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Historical "Duration of Use" Power Figure Research and Update

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Executive Summary

Compared to actual demonstrated mission usage, boundaries in recent historical figures were much higher than actual required levels, especially for primary batteries, fuel cells, and dynamic RPS. Boundaries for solar and static RPS architectures remained mostly unchanged. Beyond looking only at demonstrated mission performance, current funded programs that would change the boundaries further were also considered. Considering these programs, boundaries for primary batteries, solar, and dynamic RPS do increase modestly. The investigation of the power level versus distance (AU) revealed the most practical locations of use for each architecture. Fuel cell use has been concentrated around earth's orbit as they provide high power levels for shorter duration. Solar has been demonstrated from very close to the Sun out to Jupiter as solar power generation levels begin to dissipate. Primary batteries have been demonstrated in numerous probes from Venus out to Saturn. Finally, static RPS systems have traveled from Venus out past 150 AU outside the solar system. Considering current funded programs, power levels for solar do increase at Earth and Jupiter. The investigation of the historical power level change over time revealed that early assumed chemical power levels were quite high compared to current projections. Solar power sources appear to have matured over time and seem to have increased as chemical decreased. Static RPS systems have remained relatively stable since their introduction.

Introduction

At the request of the Radioisotope Power Systems (RPS) Program Office at the NASA Glenn Research Center (GRC), The Aerospace Corporation (Aerospace) performed a study of the historical "duration of use" power figure. The figure provides boundaries for "electric power level in kilowatts electric (kWe) versus duration of use" for various forms of power, including chemical, solar, radioisotope, and fission. The primary goal of the study was to investigate the historical boundaries drawn in recent publications of the "duration of use" power figure and attempt to validate them with actual mission performance data and redraw the boundaries as needed. Additional analyses included an investigation of the historical boundaries and how they have changed over time and development of a power level versus distance from the sun in astronomical units (AUs) figure.

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1. Background and Motivation

The first known publication of the "Duration of Use Power Figure" can be traced back to 1961 Handbook of Astronautical Engineering by Koelle shown in Figure 1. The figure has been subsequently reproduced numerous times. Over time the boundaries have shifted with little to no rationale given for the boundary changes. The boundaries also appear to be very idealized representations of power levels. A recent publication of the figure is shown in Figure 2 from the Atomic Power in Space II 2015 publication. This study attempts to validate the existing boundaries and redraw them when appropriate using actual historical power data. Additionally, a "Distance Power Figure" has been developed to show uses throughout the solar system and beyond.

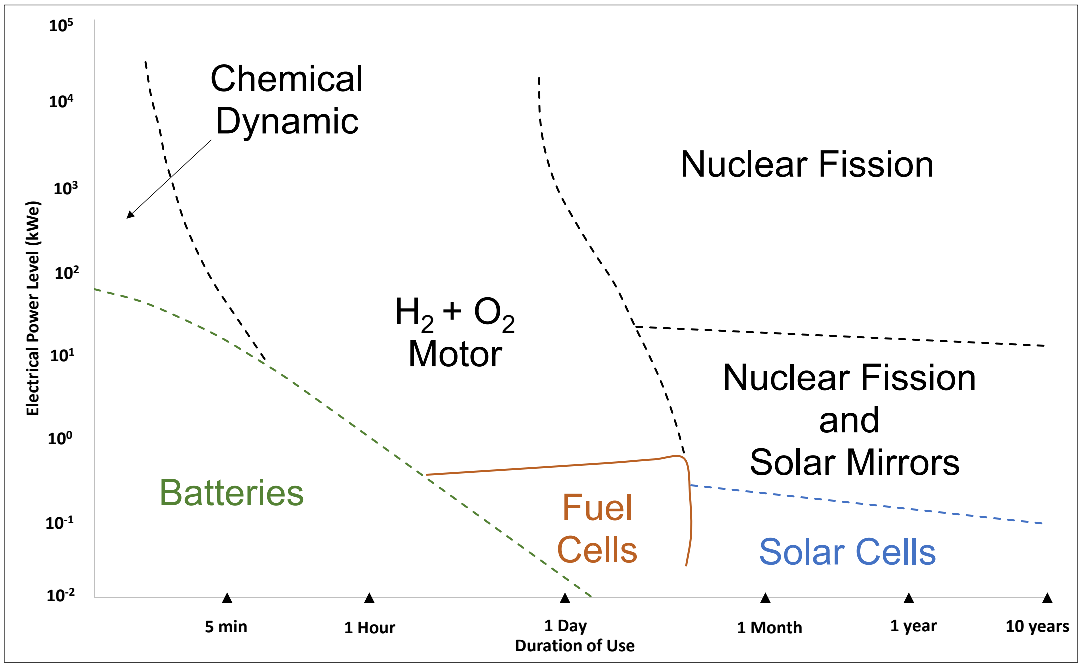


Figure 1. Reproduction of Power Figure from the Handbook of Astronautical Engineering, Koelle, 1961

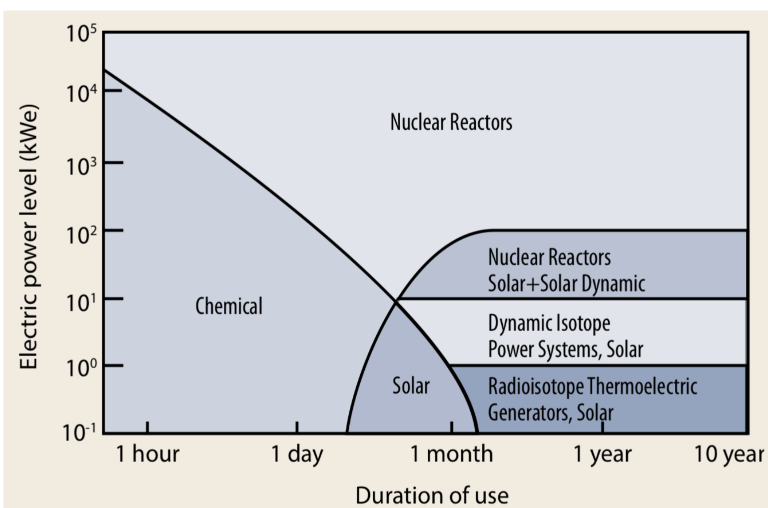


Figure 2. Power Figure from Atomic Power in Space II 2015

2. Boundary Changes Over Time

To investigate "duration of use" power figure boundary changes over time, as many published power figures that could be located were consulted. Table 1 provides a list of published historical power figures that were consulted.

Table 1. List of Historical Published Power Figures Consulted

Reference	Year
Spacecraft Design - Electrical Power Systems (2020)	2020
Atomic Power in Space II (2015)	2015
Space Power and Energy Storage Roadmap Technology Area 03 (2010)	2010
Space Vehicle Design by Griffin and French (2004)	2004
Spacecraft Power Technologies (2000)	2000
Aftergood (1989) Background on Space Nuclear Power	1989
New Scientist (1989)	1989
Space Nuclear Power (1985)	1985
PROGRESS IN SPACE NUCLEAR REACTOR POWER (1984)	1984
Nuclear Reactors in Satellites (1979)	1979
Nuclear Reactors/or Space Electric Power (1978)	1978
Handbook of Astronautical Engineering (1961)	1961

After transcribing the power levels for each architecture, it was possible to generate Figure 3. This figure depicts the power levels given in each historical figure versus the year of publication. The architectures shown include chemical, solar, and Static RPS. It was not possible to separate fuel cells and primary batteries and dynamic RPS as the same level of detail was not given in each figure. A possible interpretation of this figure is that early assumed chemical power levels were quite high compared to current projections. Solar power sources appear to have matured over time and seem to have increased as chemical decreased. Static RPS systems have remained relatively stable since their introduction.

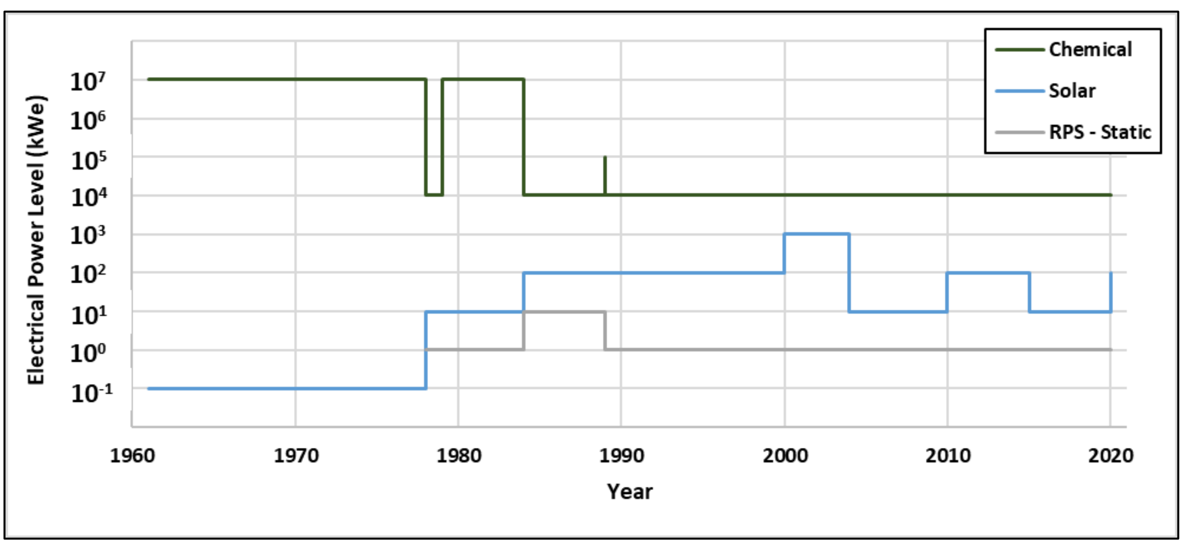


Figure 3. Historical Power Levels versus Year of Publication

3. Duration of Use Power Figure Investigation

This investigation attempts to validate and adjust "duration of use versus power level (kWe) boundaries based on demonstrated mission values. Numerous missions were investigated and considered for this study, but only the missions most impactful to the boundaries are those that are plotted and referenced. Numerous other references were also consulted beyond those listed in Appendix A. Some "actual" mission data was extrapolated as there are some measurement gaps in time for every mission. The historical figures also include nuclear fission reactors, but for simplicity they have not been included in the revised figures. SNAP-10A is the only demonstrated usage at about 500 We, and there were not any recent actual funded programs to consider during the period of study. Figure 4 provides the existing "duration of use" power figure that was used as a departure point for the subsequent revised figures. This figure is adapted primarily from the Atomic Power in Space II 2015 publication.

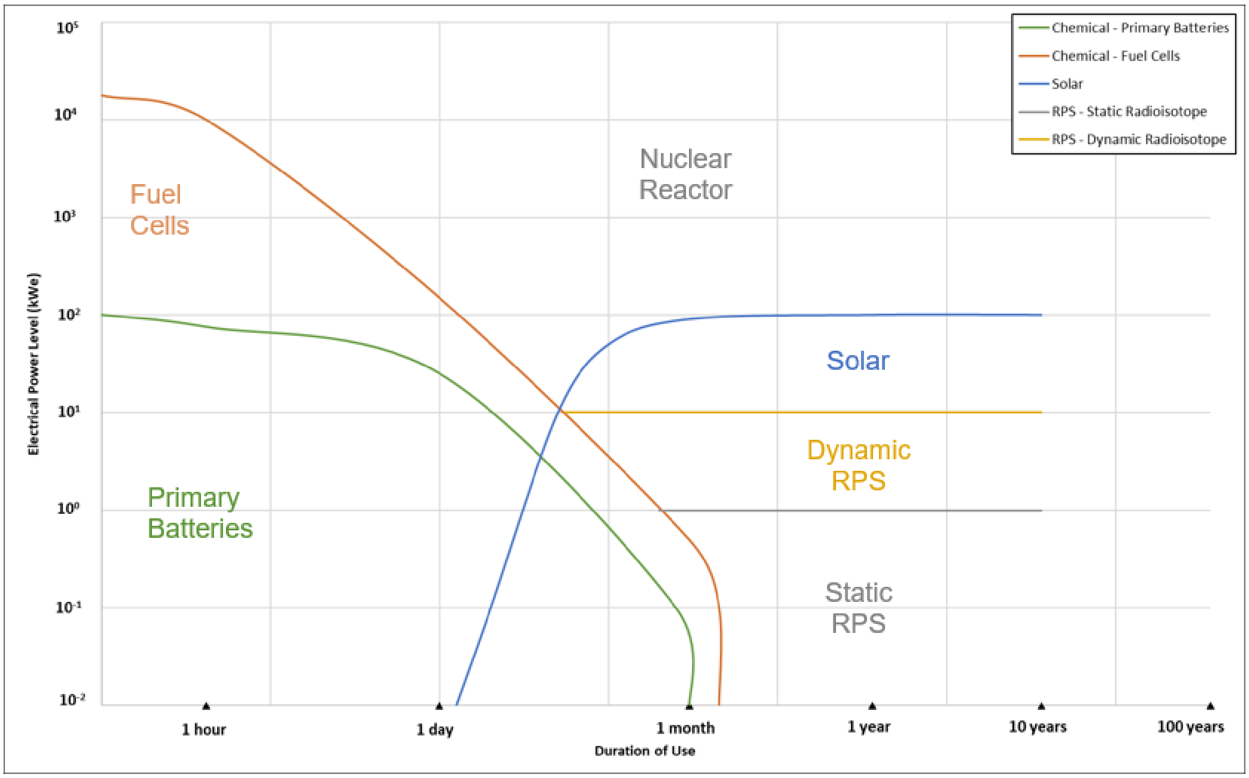
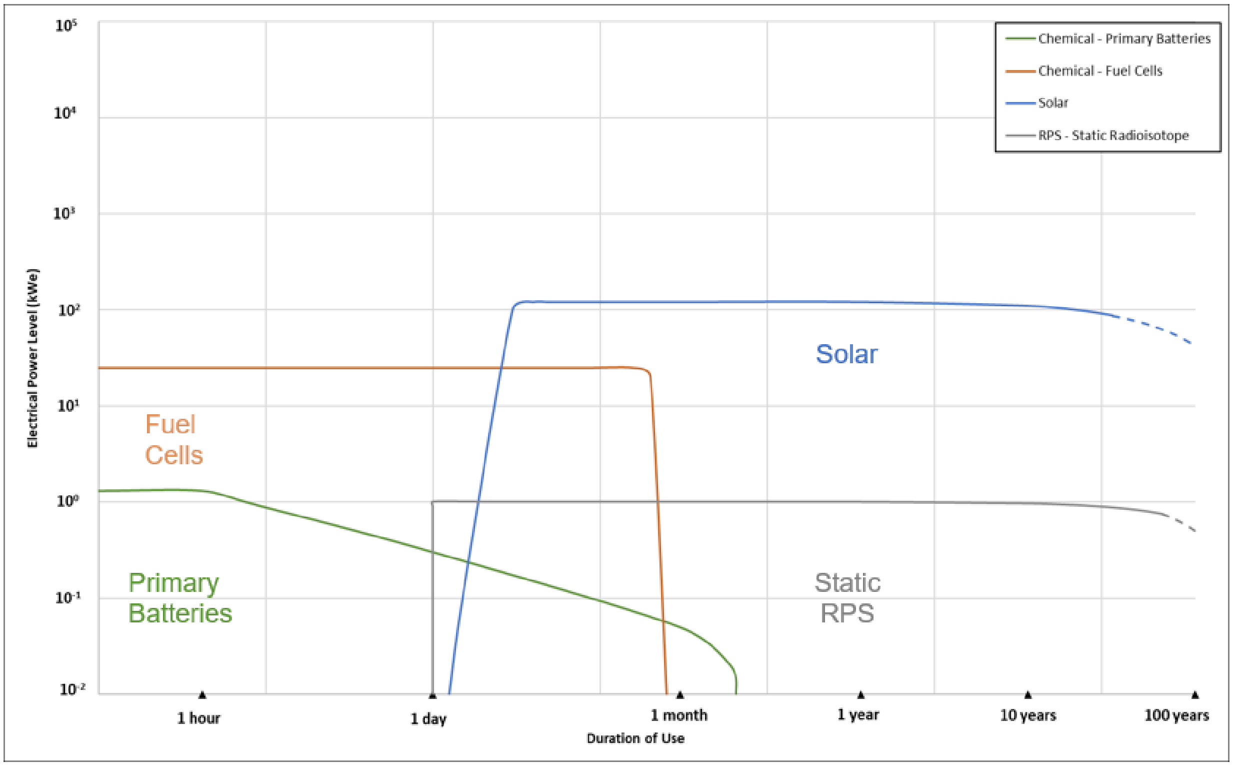


Figure 4. Existing Duration of Use Power Figure

3.1 Duration of Use Revised Boundaries – Demonstrated

Revised boundaries for the "duration of use" power figure are shown in Figure 5. Boundaries for fuel cells and primary batteries have decreased significantly based on demonstrated mission need. Also, dynamic RPS is no longer shown since it has not yet been demonstrated. Solar and static RPS remain about the same as they were. Demonstrated mission usage for chemical architectures were derived from the assumed average power based on the available power and the recorded duration of use.



Note: dashed lines indicate predicted/studied values

Figure 5. Revised Boundary Duration of Use Power Figure

3.2 Duration of Use Revised Boundaries – Key Defining Missions

The key defining missions driving the boundaries are shown in Figure 6. Fuel cells have historically been used in some crewed systems and provide relatively high power for shorter durations before they require regeneration. The most significant usage was on the Space Shuttle providing approximately 21kW average, with the longest duration mission being STS-80 for a little over 18 days. Primary batteries provide a discharge, but no recharge, and have been used in numerous probes for short duration applications. Some higher power examples included the Large Pioneer Venus Multiprobe and Cassini Huygens probe that provided approximately 1.15 kW for 54 minutes and 0.7kW for 153 minutes respectively. The longest demonstrated duration of use of a primary battery was the Mars Pathfinder Rover which provided very low power levels for approximately 61 days. This battery however was also aided by a small solar array to help extend the life of the mission. Solar mission usage is driven by the International Space Station (ISS) which produces approximately 120kW and was initiated a little over 20 years ago. This is of course caveated by the fact that ISS is a multi-launch assembly that was built up to its final configuration overtime. The first largest single launch array was SaudiGeo-Sat-1/HellasSat-4 which produces approximately 25kW. Static RPS boundary is driven by Cassini, which carried three General Purpose Heat Source (GPHS) Radioisotope Thermoelectric Generators (RTGs) which produced approximately 0.875kW at the beginning of life. The longest duration of use is Voyagers 1 and 2 which have been in operation for over 43 years. This has also resulted in the extension of the power figure beyond the 10 year mark.

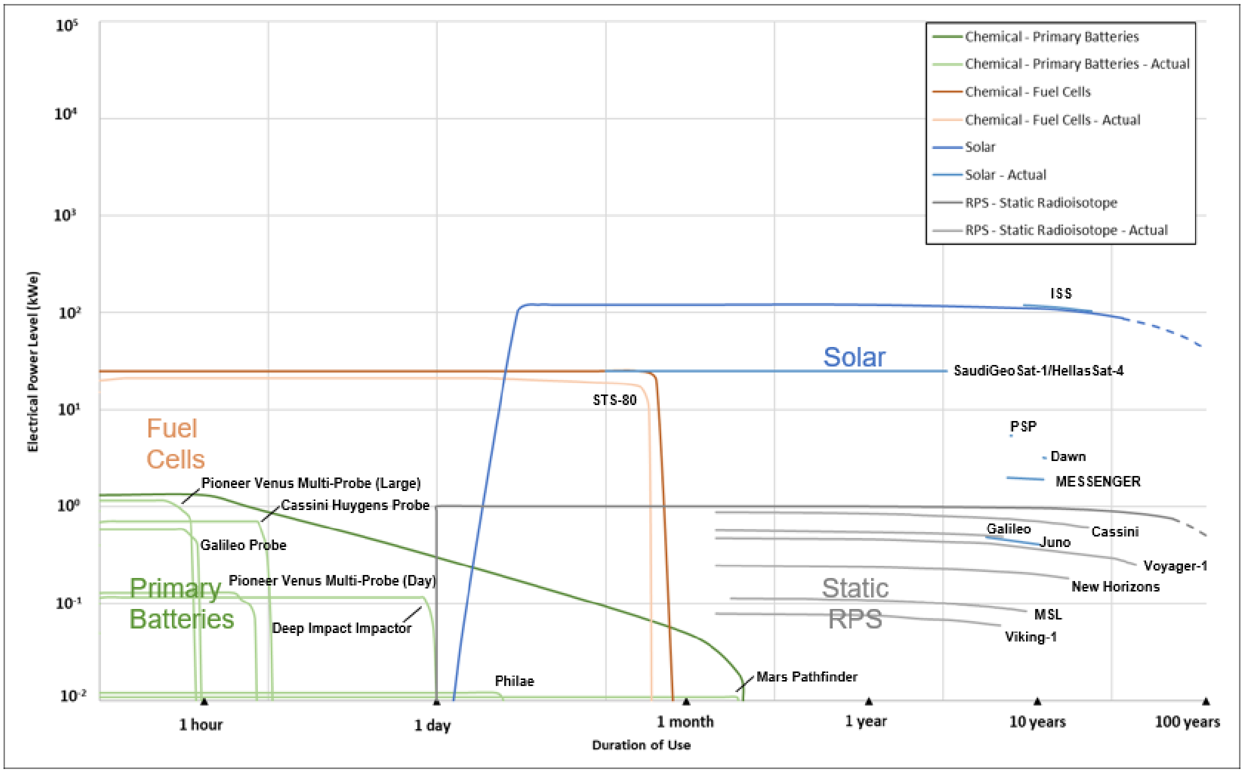
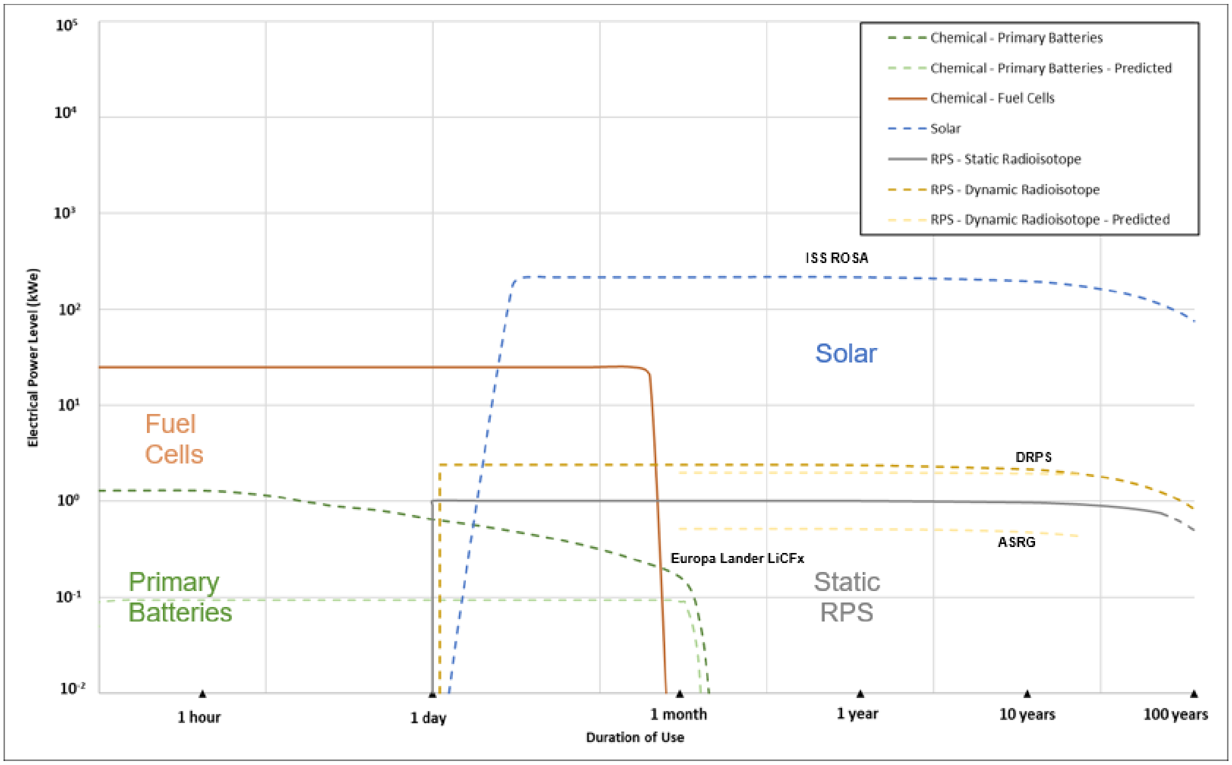


Figure 6. Key Defining Missions for Revised Boundaries

3.3 Duration of Use Funded Boundary Changing Missions

Additional currently funded programs also contribute to further revision of the boundaries that have not yet been demonstrated. Figure 7 provides a summary of these programs. For primary batteries, the Europa Lander mission plans to use Lithium CFx batteries which will increase the power level for about the same duration of use as previously demonstrated. For solar, the already underway retrofit of the ISS with Roll Out Solar Arrays (ROSAs) will increase the power output to approximately 215kW. For dynamic RPS, in development DRPS systems will produce up to 500W. Also of note, the Advanced Stirling Radioisotope Generator (ASRG) development, ended in 2015, would have produced up to 130W. For both programs it is assumed up to four units could be carried.



Note: dashed lines indicate predicted/studied values

Figure 7. Funded Boundary Changing Missions for Duration of Use Figure

4. Power Level Versus Distance (AU) Investigation

In addition to the "duration of use" figure update, an investigation of power level versus distance from the Sun was also conducted. This was intended to see if there were nominal uses throughout the solar system and beyond for the various power architectures.

4.1 Distance Power Figure – Demonstrated

Power level versus distance in AU is shown in Figure 8. This is the initial version of this figure based on demonstrated mission usage.

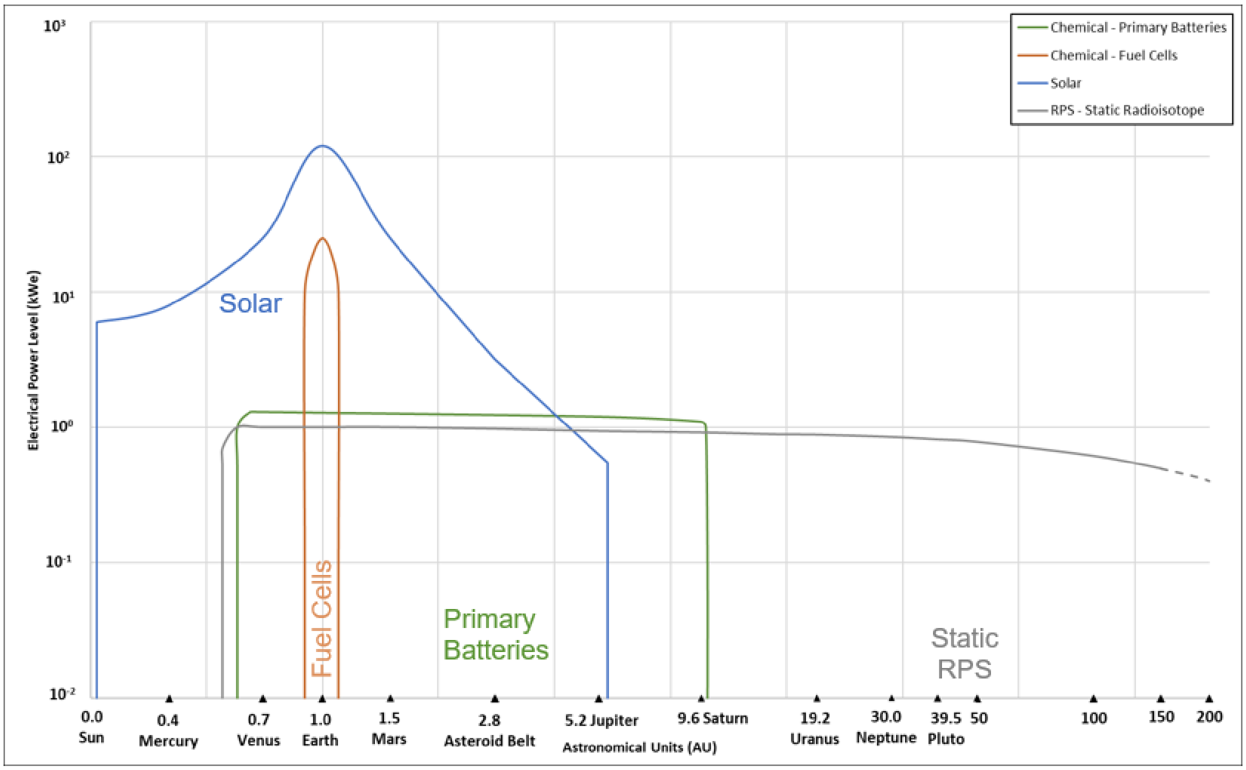
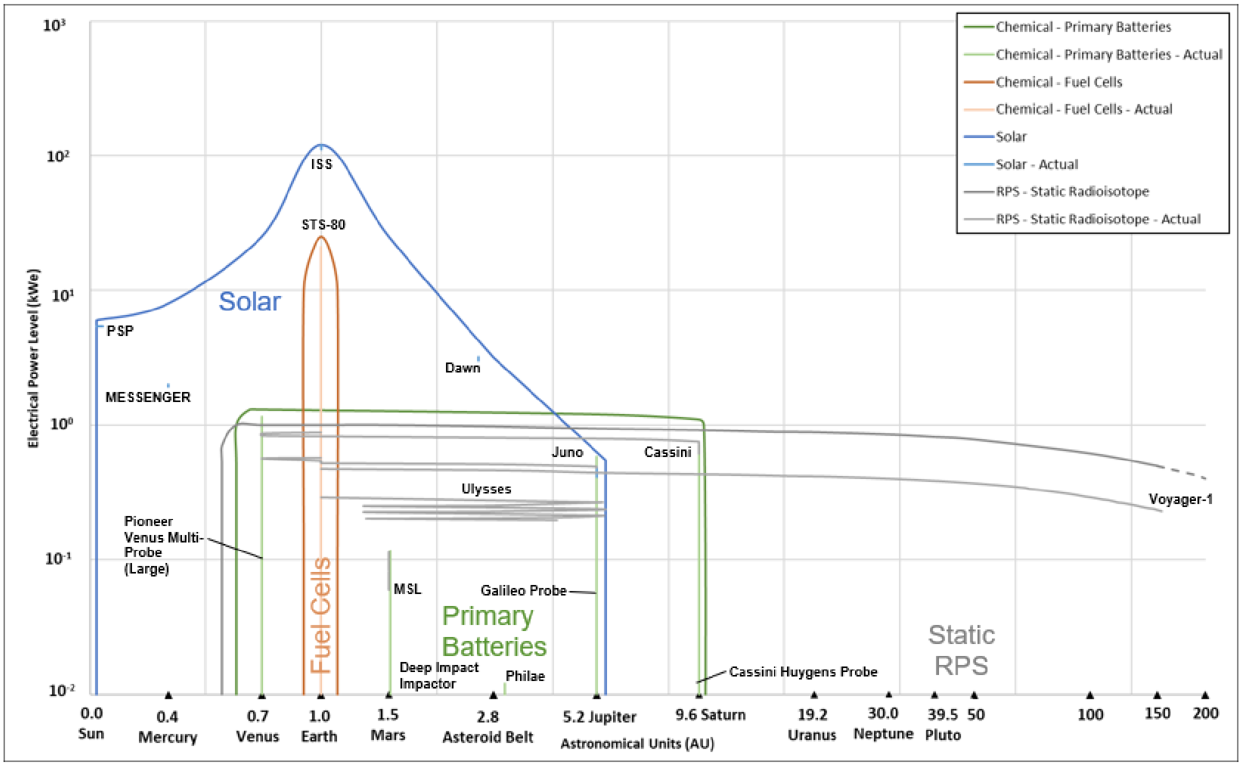


Figure 8. Astronomical Unit (AU) Distance Power Figure Developed Boundaries

4.2 Distance Power Figure - Key Defining Missions

The key defining missions that drive the distance figure are shown in Figure 9. For chemical fuel cells, the space shuttle usage again drives the highest power level, which was only used around Earth orbit at 1.0 AU. Primary batteries have been used from the inner solar system at Venus at 0.7 AU out to Saturn at 9.6 AU. Solar usage also peaks at 1.0 AU again driven by ISS. In the inner solar system Parker Solar Probe (PSP) drives the boundary where it has already made several close flybys of the Sun producing about 5.4kW peak. The outer boundary is driven by Juno producing about 0.486 kW at Jupiter. Static RPS systems have traveled through the inner solar system conducting flybys of Venus at 0.7 AU and the outer boundary is driven by Voyager-1 which has left the solar system and currently surpassed 150 AU.

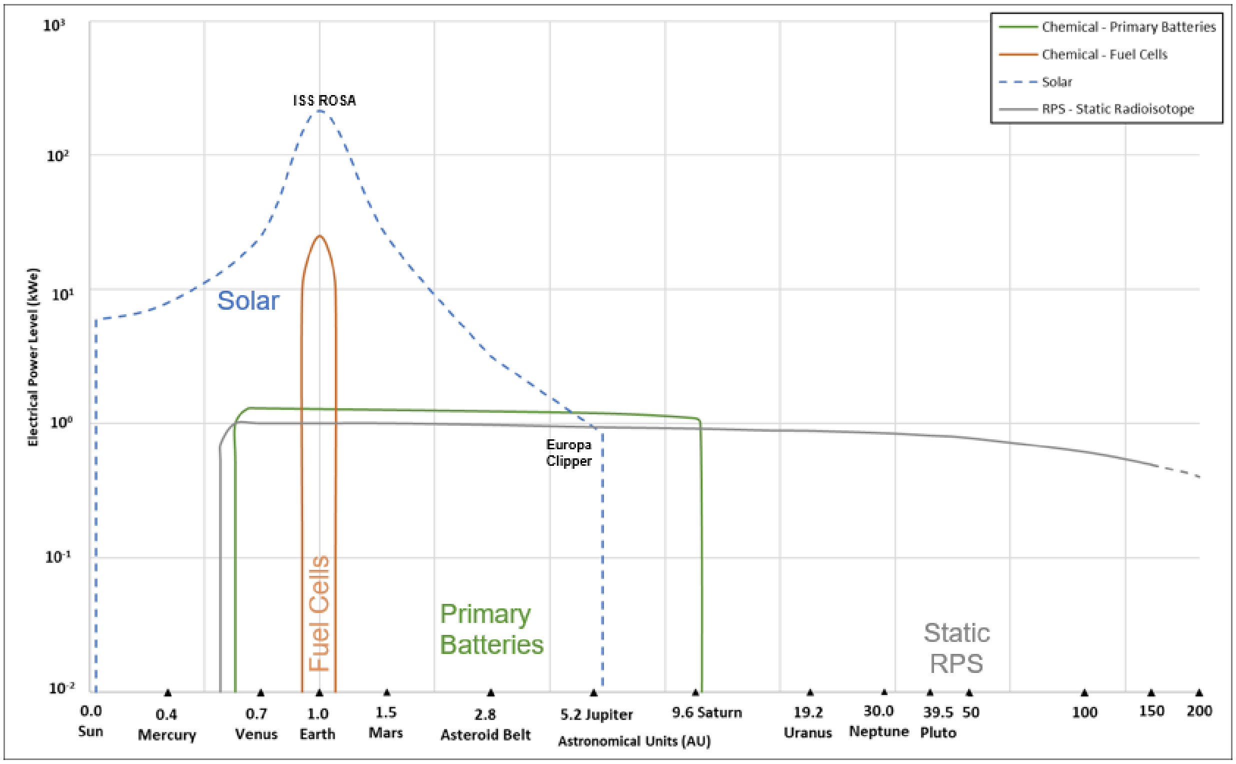


Notes: dashed lines indicate predicted/studied values; Solar mission values are plotted at destination

Figure 9. Key Defining Missions for Astronomical Unit (AU) Distance Power Figure

4.3 Distance Power Figure Funded Boundary Changing Missions

Funded boundary changing missions for the distance power level figure are shown in Figure 10. The primary changes here are the ROSA retrofit of the ISS at 1.0 AU and the Europa Clipper mission which will increase the solar output in the Jupiter vicinity to 0.853kW.



Note: dashed lines indicate predicted/studied values

Figure 10. Funded Boundary Changing Missions for Astronomical Unit (AU) Distance Power Figure

5. Conclusion

This report has provided a summary the research conducted to validate historical duration of use power level figures, changes of power level over time, develop revised duration of use boundaries, and develop a new power level versus distance figure. This research provides a snapshot at the time of publication, and may be revisited and revised as technologies continue to evolve and new power levels are demonstrated in the space environment.

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