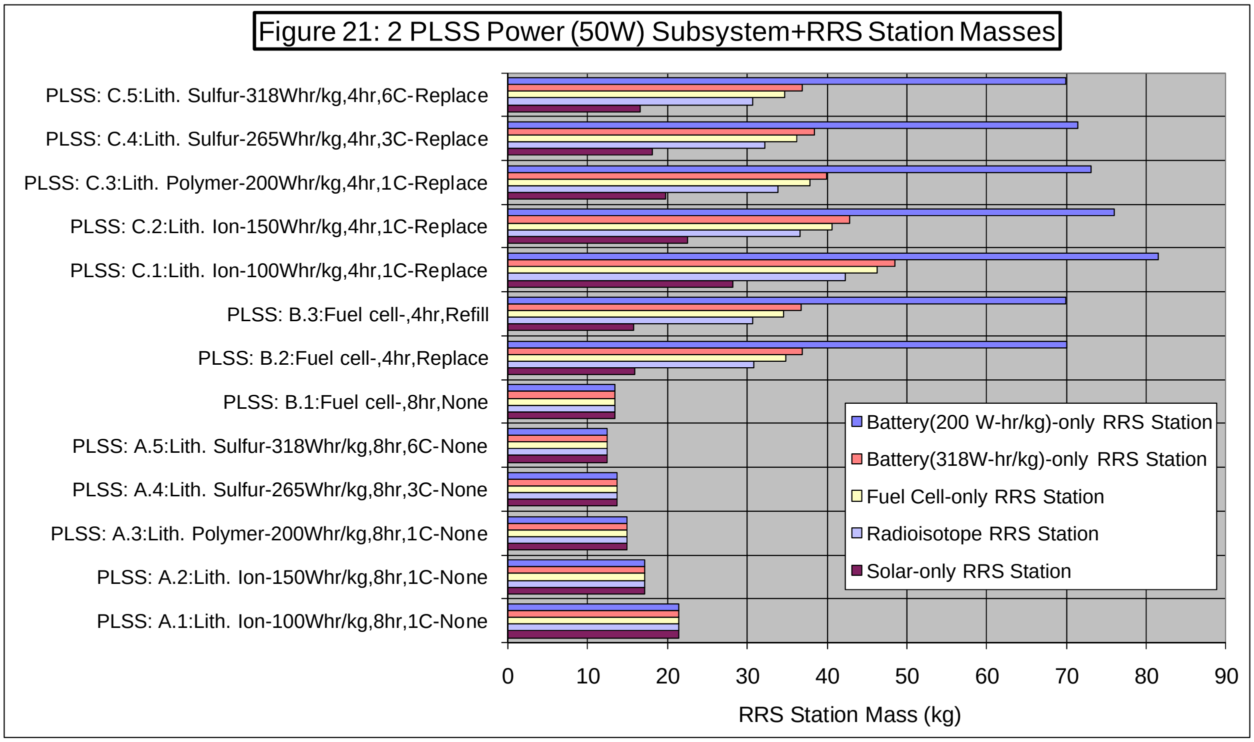


Figure 21: 2 PLSS Power (50W) Subsystem+RRS Station Masses
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: C.4:Lith. Sulfur-265Whr/kg,4hr,3C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.2:Lith. Ion-150Whr/kg,4hr,1C-Replace
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: B.2:Fuel cell-,4hr,Replace
PLSS: B.1:Fuel cell-,8hr,None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None
PLSS: A.4:Lith. Sulfur-265Whr/kg,8hr,3C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.2:Lith. Ion-150Whr/kg,8hr,1C-None
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
Battery(200 W-hr/kg)-only RRS Station
Battery(318W-hr/kg)-only RRS Station
Fuel Cell-only RRS Station
Radioisotope RRS Station
Solar-only RRS Station
0
10
20
30
40
50
60
70
80
90
RRS Station Mass (kg)

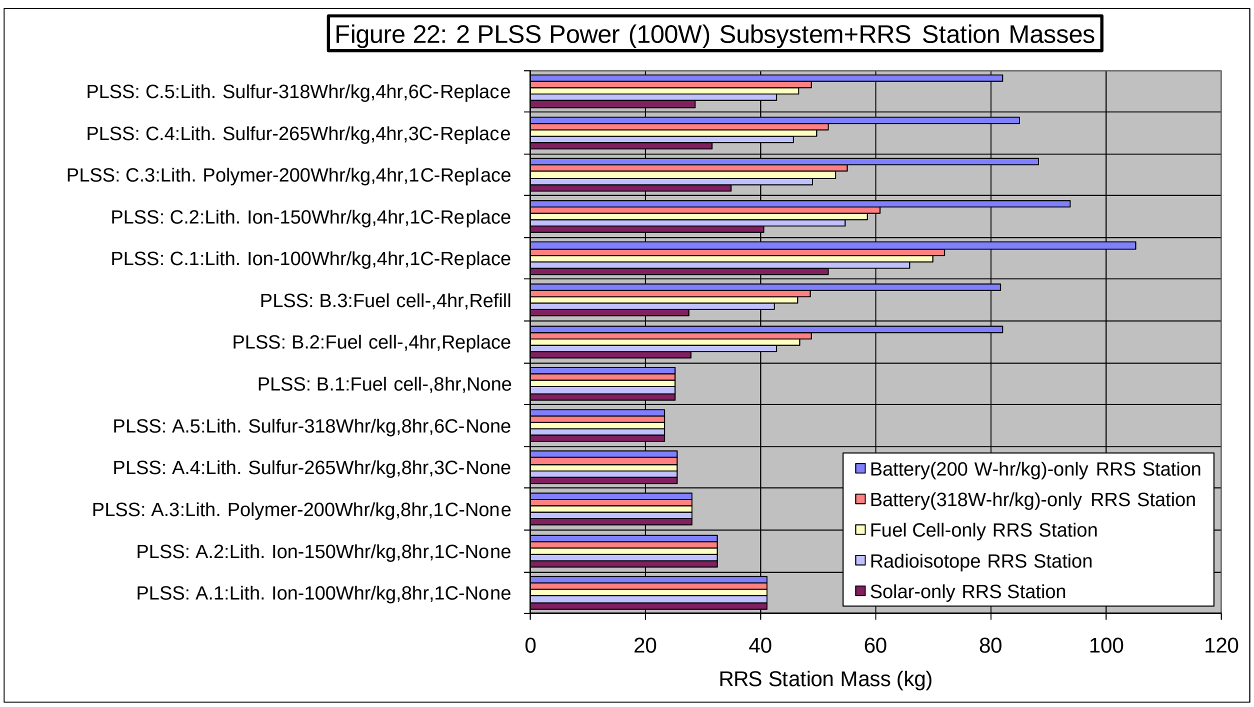


Figure 22: 2 PLSS Power (100W) Subsystem+RRS Station Masses
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: C.4:Lith. Sulfur-265Whr/kg,4hr,3C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.2:Lith. Ion-150Whr/kg,4hr,1C-Replace
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: B.2:Fuel cell-,4hr,Replace
PLSS: B.1:Fuel cell-,8hr,None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None
PLSS: A.4:Lith. Sulfur-265Whr/kg,8hr,3C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.2:Lith. Ion-150Whr/kg,8hr,1C-None
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
Battery(200 W-hr/kg)-only RRS Station
Battery(318W-hr/kg)-only RRS Station
Fuel Cell-only RRS Station
Radioisotope RRS Station
Solar-only RRS Station
0
20
40
60
80
100
120
RRS Station Mass (kg)

Figure 23: 2 PLSS Power (25W) Power Subsystem+RRS Station Masses

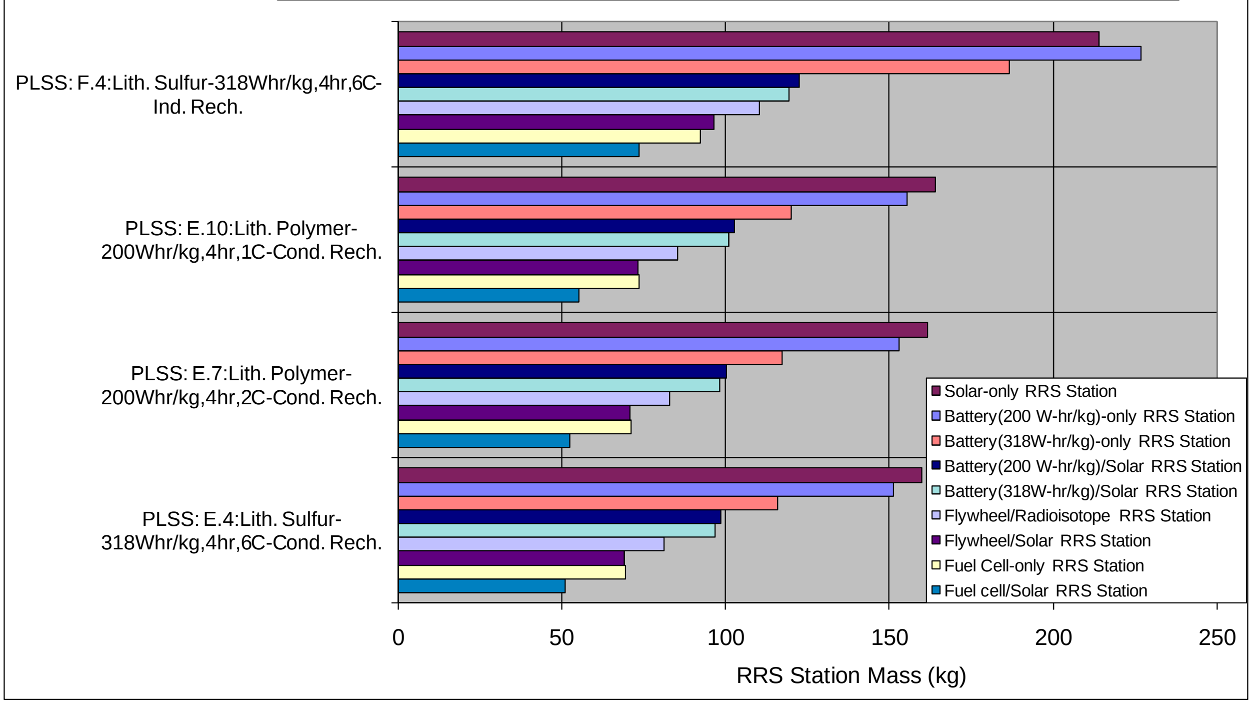
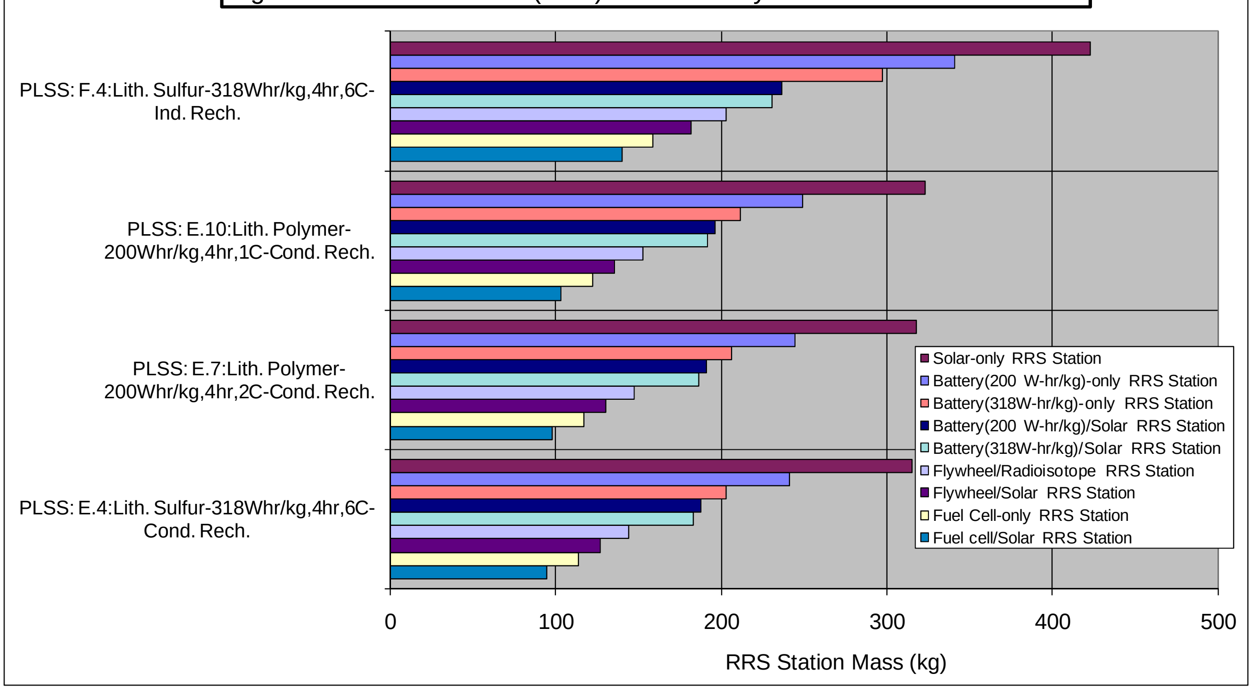


Figure 24: 2 PLSS Power (50W) Power Subsystem+RRS Station Masses



Figures 26 through 34 show the combined results from the previous figures in a different format to permit the reader to select different PLSS user powers from the 25, 50 and 100 W values. Each figure represents a different RRS Station power subsystem options as reflected in its title. The legend for each figure lists the various PLSS power subsystem options. The order of the items in the legend is based on the magnitude of the line in the figure. Recharge RRS Station options have much steeper slopes and relatively higher magnitudes compared to replace/refill RRS Station options.

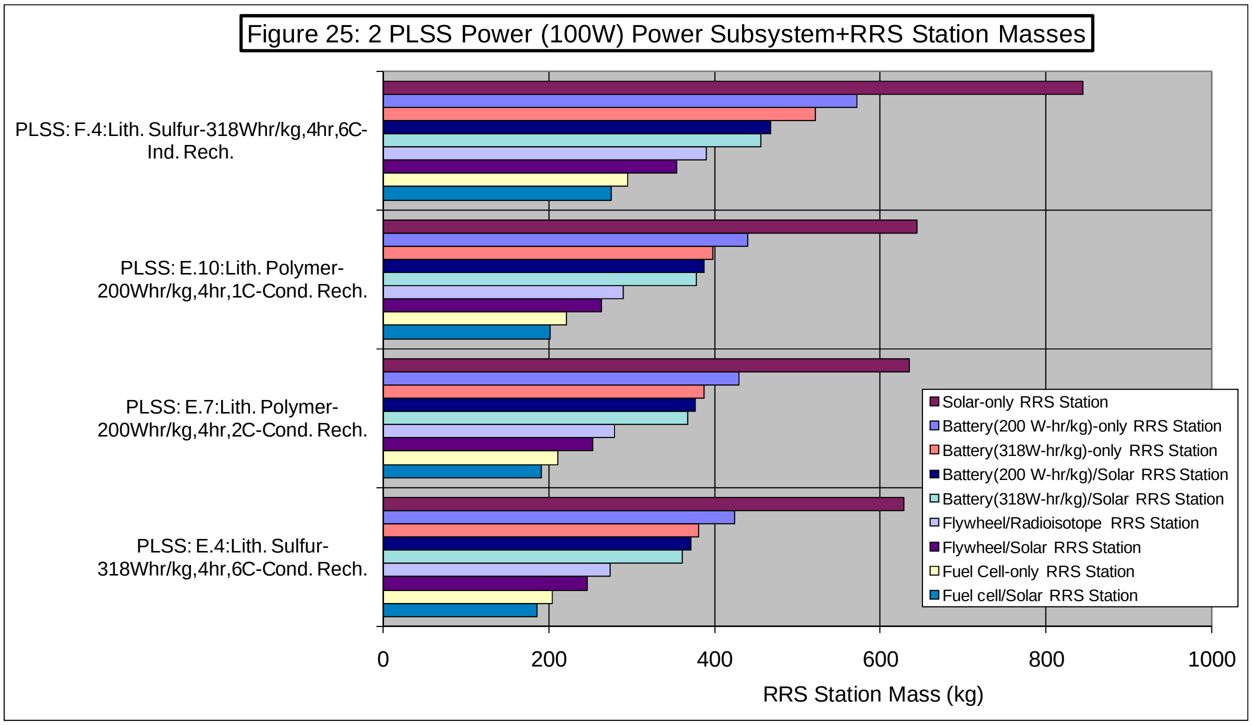


Figure 25: 2 PLSS Power (100W) Power Subsystem+RRS Station Masses

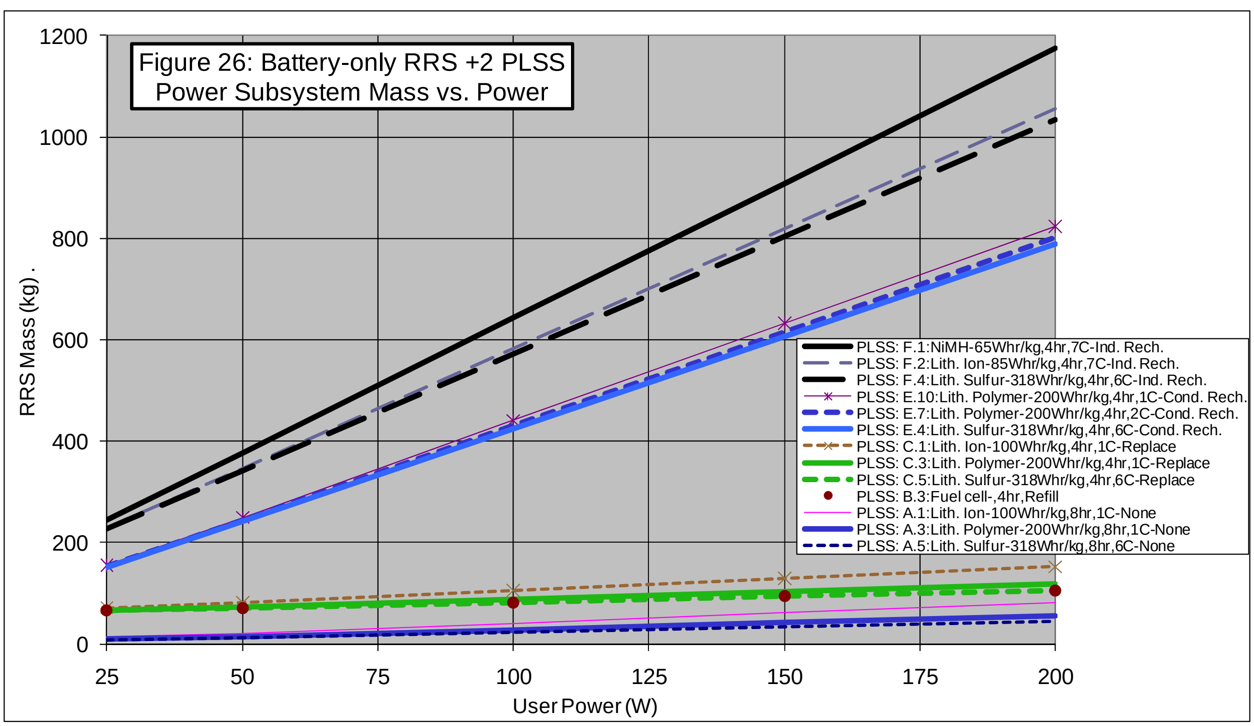


Figure 26: Battery-only RRS +2 PLSS Power Subsystem Mass vs. Power

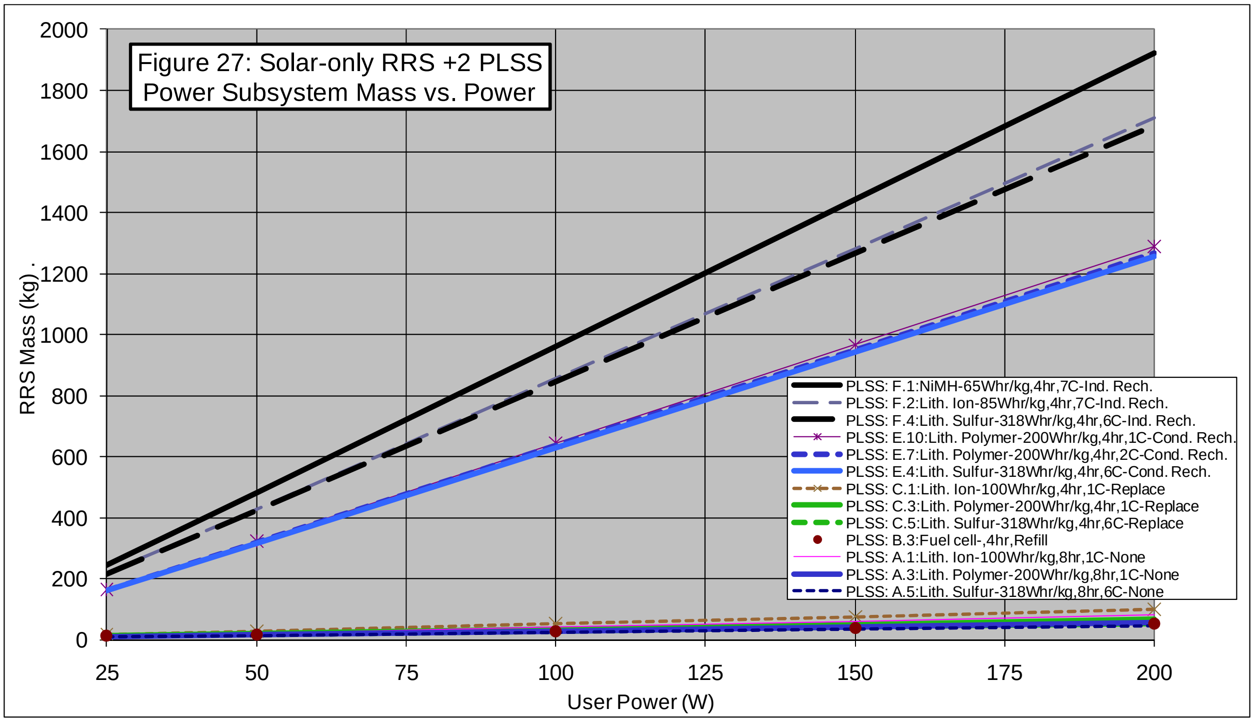


Figure 27: Solar-only RRS +2 PLSS Power Subsystem Mass vs. Power
RRS Mass (kg)
User Power (W)
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

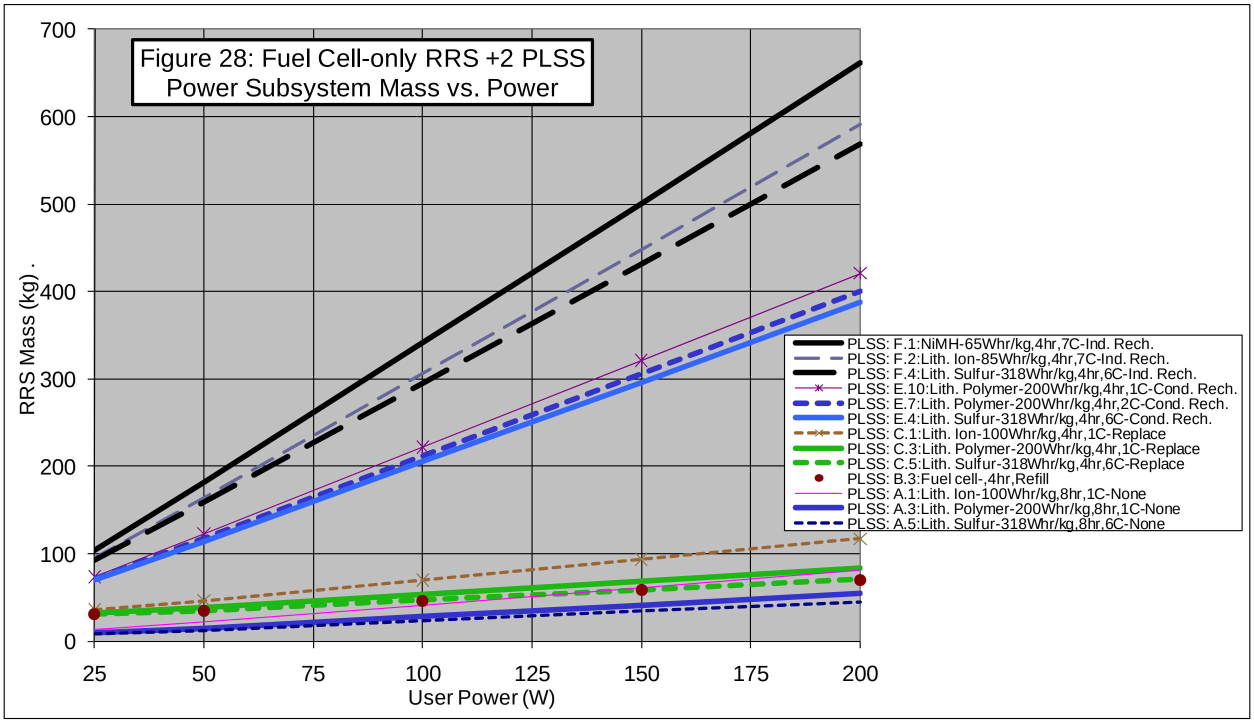


Figure 28: Fuel Cell-only RRS +2 PLSS Power Subsystem Mass vs. Power
RRS Mass (kg)
User Power (W)
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

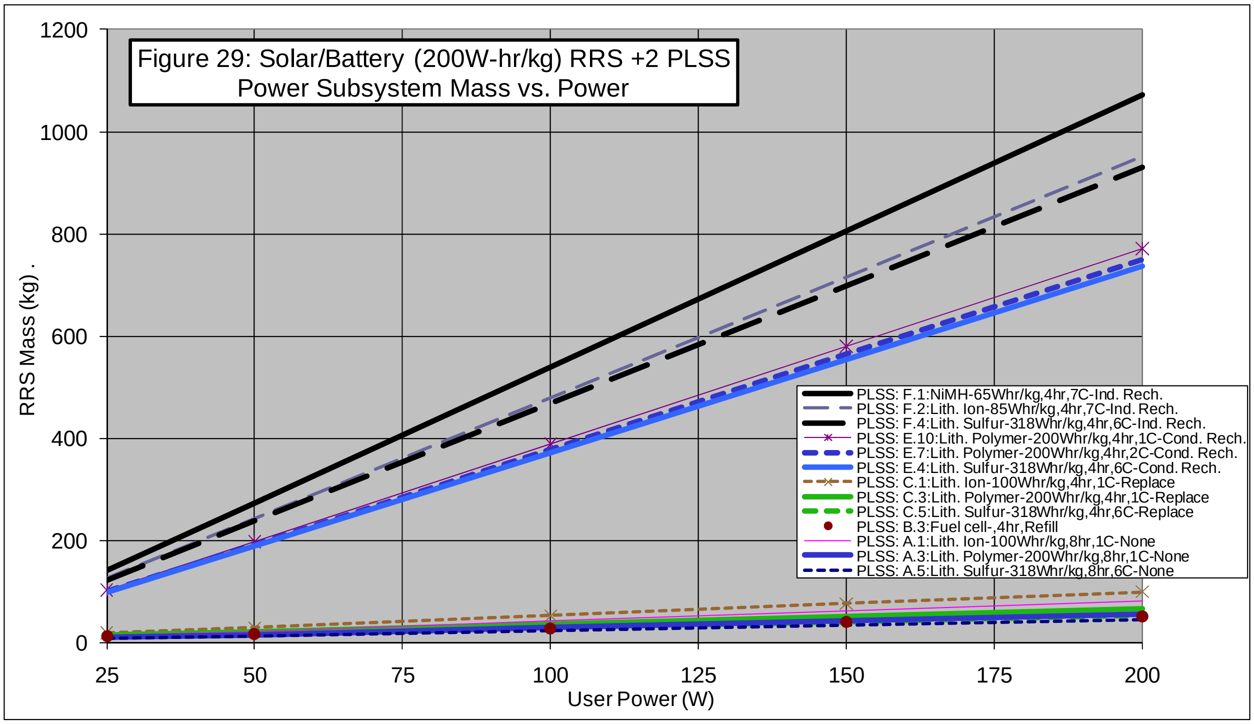


Figure 29: Solar/Battery (200W-hr/kg) RRS +2 PLSS
Power Subsystem Mass vs. Power
RRS Mass (kg) .
User Power (W)
0
200
400
600
800
1000
1200
25
50
75
100
125
150
175
200
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

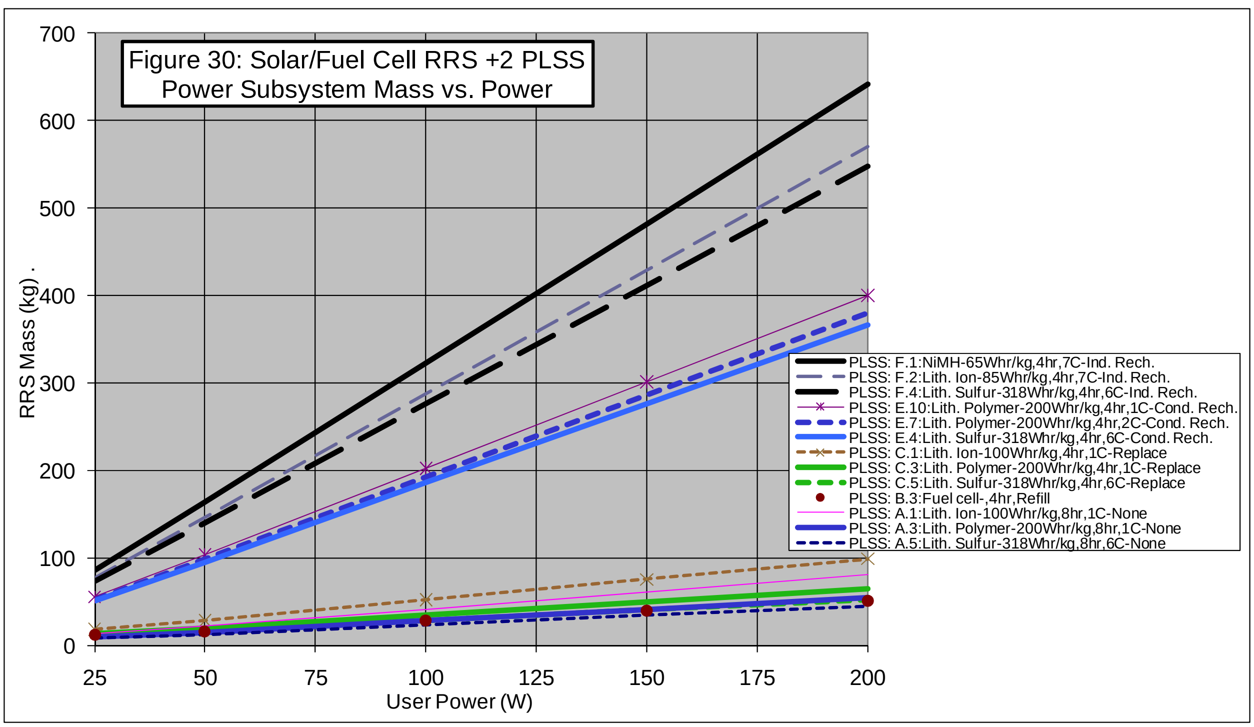


Figure 30: Solar/Fuel Cell RRS +2 PLSS
Power Subsystem Mass vs. Power
RRS Mass (kg) .
User Power (W)
0
100
200
300
400
500
600
700
25
50
75
100
125
150
175
200
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

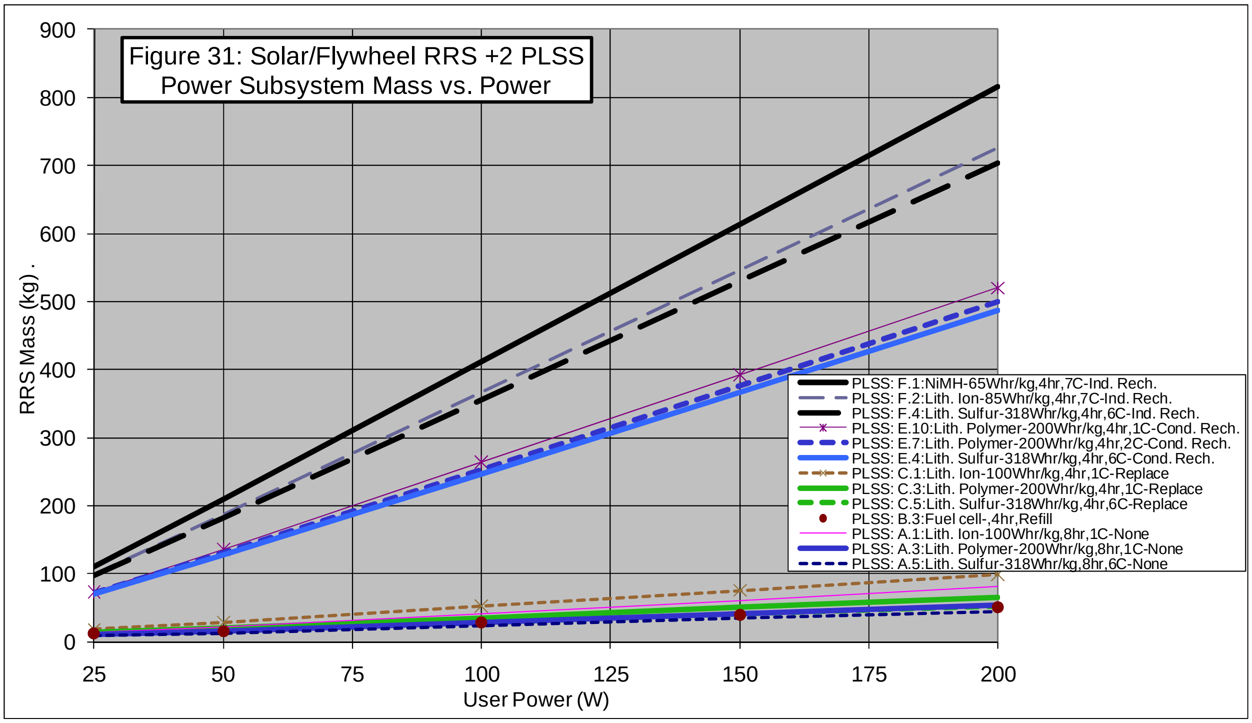


Figure 31: Solar/Flywheel RRS +2 PLSS Power Subsystem Mass vs. Power

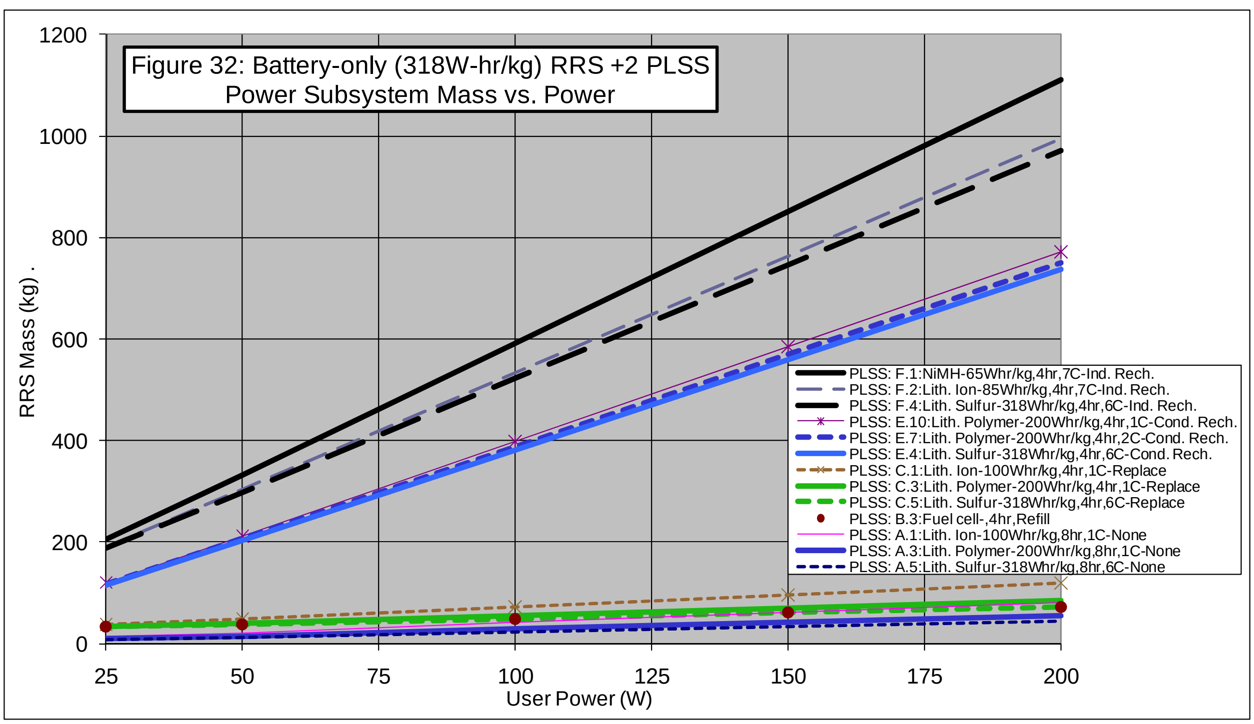


Figure 32: Battery-only (318W-hr/kg) RRS +2 PLSS Power Subsystem Mass vs. Power

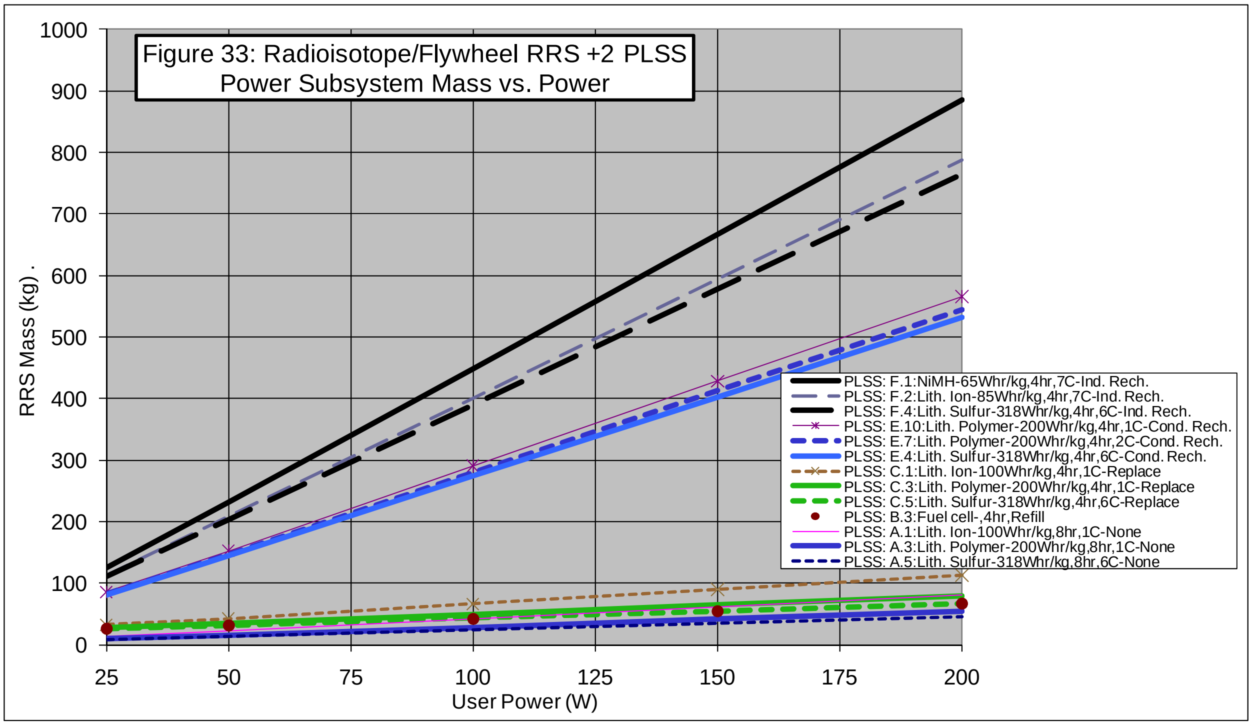


Figure 33: Radioisotope/Flywheel RRS +2 PLSS
Power Subsystem Mass vs. Power
RRS Mass (kg) .
User Power (W)
1000
900
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
175
200
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

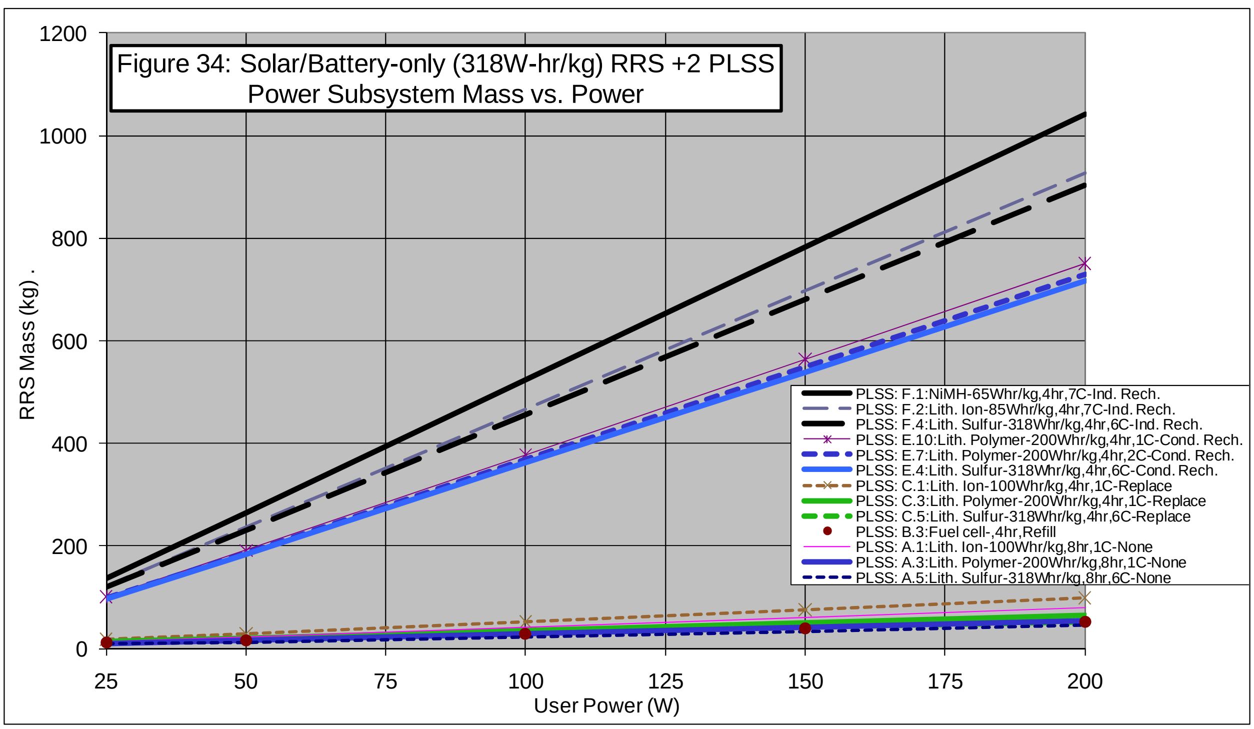


Figure 34: Solar/Battery-only (318W-hr/kg) RRS +2 PLSS
Power Subsystem Mass vs. Power
RRS Mass (kg) .
User Power (W)
1200
1000
800
600
400
200
0
25
50
75
100
125
150
175
200
PLSS: F.1:NiMH-65Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.2:Lith. Ion-85Whr/kg,4hr,7C-Ind. Rech.
PLSS: F.4:Lith. Sulfur-318Whr/kg,4hr,6C-Ind. Rech.
PLSS: E.10:Lith. Polymer-200Whr/kg,4hr,1C-Cond. Rech.
PLSS: E.7:Lith. Polymer-200Whr/kg,4hr,2C-Cond. Rech.
PLSS: E.4:Lith. Sulfur-318Whr/kg,4hr,6C-Cond. Rech.
PLSS: C.1:Lith. Ion-100Whr/kg,4hr,1C-Replace
PLSS: C.3:Lith. Polymer-200Whr/kg,4hr,1C-Replace
PLSS: C.5:Lith. Sulfur-318Whr/kg,4hr,6C-Replace
PLSS: B.3:Fuel cell-,4hr,Refill
PLSS: A.1:Lith. Ion-100Whr/kg,8hr,1C-None
PLSS: A.3:Lith. Polymer-200Whr/kg,8hr,1C-None
PLSS: A.5:Lith. Sulfur-318Whr/kg,8hr,6C-None

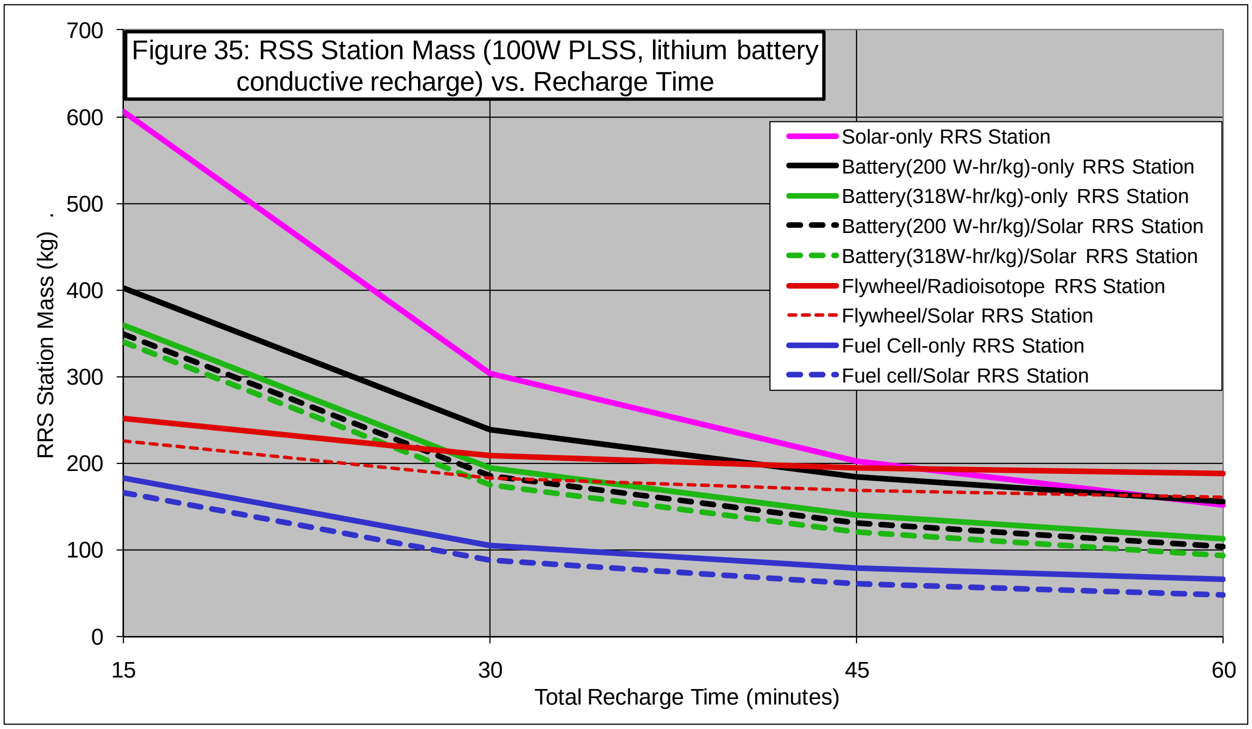


Figure 35: RSS Station Mass (100W PLSS, lithium battery conductive recharge) vs. Recharge Time

4.6.3 Recharge Time Effect on RRS Station Mass

15 min simultaneous recharging has a significant effect on RRS Station mass due to thermal and electronics sizing for peak powers that must be transferred to the PLSS in the short time period. Consideration should be given to extending this time period or removing the requirement for simultaneous recharging.

4.6.4 Quantitative and Qualitative Ranking Comparison of Options

A ranking table (Table 5) was created to numerically compare a combination of PLSS and RRS Station power subsystem qualitative and quantitative attributes for each option. Along the top of the table going from left to right are the various PLSS power subsystem options. A.1-A.5 and B.1 are the 8 hr PLSS power subsystem options. B.2-B.3 and C.1-C.5 are the replace and refill PLSS power subsystem options. E.1-E.10 are the conductive recharge PLSS power subsystem options. F.1-F.4 are the inductive recharge PLSS power subsystem options. For purposes of this table, only the best combined solar (housekeeping power)/battery (recharge power, if applicable) RRS Station option was considered as it applies to each PLSS power subsystem option. The list of questions in the left column are either answerable with a ‘Yes’ (given a point value of 1) and ‘No’ (given a point value of 0). The question ‘Below median PLSS mass?’ provided a simple way to compare PLSS power subsystem masses. Those PLSS power subsystems below the median were given a ‘Yes’ (1). Similarly, the question ‘Combined mass of solar+battery RRS AND two suit power systems are below median RRS mass?’ relatively compares the total power subsystem mass metric (‘Yes’ for a combined mass less than the median). The other nine questions were arbitrarily selected as pertinent to the lunar surface EVA suit. They address dust, thermal, complexity, safety and technology readiness.

Based on this table’s equal weighting of questions, it is clear from the ‘Sum’ row at the bottom, that most ‘8 hr’ PLSS options are superior to the other options. Also, most ‘replace’ options are superior to any recharge options. Different weighting systems were tried to examine their impact on the results. When normalized PLSS and RSS Station power subsystem masses were used instead of rounded values, the PLSS mass weighting factor increased to 10.0 and the RRS Station mass weighting factor increased to

5.0, the results were fairly close to this table except that replace options (C.4-C.5) moved closer to the 8 hr PLSS options (A.2-A.5), especially for lower PLSS user power levels.

TABLE 5.—METRIC COMPARISONS/RANKING OF OPTIONS

Metrics (equally weighted)	A.1:Lith. Ion-100 W-hr/kg,8 hr,1C-None	A.2:Lith. Ion-150 W-hr/kg,8 hr,1C-None	A.3:Lith. Polymer-200 W-hr/kg,8 hr,1C-None	A.4:Lith. Sulfur-265W-hr/kg,8 hr,3C-None	A.5:Lith. Sulfur-318W-hr/kg,8 hr,6C-None	B.1:Fuel cell-,8 hr, None	B.2:Fuel cell-,4 hr, Replace	B.3:Fuel cell-,4 hr, Refill	C.1:Lith. Ion-100 W-hr/kg,4 hr,1C-Replace	C.2:Lith. Ion-150 W-hr/kg,4 hr,1C-Replace	C.3:Lith. Polymer-200 W-hr/kg,4 hr,1C-Replace	C.4:Lith. Sulfur-265 W-hr/kg,4 hr,3C-Replace	C.5:Lith. Sulfur-318 W-hr/kg,4 hr,6C-Replace	E.1:NiMH-65 W-hr/kg,4 hr,7C-Cond. Rech.	E.2:Lith. Ion-85 W-hr/kg,4 hr,7C-Cond. Rech.	E.3:Lith. Sulfur-265 W-hr/kg,4 hr,3C-Cond. Rech.	E.4:Lith. Sulfur-318 W-hr/kg,4 hr,6C-Cond. Rech.	E.5:Lith. Ion-100W-hr/kg,4 hr,2C-Cond. Rech.	E.6:Lith. Ion-150W-hr/kg,4 hr,2C-Cond. Rech.	E.7:Lith. Polymer-200 W-hr/kg,4 hr,2C-Cond. Rech	E.8:Lith. Ion-100 W-hr/kg,4 hr,1C-Cond. Rech.	E.9:Lith. Ion-150 W-hr/kg,4 hr,1C-Cond. Rech.	E.10:Lith. Polymer-200 W-hr/kg,4hr,1C-Cond. Rec	F.1:NiMH-65 W-hr/kg,4 hr,7C-Ind. Rech.	F.2:Lith. Ion-85 W-hr/kg,4 hr,7C-Ind. Rech.	F.3:Lith. Sulfur-265 W-hr/kg,4 hr,3C-Ind. Rech.	F.4:Lith. Sulfur-318 W-hr/kg,4 hr,6C-Ind. Rech.
Below median PLSS mass?	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0
Combined mass of solar+battery RRS AND two suit power systems are below median RRS mass?	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No dust environment electrical power connections(assume sensors are RF or also carried inductively)?	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
No dust environment gas/fluid connections?	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No dust environment mechanisms?	1	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
No pressurized gas safety issue?	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
No high current charging safety issue?	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No high thermal loads in charging/nominal operation?	1	1	1	1	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Low complexity in mechanisms?	1	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Low thermal complexity in charging?	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Available sooner than later?	1	1	0	1	0	0	0	0	1	1	0	1	0	1	1	1	0	1	1	0	1	1	0	1	1	1	1
Sum	**10**	**11**	**10**	**11**	**10**	**8**	**5**	**6**	**8**	**8**	**7**	**8**	**7**	**4**	**5**	**5**	**4**	**4**	**5**	**4**	**4**	**4**	**3**	**5**	**5**	**5**	**5**

4.7 Conclusions

The most important finding was that, because of the relatively low PLSS power subsystem masses involved, ***an '8 hr' PLSS power subsystem is superior to 4 hr PLSS recharging/ refilling/replacing for PLSS power levels =<100 W***. Replacement of battery modules or fuel cell tank clusters and refilling of fuel cell tanks seems to be the next most practical solution in that although the PLSS may be modestly less heavy, including the RRS Station in consideration makes the options less competitive with the '8 hr' PLSS options (which does not 'need' a RRS Station and thus the RRS Station mass contribution is essentially zero).

For the replace/refill RRS Station options, the mass of its power subsystem is modest for housekeeping power. Solar power, which provides the lowest RRS Station mass, can be used to handle the housekeeping power needs if the Station is used in illuminated areas. Other alternatives are available that can operate in un-illuminated conditions at a moderate mass penalty. Any replace or refill PLSS options requires dust mitigation for electrical/fluid connections and mechanical parts. Refilling of high pressure tanks and handling of high pressure tanks may present a safety concern. Battery modules must be placed in a thermally controlled RRS Station container to maintain life until the battery is used in the EVA and may need specialized charging prior to use to maintain battery readiness (i.e., some batteries discharge slightly over time in a stored state). In addition, the RRS Station should provide the same kind of container to store 'spent' battery modules in a thermally safe environment until return to 'Base'. Specialized charging may also be needed for this time period. In a related spin-off benefit, using traditional (battery life friendly, safe) recharging rates to recharge battery modules at the RRS Station could increase the potential number of EVA sorties. Since no requirements existed for this potential use, it was not considered in this trade study.

Recharging options, from both the PLSS power subsystem and RRS Station perspective, generally had the highest mass. Solar power is not viable for recharge power due to the large deployed area and high mass. Batteries or fuel cells are required, but have relatively high mass. The high mass is the result of high charging power level which is used to size electronics and thermal components. Another important finding of this trade study is that ***the RRS Station size can be reduced significantly with sequential instead of simultaneous recharging.***

Li battery types and primary fuel cells have advantageous mass characteristics assuming continued improvement of specific energy. Technology development may be needed for some battery types to increase battery charge/discharge rates from 1C to 2C with minimal impact on battery life.

Inductive charging is not suitable for rapid charging due to high power levels (and thus mass) and reduced efficiency. Low power inductive applications may still be viable elsewhere in lunar activities (such as lunar robotic/manned rovers). Conductive charging is preferred due primarily to reduced losses during high power charging. High thermal rates due to rapid recharging over a 15 min period may require thermal cooling loops to be connected to the PLSS from the RRS Station during recharging, adding to the overall mass and complexity of the charging option. In addition, safety concerns from high currents/thermal loads during charging and dust effects on conductive/fluid connections make recharging options much less attractive.

4.8 Additional Information: Rapid Recharge Battery Data

A literature search regarding the state of the art of rapid recharge batteries was performed. The sources of data examined included technical papers, manufacturer presentations, patent applications, press releases and web sites. It is apparent that current state-of-the-art rapid recharge battery data is somewhat difficult to obtain due to the competitive market pressures. Such batteries have tremendous potential in the electric vehicle and consumer electronics markets. Space applications are hardly a consideration for such manufacturers.

4.8.1 Charge Rates and Times

Secondary (i.e., rechargeable) batteries have different kinds of charging times. These can be grouped as ‘slow’ (>3 hr), ‘fast’ (30 min-3 hr) and ‘rapid’ (~15 min). Each type corresponds to a charge rate and charging profile which differ based on battery type.

A charge rate of ‘1C’ means the entire Amp-hour capacity of a battery can be recharged in 1 hr. Thus, a 10 A-hr battery can be recharged at 1C (i.e., at 10 A over a period of 1 hr). Also, a 10 A-hr battery can be recharged as 2C (i.e., at 20 A over a period of 30 min). Typical charge rates for Li or NiMH batteries are 1C although 1.5C and 2C have been indicated to be practical limits.

4.8.2 Charging Profiles

Charging profiles can either be constant current (for NiMH battery types) or constant current-constant voltage (for Li battery types). Constant current (CC) means that the battery is charged at a specific current until the battery is fully charged. Constant current-constant voltage (CCCV) means that most of the battery is charged at a constant current until a specific voltage is reached and then the remainder of the charging period is performed at this voltage (with a gradually reducing, linear current drop-off). For this reason, charging of Li batteries can take longer since the constant current portion (the highest current level) can charge from 0 to 80 percent state of charge, but time must be taken for constant voltage charging at lower current levels for going from 80 to 100 percent state of charge.

4.8.3 Rapid Recharge Battery Sizing Based on Charge Rates

There are two ways to handle the rapid recharge requirement: oversize the battery (effectively lowers the depth-of-discharge from 100 to 50 percent for twice the capacity for instance) or use rapid charge batteries.

With oversizing, nonrapid recharge type batteries (e.g., which recharge >30 min) are used, yet they are recharged only for 15 min. This method implies longer battery life and enhanced battery safety due to slower recharging rates but this occurs at the price that the battery can only be partially recharged within the allotted time of 15 min. In order to still provide the required user energy, more batteries must be stored in the PLSS. Thus, effectively the batteries must be oversized to provide the same energy as one could obtain if the batteries were allowed to completely be discharged.

Another aspect of the oversizing method, as applied to Li batteries, is that most of the charging can be performed in the constant current part of the charge profile while the constant voltage portion is neglected to save time. Of course, this requires life testing to understand the ramifications of such partial charging. It is possible that reconditioning methods could be developed.

Using rapid recharge batteries is the other option. Although these can easily meet the 15 min recharge requirements, many questions exist regarding the limitations and applicability of these batteries. More testing is required to verify vendor data especially as it applies to a space-rated lunar EVA suit application.

4.8.4 Thermal Effects

Rapid recharge increases the battery temperature and the entire thermal load on the EVA suit.

4.8.5 Safety

Fast or rapid recharging requires sophisticated monitoring and control to ensure battery safety and battery life. This includes temperature, pressure and charge monitoring. Hardware designs must address these aspects. For example, rapid recharge NiMH batteries may require a pressure vessel to withstand at least 150 psi (10.2 atm) while Li type batteries do not seem to have such a requirement. These considerations are critical since recharging is proposed to occur with the astronaut inside the suit adjacent to the PLSS. Although it is likely that adequate hardware and software designs can alleviate this concern, a 15 min recharge is extremely aggressive and will require a great deal of testing to verify its safety and effect on battery life.

4.8.6 Battery Life

Fast or rapid recharging of batteries has a direct impact on battery capacity reduction over time. Research and development is usually focused on reducing such life effects. In addition, partial recharging of batteries may have long term battery life effects. It is unknown whether battery reconditioning methods can be developed to restore battery capacity to NiMH, Li ion and Li sulfur battery types. Research and development is required in this area.

4.8.7 Rapid Recharge Vendors

Three primary rapid recharge battery vendors were identified: Electronenergy for NiMH batteries, A123 for Li ion batteries, and Sion for Li sulfur batteries.

4.8.7.3 Electroenergy NiMH batteries

A technical presentation (Ref. A.1) for the Electroenergy NiMH battery in Nov 2004 shows that their 6.5 A-hr/1.25V cell with 65 W-hr/kg specific energy can completely recharge in 8.5 min or 7 °C (a 13 A-hr cell in 12.3 min). Details about the life effects of such fast recharging are not available and independent confirmation of the test data is not available. Also, it is not clear whether there was battery pressure venting or whether the battery was completely sealed. For instance, for a 6.6 A-hr rapid charge cell that recharges in 8.5 min has a pressure rise of 15 psi and a 13 A-hr cell that recharges in 12.3 min has a pressure rise of 10 psi. NiMH batteries can vent hydrogen if they are overcharged.

4.8.7.4 A123 Li Ion

A patent application for the A123 Li battery (Ref. A.2) in October 2005 shows that their 0.72 A-hr cell with 85 W-hr/kg specific energy can be recharged from 0 to 80 percent state of charge in a 6 min (constant current) and 80 to 100 percent in 9 min. The A123 patent application covers many versions of their product but only one specific energy is listed. It is possible that each version has a different specific energy. The A123 website presents data that can be inferred to mean that the cell is either 30 or 43 W-hr/kg. It is not specifically stated in the patent whether the cell must be completely recharged and how partial recharging would affect cell life. It is generally accepted that batteries must be fully recharged prior to use. A123 states they can recharge most of the battery in 5 min although the data shows they also follow a standard charge cycle of up to 10 min. Pressurization is not required for Li ion battery types.

4.8.7.5 Sion Li Sulfur

Technical papers of 2004 by Sion discuss Li sulfur battery data (Ref. A.3, A.4) and indicate that prototype Li sulfur cells, operating at 250 to 300 W-hr/kg, demonstrated a >3C charge or discharge rate and a temperature range of –60° to 60 °C. Also, 300 to 350 W-hr/kg cells were being tested in 2004. The reports show that cycle life (capacity over time) drops off significantly for the high specific energy cells (30 percent capacity reduction over 100 cycles for tested 2004 cells, 10 percent capacity reduction over 100 cycles for estimated 2004 new cells). Cells were used to make batteries for ‘pen tablet’-type computers. The projected battery specific energy was 265 W-hr/kg (assuming a cell specific energy of 350 W-hr/kg contributing 75 percent of the mass). The projected battery volumetric energy was 320 W-hr/liter (assuming a cell volumetric energy of 400 W-hr/liter contributing 80 percent of the volume). Pressurization is not required for Li sulfur battery types. Independent replication of Li sulfur battery test data is required.

4.8.7.6 Other References for Rapid Recharging of Batteries

1) Technical papers (Refs. A.5, A.6, and A.7) from 2000 to 2002 indicate that an 85 A-hr NiMH battery (11 cells) with 60 W-hr/kg specific energy can be recharged from 20 percent to 70 percent in 16 min (2.0C). This had a pressure charge control of 150 psi. The implication from the paper is that it is all right to partially recharge the battery (it only has a constant charge phase, unlike the Li battery which has a constant current and then constant voltage part). However, the authors indicate that more testing is needed to determine the battery life impacts of partial recharge.

2) A technical paper (Ref. A.8) describes the temperature behavior of 1.6 A-hr NiMH batteries. A charge input of 80 percent at 3C increases cell temperature from 15 to 60 °C, for 2C it is from 15 to 40 °C, and for 1C it is from 15 to 30 °C.

3) A technical paper (Ref. A.9) indicates that a 0.7 A-hr Li battery can be rapidly recharged from 20 to 100 percent state of charge at 1.5 °C in 34 min. The charging requires constant current and constant voltage portions and states that it is critical to monitor temperature and voltage to prevent damage to the battery.

4) A technical paper (Ref. A.10) explores the rapid charging profile using computer-designed algorithms and determined that a 2C charge rate can be attained for a 0.93 A-hr Li battery.

5) A technical paper (Ref. A.11) discusses a rapid charging method (bootstrap charging) for Li batteries which applies high currents for a short period at the beginning of charge, but continuing with the standard constant current-constant voltage method afterwards. The best that this method can achieve is 30 min full recharge from starting at 20 percent state of charge (for a 1.1 A-hr battery). Data show that life is relatively unaffected by this method (assuming a mandatory standard Li type charge profile after the bootstrap). The method works best for a very low starting battery state of charge. Partial charging using this method is not considered in the report and testing of this method is required to determine life

effects. The report indicates recharge of 20 to 59 percent SOC in 15 min (if partial recharging is allowed then the battery must be oversized by 41 percent). In comparison, for a standard Li 15 min charging method for the same battery, the recharge would only go from 20 to 45 percent SOC (thus if partial recharging is allowed, the batteries must be oversized by 55 percent).

6) Incomplete and contradictory press release information (Ref. A.12-A.18) from companies called Altairnano and ABAT describe a Li battery with specific energies from 40 to 112 W-hr/kg and recharge times from 3 to 34 min. Altairnano demonstrated a 3 to 6 min recharge but the Li battery was 40 W-hr/kg. Altairnano provided materials to a Li battery manufacturer called ABAT, which has demonstrated a 30 to 45 min recharge time (although Altair claims better electrode design can reduce this time). Altair claimed that the energy density is 3.75 times that of sealed lead-acid battery (30 W-hr/kg) or 100 W-hr/kg. No technical data is available and the properties cannot be confirmed. These vendor's claims are not considered in this trade study.

7) Older Li sulfur battery research and development by Moltech Corporation (aka Sion Power Corporation) is discussed (Ref.A.19). The specific energy of a prototype 0.8 A-hr cell is 180 W-hr/kg with a charge rate of 4C. The 2003 projected values are 300 W-hr/kg with a charge rate of 2C. In addition, the presentation says the future capability may range from 300 to 450 W-hr/kg. In another reference for that same year (Ref.A.20), the company projects 300 to 500 W-hr/kg as the future capability.

4.8.8 Assumed Analysis Data

Because of the broad range of possible values of specific energy, three groups of battery characteristics were analyzed in this trade study. The first group is the currently reported battery characteristics that are derived from testing by the battery vendors. For NiMH batteries, this is Electroenergyinc with a 15 min recharge and 65 W-hr/kg. For Li ion batteries, this is A123 with a 15 min recharge and 85 W-hr/kg. For Li sulfur batteries, this is Sion with a 3C recharge rate and 265 W-hr/kg. Note that these values have not been independently verified. The second group includes selected vendor future projections of their battery technology. The only member of this group is Sion with a 15 min recharge rate and 318 W-hr/kg. Other vendors were excluded from this group due to their lower specific energies. The final group includes technology projections of traditional Li ion and Li polymer battery types. Official NASA projections of these battery characteristics (Ref. A.21) are typically based on low charging rates (<2C). It is difficult to project the impact of higher charge rates on specific energy so the approach taken was to assume a range of likely specific energies (100, 150 and 200 W-hr/kg) and two maximum charge rates (1C and 2C). NiMH batteries were not included in this 'projected' group because the NiMH characteristics are similar to Li types (Ref. A.22).

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4.9 Additional Information: Lunar Surface Recharging Methods

For battery-type energy storage, there are two methods to recharge the modules in place. First is a direct electrical hookup. This method requires some level of dust mitigation, high levels of current (for rapid recharge) and high heat loads in the batteries, charge regulators and cables. The second method is called inductive charging. It relies upon half of a transformer coil placed on the suit and the other half of the coil at the RRS Station. The each coil is surrounded with a nonconductive shell which is designed to self-align when the recharging procedure is to begin. This method has been designed for underwater vehicle recharging (Ref. B.1, B.2) where fouling of electrical connector ports is a problem. This system converts a DC power source (as would be generated by the RRS Station battery, fuel cell, solar array or radioisotope power system source) to 65 to 80 kHz sine wave AC power using an inverter so that the power can be transferred using a transformer. When the coil halves are placed in close proximity to each other, the power is transferred across the RRS Station coil to the PLSS power subsystem-side coil. A rectifier converts the AC power back to DC power. Finally, a power conditioner (dc-dc converter) is needed to provide the PLSS power subsystem battery charger with regulated voltage and current. For the underwater system (which was built and tested successfully), the efficiency of the power transfer was 80 percent for power levels around 200 W.

The following information lists the details of the referenced underwater system. The coil design used a type 78 ferrite material because of its low-loss, high-frequency properties. The windings of each coil used 28 bi-filar turns of #22 Heavy Poly-Thermaleze insulated magnet wire. The winding conformation had an aspect ratio of 2 to 1 and was chosen to minimize the profile of the winding. The input voltage level was 48 to 60 V. The protective housing of each coil was made of Lexan. The maximum energy transfer capability was rated at 200 W-hr/hr (Ref. B.3). The weight of the system was 11 lb and 6.5 in. in diameter (Ref. B.4).

A high power design (Ref. B.4) is described to be a 5 in.^{3} battery-side transformer weighing less than 5 lb (same weight and size for the charger side) with the potential to provide 1000 W using four separate transformer couplings (at 250 W each). Since this system seems to be the most applicable to the EVA suit recharging since it can be scaled to the appropriate power level or 1000 W/5 lb (.0027 kg/w). Such a unit has not been built, but seems practical.

Note that inductive charging is also currently in use with terrestrial electric vehicles (Ref. B.5) in lieu of direct electrical connection. The reason for considering inductive charging is that direct electrical connections may have safety issues (incorrect plugging, shock hazard, etc). Although several brands of inductive electric vehicle chargers have been produced (Delco Electronics is the most popular), direct electrical connection seems more popular. The power level of such chargers are high (6500 W) but they are for high charge voltages (200 to 500 V). The efficiency of these inductive charging systems is around 90 percent. The weight of the entire inductive charge system is not clear from the literature but they are not weight optimized since most of the electronics are not on the vehicle, only the inductive coupler is likely to be low weight. Charge times are typically multi-hour.

The most obvious drawback for inductive charging is that since there are inherent losses in such a system, an inductive-type RRS Station must be larger than one using direct electrical connections. However, this drawback must be weighed against the enhanced safety due to the reduced dust interfaces impacts of the inductive system.

Inductive charging is not a valid approach for rapid recharging at high power levels since the mass of the transformer couplings on the PLSS-side is too high. For lower power levels below 250 W, the mass is likely acceptable, but this results in much longer recharge times. The most likely application may be for power transfer from a rover seat transformer coupler during long drives or perhaps for manned or robotic rover charging outside the manned base.

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-11-2009

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Compilation of Trade Studies for the Constellation Program Extravehicular Activity Spacesuit Power System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Fincannon, James

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 731384.06.04.01.31.06.50

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17066

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2009-215803

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 54
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This compilation of trade studies performed from 2005 to 2006 addressed a number of power system design issues for the Constellation Program Extravehicular Activity Spacesuit. Spacesuits were required for spacewalks and in-space activities as well as lunar and Mars surface operations. The trades documented here considered whether solar power was feasible for spacesuits, whether spacesuit power generation should be a distributed or a centralized function, whether self-powered in-space spacesuits were better than umbilically powered ones, and whether the suit power system should be recharged in place or replaced.

15. SUBJECT TERMS
Extravehicular activity; Spacesuit; Power system; Solar power; Battery; Energy storage; Fuel cell; Solar arrays; Umbilical power; Power distribution; Centralized versus distributed power; Inductive versus direct power coupling; Flywheel; Radioisotope

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	86	443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18