National Aeronautics and Space Administration

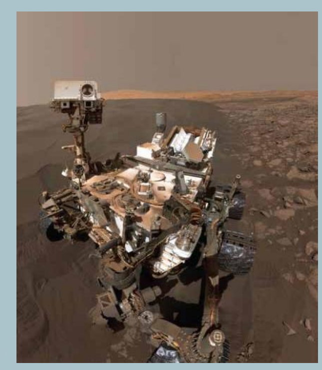
A Historical Look at Performance Parameters and Decision Criteria for Robotic Planetary Exploration Power Systems Selections

Marc −ayhurst, Eric Mahr, Robert Bitten, Vincent Bilardo | **The Aerospace Corporation**
June Zakrajsek | **NASA Glenn Research Center**

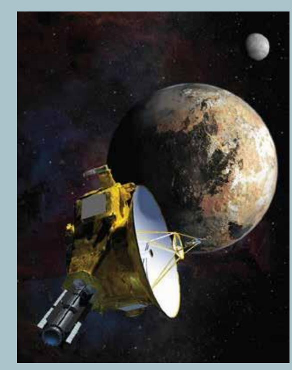
In an effort to better understand the decision-making process and provide insight for potential future missions, the NASA Radioisotope Power Systems (RPS) Program tasked The Aerospace Corporation (Aerospace) to study historical missions that used RPS and solar architectures.

- Data was collected for a variety of RPS and solar missions to look for possible trends from the selected implementation
- Mission case studies were also developed based on interviews with mission personnel who were responsible for defining the power architecture of their mission
- A cost based Measure of Effectiveness (MoE), informed by the collected data and case studies, was developed.

RPS enabled missions, like Mars Science Lab, Curiosity and New Horizons, do not meet requirements of a solar powered mission due to sunlight or thermal constraints.



Mars Science Lab (MSL)
Image Credit: NASA/JPL-Caltech/MSSS



New Horizons
Image Credit: Johns Hopkins University Applied Physics Laboratory

MISSION COLLECTION TARGETS

NASA RPS MISSIONS; All years, 16 TOTAL

MISSION	LAUNCH YEAR	DESTINATION	PROGRAM
MSL	2011	Mars	Mars
New Horizons	2006	Pluto	New Frontiers
Cassini	1997	Saturn	
Ulysses	1990	Sun	
Galileo	1989	Jupiter	
Voyager 1	1977	Jupiter/Saturn	
Voyager 2	1977	Jupiter/Saturn/ Uranus/Neptune	
Viking 1	1975	Mars	
Viking 2	1975	Mars	
Pioneer 11	1973	Jupiter/Saturn	
Pioneer 10	1972	Jupiter	
Apollo 16 LSEP	1972	Moon	Apollo
Apollo 17 LSEP	1972	Moon	Apollo
Apollo 14 LSEP	1971	Moon	Apollo
Apollo 15 LSEP	1971	Moon	Apollo
Apollo 12 LSEP	1969	Moon	Apollo

NASA SOLAR MISSIONS; Since 2000, 18 TOTAL

MISSION	LAUNCH YEAR	DESTINATION	PROGRAM
OSIRIS-Rex	2016	Asteroid	New Frontiers
MAVEN	2013	Mars	Mars Scout
LADEE	2013	Moon	Lunar Quest
GRAIL	2011	Moon	Discovery
Juno	2011	Jupiter	New Frontiers
LRO	2009	Moon	Lunar Quest
Kepler	2009	Earth-trailing	Discovery
LCROSS	2009	Moon	
Phoenix	2007	Mars	Mars Scout
Deep Impact	2005	Asteroid	Discovery
MRO	2005	Mars	Mars
Messenger	2004	Mercury	Discovery
MER	2003	Mars	Mars
CONTOUR	2002	Comet	Discovery
Genesis	2001	Sun-Earth L1	Discovery
Mars Odyssey	2001	Mars	Mars
MGS	1996	Mars	Mars
Magellan	1989	Venus	

CASE STUDIES OVERVIEW

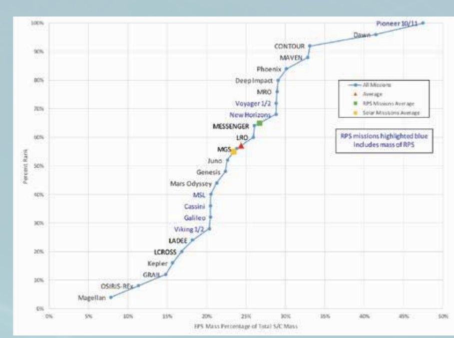
- Mission case studies developed based on interviews with mission personnel who were responsible for defining the power architecture of their mission
- Missions identified
  - Change from RPS to Solar: PSP and Europa Clipper
  - Change from Solar to RPS: MSL
  - Trade space exploration: Juno and Europa Lander
- For the choice of power source, the discussion was focused on the decision-making process and not any difficulties encountered during development as a result of the decision
- Case studies show that unique mission design and planned science have the greatest impact on the selection of RPS
  - No common reason for the choice of power source among the case studies
  - Primary decision factors include cost, availability of RPS, and planetary protection
  - RPS excels in reliability and technically enabling qualities
  - Policy limits use of RPS and cost and schedule are other major considerations

MISSION	BACKGROUND	DECISION CRITERIA
Parker Solar Probe Launch: 2018 Target: Sun Power Source: Solar	• Originally designed to swing by Jupiter and flyby the sun • At the time, RPS was thought to be the only way	• Cost reduction direction from NASA HQ • Solar presumed to be the cheaper option • Able to develop trajectory that used Venus flybys • Also guided by availability of plutonium for RPS
Europa Clipper Launch: 2020's Target: Europa (Jupiter) Power Source: Solar	• Performed formal trade study evaluating 5 RPS, solar, and hybrid options	• Cost • Not significantly enabling to perform mission • If cost and schedule criteria were eliminated RPS would have ranked highest
Europa Lander Launch: 2020's Target: Europa (Jupiter) Power Source: Batteries (Lander) / Solar (Carrier)	• Performed a broad review of options for the both the carrier and the lander	• Planetary protection was a primary concern due to possible effect on potential indigenous life • Heat from RPS could have melted ice creating unstable footing • RPS would have enabled increased surface time to do long-term science (e.g., seismometry) • Carrier followed decision made for Europa Clipper
Juno Launch: 2011 Target: Jupiter Power Source: Solar	• Baselined as an RPS mission; given guidance of 2003 New Frontiers AO • Sought to demonstrate solar was a viable fall-back given uncertainty of RPS development timeline	• Assumed proposing RPS would lead to the mission not being selected if RPS would not be available on time • Would have preferred RPS as using solar at Jupiter is more operationally complex • Further complicated by lengthened mission due to propulsion issue which includes more eclipse periods
Mars Science Laboratory Launch: 2011 Target: Mars Power Source: RPS–MMRTG	• Studies started in 2000 for Mars Smart Lander • Wanted to consider a wide range of landing sites to look for water	• RPS chosen primarily due to desire not to limit the landing site • Best choices for looking for water reside in higher latitudes of northern hemisphere • Solar only feasible at lower latitudes

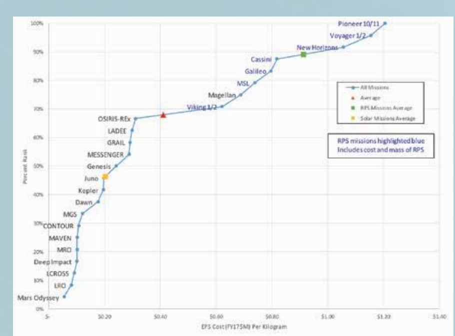
POWER SUBSYSTEM COST COMPARISON

- EPS mass as percentage of spacecraft bus mass is comparable
  - RPS = 27%, Solar = 23%
- EPS cost as a percentage of spacecraft bus cost is higher for RPS
  - RPS = 21%, Solar = 11%
- EPS subsystem cost per EPS subsystem mass (FY17$M per kg) is higher for RPS
  - RPS = $.90, Solar = $.20

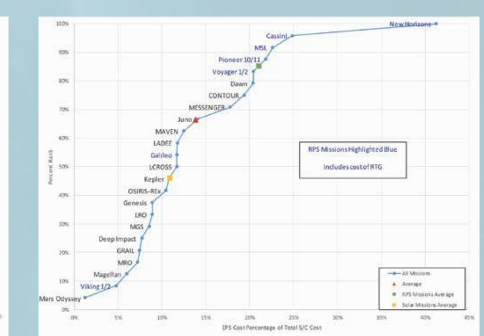
EPS MASS % OF TOTAL S/C MASS



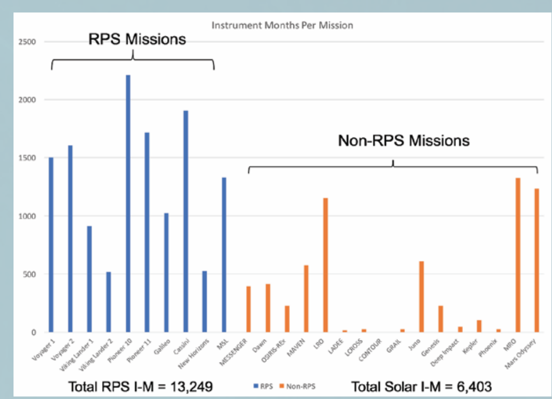
EPS S/S COST PER MASS

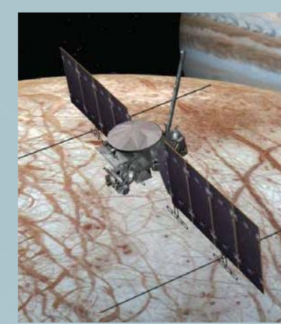


EPS COST % OF TOTAL COST



SCIENCE VALUE COMPARISON





Europa Clipper
Image Credit: NASA/JPL-Caltech

Cassini
Image Credit: NASA/JPL-Caltech

Selection of RPS for a given mission depends on many factors including the ability of meeting science requirements, ease of design integration, policy, schedule, cost and risk.

SCIENCE VALUE COST-EFFECTIVENESS RESULTS

- Comparing results for RPS (10) and non-RPS (16) missions show that the average number of instrument-months per mission is higher (i.e., more science per mission) and the Class Science Mission Cost-Effectiveness is similar.
  - Average instrument-months per mission is 1656 for RPS versus 400 for non-RPS.
  - Class SMCE for all RPS missions is 0.60 instrument-months per FY17$M versus 0.59 instrument-months per FY$17M for non-RPS missions.

MISSION TYPE	AVERAGE INSTRUMENT-MONTHS	CLASS SCIENCE MISSION COST EFFECTIVENESS
RPS	1,656	0.60 I-M/$M
Non-RPS	400	0.59 I-M/$M

  - RPS-based missions typically enable a larger spacecraft with multiple instruments over a much longer operating time, increasing science value over non-RPS missions.

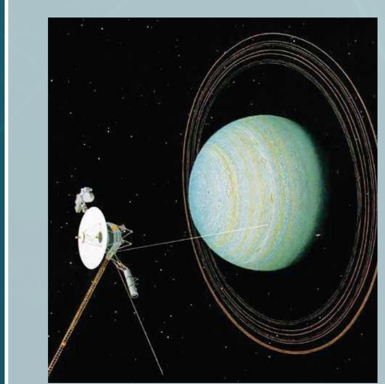
MoE CALCULATION STEPS

1. Calculate Solar Array Beginning of Life (BOL) power requirement based on End of Mission (EOM) power requirement & mission lifetime
   - BOL Required = EOM/((1-% Annual Degradation)^(Mission Lifetime in years) * (1/Distance from Sun in AU)^2)
2. Calculate RPS BOL requirement based on EOM requirement & lifetime
   - BOL Required = EOM/((1-% Annual Degradation)^(Mission Lifetime in years + 3 years prior to launch for fueling)
3. Calculate solar array size based on BOL requirement
4. Calculate solar-based EPS subsystem Cost based on solar array size and EOM power
5. Calculate RPS–based EPS subsystem cost based on #RTG's needed
6. Calculate the ratio of solar-based to RPS based EPS subsystem
   - Solar/RPS < 0.8 = Light Green
   - Solar/RPS < 1 = Dark Green
   - 0.8 < x < 1 = Medium Green

RESULTS

MoE assessment shows that, from a cost perspective, RPS is primarily cost effective for Outer Planet orbiter missions (to Saturn and beyond).

If the cost of RPS were reduced and performance enhanced beyond eMMRTG and DRPS, RPS systems could be readily adoptable for a broader range of missions and enable more challenging missions.



Voyager 2
Image Credit: NASA/JPL-Caltech

MMRTG
Image Credit: Teledyne

MMRTG CASE

- Cost (FY17$M) = $80M for 1 unit, $98M for 2, $122M for 3 and $21M for each additional unit
- BOL Power = 110 W
- Degradation = 4.8% per year

Mission Lifetime (Years) — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
250	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07
500	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06
750	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05
1000	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05
1250	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
1500	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
1750	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04
2000	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
400	0.29	0.26	0.27	0.28	0.28	0.26	0.26	0.27	0.25	0.26
450	0.29	0.29	0.27	0.27	0.28	0.26	0.27	0.27	0.25	0.26
500	0.28	0.29	0.29	0.27	0.28	0.28	0.27	0.27	0.26	0.26
550	0.30	0.28	0.29	0.29	0.28	0.28	0.27	0.27	0.28	0.26
600	0.30	0.30	0.28	0.29	0.30	0.28	0.29	0.27	0.28	0.27
650	0.32	0.30	0.31	0.29	0.29	0.28	0.29	0.27	0.28	0.27
700	0.31	0.32	0.30	0.31	0.29	0.30	0.29	0.27	0.28	0.27
750	0.30	0.31	0.30	0.30	0.29	0.30	0.28	0.29	0.28	0.27

Mission Lifetime (Years)* — EOM Power Required (W)

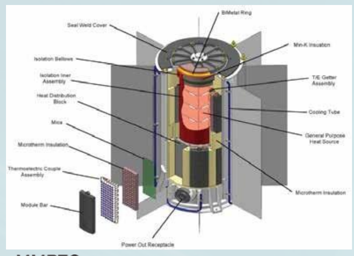
	3	4	5	6	7	8	9	10	11	12
100	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52
200	0.61	0.63	0.64	0.66	0.68	0.59	0.60	0.62	0.63	0.65
300	0.75	0.77	0.68	0.70	0.72	0.74	0.76	0.69	0.71	0.72
400	0.85	0.77	0.79	0.81	0.83	0.77	0.79	0.81	0.75	0.77
500	0.83	0.85	0.88	0.81	0.84	0.86	0.81	0.83	0.78	0.80
600	0.90	0.92	0.86	0.89	0.91	0.86	0.88	0.84	0.86	0.83
700	0.95	0.98	0.92	0.95	0.90	0.93	0.88	0.85	0.87	0.84
800	1.00	0.95	0.97	0.93	0.95	0.92	0.89	0.91	0.88	0.86

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	1.46	1.50	1.54	1.58	1.62	1.67	1.71	1.76	1.80	1.85
125	1.81	1.86	1.91	1.96	2.01	2.06	1.68	1.72	1.77	1.82
150	2.15	2.21	1.79	1.84	1.89	1.95	2.00	2.05	2.11	2.17
175	1.97	2.03	2.08	2.14	2.20	2.26	2.32	2.02	2.07	2.13
200	2.25	2.31	2.37	2.44	2.50	2.18	2.24	2.30	2.36	0.05
225	2.52	2.59	2.25	2.31	2.38	2.44	2.51	2.58	2.30	0.05
250	2.36	2.43	2.50	2.56	2.63	2.71	2.41	2.48	2.55	2.62
275	2.59	2.67	2.74	2.82	2.51	2.58	2.65	2.72	2.80	2.54

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	3.47	3.56	3.66	3.76	3.87	3.97	4.08	4.20	4.31	4.43
125	4.32	4.44	4.56	4.69	4.82	4.95	4.02	4.13	4.25	4.37
150	5.16	5.31	4.31	4.43	4.55	4.68	4.81	4.95	5.08	5.23
175	4.75	4.88	5.02	5.16	5.30	5.45	5.60	4.87	5.01	5.15
200	5.42	5.57	5.73	5.89	6.05	5.26	5.41	5.56	5.72	5.88
225	6.09	6.26	5.44	5.60	5.75	5.91	6.08	6.25	5.57	5.72
250	5.72	5.88	6.04	6.21	6.39	6.57	5.85	6.01	6.18	6.35
275	6.29	6.46	6.64	6.83	6.08	6.25	6.43	6.61	6.79	6.16



eMMRTG
Image Credit: NASA/JPL-Caltech

eMMRTG CASE

- Cost (FY17$M) = $80M for 1 unit, $98M for 2, $122M for 3 and $21M for each additional unit
- BOL Power = 148 W
- Degradation = 2.5% per year

Mission Lifetime (Years) — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
250	0.11	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
500	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
750	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08
1000	0.09	0.08	0.08	0.09	0.09	0.09	0.08	0.08	0.08	0.08
1250	0.09	0.08	0.08	0.09	0.09	0.08	0.08	0.08	0.08	0.08
1500	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
1750	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
2000	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
400	0.34	0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.40	0.41
450	0.37	0.38	0.39	0.40	0.41	0.36	0.37	0.38	0.39	0.40
500	0.41	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.43	0.44
550	0.39	0.39	0.40	0.41	0.42	0.43	0.39	0.40	0.41	0.42
600	0.42	0.43	0.44	0.39	0.40	0.41	0.42	0.43	0.44	0.46
650	0.39	0.40	0.41	0.42	0.43	0.44	0.46	0.42	0.43	0.44
700	0.42	0.43	0.44	0.45	0.42	0.43	0.44	0.45	0.46	0.47
750	0.45	0.41	0.42	0.43	0.44	0.45	0.46	0.43	0.44	0.45

Mission Lifetime (Years)* — EOM Power Required (W)

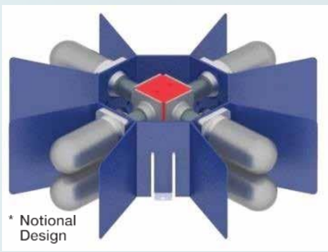
	3	4	5	6	7	8	9	10	11	12
100	0.53	0.54	0.55	0.57	0.58	0.59	0.61	0.62	0.64	0.65
200	0.77	0.79	0.81	0.83	0.86	0.88	0.90	0.92	0.95	0.97
300	0.89	0.91	0.93	0.96	0.98	1.01	1.04	1.06	1.09	1.12
400	0.98	1.01	1.04	1.06	1.09	1.12	1.15	1.18	1.21	1.25
500	1.22	1.08	1.11	1.14	1.17	1.20	1.24	1.27	1.30	1.34
600	1.26	1.29	1.32	1.20	1.23	1.27	1.30	1.34	1.37	1.41
700	1.29	1.32	1.36	1.39	1.28	1.32	1.35	1.39	1.43	1.46
800	1.31	1.35	1.38	1.42	1.46	1.36	1.39	1.43	1.47	1.51

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	1.82	1.87	1.91	1.97	2.02	2.07	2.13	2.19	2.24	2.31
125	1.81	1.86	1.91	1.96	2.01	2.06	2.12	2.18	2.24	2.30
150	2.15	2.21	2.27	2.33	2.40	2.46	2.53	2.60	2.67	2.74
175	2.50	2.57	2.64	2.71	2.78	2.86	2.94	3.02	3.10	3.19
200	2.84	2.92	3.00	3.08	3.17	3.26	3.35	3.44	3.53	3.63
225	3.19	3.28	3.37	3.46	3.55	2.89	2.97	3.05	3.13	3.22
250	3.53	2.87	2.95	3.03	3.12	3.20	3.29	3.38	3.47	3.57
275	3.07	3.15	3.24	3.33	3.42	3.52	3.61	3.71	3.82	3.92

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	4.31	4.43	4.56	4.68	4.81	4.94	5.08	5.22	5.37	5.51
125	5.37	4.44	4.56	4.69	4.82	4.95	5.09	5.23	5.37	5.52
150	5.16	5.31	5.45	5.61	5.76	5.92	6.09	6.26	6.43	6.61
175	6.01	6.18	6.35	6.53	6.71	6.90	7.09	7.29	7.49	7.70
200	6.86	7.05	7.25	7.45	7.66	7.87	8.09	8.32	8.55	8.79
225	7.71	7.92	8.14	8.37	8.61	6.99	7.19	7.39	7.60	7.81
250	2.36	6.95	7.14	7.34	7.55	7.76	7.98	8.20	8.43	8.67
275	2.59	7.64	7.85	8.07	8.30	8.53	8.77	9.02	9.27	9.53



DRPS
Image Credit: NASA/American Superconductor, Inc.

DRPS CASE

- Cost (FY17$M) = $107M for 1 unit and $25M for each additional unit
- BOL Power = 500 W
- Degradation = 1.3% per year

Mission Lifetime (Years) — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
250	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11
500	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.12
750	0.13	0.14	0.14	0.14	0.14	0.14	0.12	0.12	0.12	0.12
1000	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15
1250	0.15	0.16	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15
1500	0.15	0.15	0.15	0.16	0.16	0.16	0.14	0.14	0.15	0.15
1750	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.15
2000	0.16	0.17	0.17	0.15	0.15	0.16	0.16	0.16	0.16	0.17

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
400	0.46	0.47	0.48	0.49	0.50	0.51	0.53	0.54	0.55	0.56
450	0.51	0.52	0.53	0.43	0.44	0.45	0.47	0.48	0.49	0.50
500	0.44	0.45	0.46	0.48	0.49	0.50	0.51	0.52	0.54	0.55
550	0.48	0.49	0.51	0.52	0.53	0.54	0.56	0.57	0.58	0.60
600	0.52	0.53	0.55	0.56	0.57	0.59	0.60	0.62	0.63	0.65
650	0.56	0.57	0.59	0.60	0.62	0.63	0.65	0.66	0.68	0.70
700	0.60	0.61	0.63	0.64	0.66	0.68	0.69	0.71	0.73	0.75
750	0.64	0.65	0.67	0.69	0.70	0.72	0.74	0.76	0.78	0.70

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.45	0.47	0.48
200	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88
300	1.02	1.05	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.29
400	1.34	1.37	1.41	1.45	1.48	1.52	1.56	1.61	1.65	1.69
500	1.32	1.36	1.39	1.43	1.47	1.51	1.55	1.59	1.63	1.68
600	1.57	1.62	1.66	1.71	1.75	1.80	1.85	1.90	1.95	2.00
700	1.83	1.88	1.93	1.98	2.03	2.09	2.15	2.20	2.26	2.33
800	2.08	2.14	2.20	2.25	2.32	2.38	2.44	2.51	2.58	2.65

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	1.33	1.36	1.40	1.44	1.47	1.51	1.56	1.60	1.64	1.68
125	1.64	1.69	1.73	1.78	1.83	1.88	1.93	1.98	2.03	2.09
150	1.96	2.01	2.06	2.12	2.18	2.24	2.30	2.36	2.42	2.49
175	2.27	2.33	2.39	2.46	2.53	2.60	2.67	2.74	2.82	2.89
200	2.58	2.65	2.73	2.80	2.88	2.96	3.04	3.12	3.21	3.30
225	2.90	2.98	3.06	3.14	3.23	3.32	3.41	3.50	3.60	3.70
250	3.21	3.30	3.39	3.48	3.58	3.68	3.78	3.89	3.99	4.10
275	3.53	3.62	3.72	3.83	3.93	4.04	4.15	4.27	4.39	4.51

Mission Lifetime (Years)* — EOM Power Required (W)

	3	4	5	6	7	8	9	10	11	12
100	3.15	3.24	3.33	3.42	3.51	3.61	3.71	3.81	3.92	4.03
125	3.92	4.03	4.14	4.26	4.37	4.50	4.62	4.75	4.88	5.02
150	4.69	4.82	4.96	5.09	5.24	5.38	5.53	5.69	5.84	6.01
175	5.46	5.61	5.77	5.93	6.10	6.27	6.44	6.62	6.81	7.00
200	6.23	6.41	6.58	6.77	6.96	7.15	7.35	7.56	7.77	7.99
225	7.00	7.20	7.40	7.61	7.82	8.04	8.26	8.49	8.73	8.98
250	7.77	7.99	8.21	8.44	8.68	8.92	9.17	9.43	9.69	9.97
275	8.54	8.78	9.03	9.28	9.54	9.81	10.08	10.37	10.66	10.95

* Some solar solutions are currently not feasible at these science destinations

RECOMMENDATIONS

- Document the additional cost impact to launch services due to RPS for completeness
- Drive higher performance and lower cost into future RPS (Next-Gen, DRPS and beyond) to be more competitive with Solar power
  - Performance goal: higher BOL power and lower power degradation rate
  - Cost goal: be less expensive than MMRTG and eMMRTG
- Assess future mission targets using these MOEs and other factors identified in case studies
  - Use to identify the most reasonable RPS missions
  - Generate a quick reference table to inform mission trade studies