

# Kuiper Belt Object Orbiter Using Advanced Radioisotope Power Sources and Electric Propulsion

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**Abstract.** A joint NASA GRC / JPL design study was performed for the NASA Radioisotope Power Systems Office to explore the use of radioisotope electric propulsion for flagship class missions. The Kuiper Belt Object Orbiter is a flagship class mission concept projected for launch in the 2030 timeframe. Due to the large size of a flagship class science mission larger radioisotope power system ‘building blocks’ were conceptualized to provide the roughly 4 kW of power needed by the NEXT ion propulsion system and the spacecraft. Using REP the spacecraft is able to rendezvous with and orbit a Kuiper Belt object in 16 years using either eleven (no spare) 420 W advanced RTGs or nine (with a spare) 550 W advanced Stirling Radioisotope systems. The design study evaluated integrating either system and estimated impacts on cost as well as required General Purpose Heat Source requirements.

**Keywords:** ASRG, SRG-550, ARTG, radioisotope power, REP

## INTRODUCTION

NASA has successfully developed and launched many deep space probes powered by radioisotope power systems (RPSs). Pioneer, Voyager, Galileo, Cassini all used RPS systems (100’s of Watts range) to enable these deep space missions that travel too far from the sun to effectively use solar cells. Over the last decade studies have looked at using plutonium-based power for operating electric thrusters to allow deep space probes to orbit or land on small outer bodies as well as enhance operations around large planets.<sup>1,2</sup> Termed radioisotope electric propulsion (REP), these studies assumed low power radioisotope building blocks (~150 W) that, by using as many as 6 to 8 systems, could provide New Frontiers-class science.<sup>3</sup> In order to provide greater power to the electric propulsion system, larger RPS building blocks are needed. This design study was commissioned by NASA’s RPS Office in order to determine the best size for next generation RPS Systems (output power and specific mass) when used for Flagship-class REP missions.

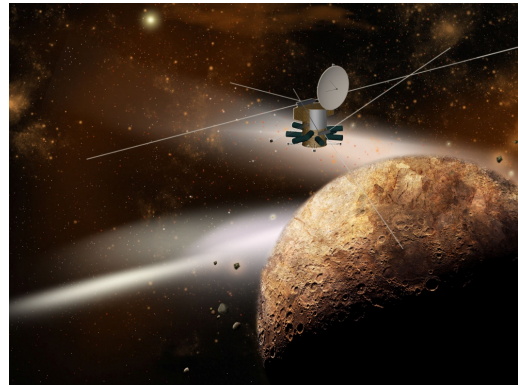


FIGURE 1—KBOO Spacecraft on Orbit

To determine the appropriate REP system size, both the NASA Glenn Research Center’s (GRC) COMPASS team and the NASA Jet Propulsion Laboratory’s (JPL) Team X were commissioned to evaluate a different REP Flagship spacecraft (S/C) mission design using advanced RPS. The JPL Team X evaluated the use of REP for a Neptune Flagship Orbiter and the GRC COMPASS team evaluated REP for a Kuiper Belt Object Orbiter (KBOO). An artists concept of KBOO on-orbit around the KBO is shown in Figure 1. The approach allowed for both teams to provide support to the other during the design phase (done sequentially) in order to allow for similar inputs and common solutions. The In-Space Propulsion Office was also included to provide support for designing representative future electric propulsion systems capable of providing the long life needed for REP missions.

A joint science team determined a representative suite of instruments and a science mission approach for orbiting a Kuiper belt object (KBO). Mission analysis found that a direct trajectory using a Jupiter flyby could reach these >32 AU distance objects in 16 yr, and allow a year for science operations. For objects in the 33 AU range, the current Delta IV heavy with a Star 63 upper stage was sufficient to orbit the KBO in 16 years. For KBOs beyond this distance, upgrades to the heavy lift launch vehicle (LV) would be required. Given the launch date of 2030, such upgrades might occur. The trades for the RPS systems included a 420 W Advanced Radioisotope Thermoelectric Generator (ARTG) system and a 550 W Stirling Radioisotope Generator system (SRG-550) and a 160 W Stirling

Radioisotope Generator (SRG-160) system. The last case was based on more near term technology and represented a worst case in terms of mass, efficiency, etc of the power system. The three concept designs (shown in Figure 2) showed that by using 11 ARTGs, 9 SRG-550s (includes a spare due to perceived lifetime risks of moving parts), or 28 SRG-160s, respectively, approximately 3 kW of power would be available for the electric propulsion system. This system is based on assuming a high throughput NEXT ion thruster system using carbon-based grids and long life cathodes. This relatively large amount of power for the cruise phase thrust could be used to great advantage at the KBO for science and communications. The main interface issues identified during the study for the RPS systems were structural integration, on-pad installation, and thermal management. The first two systems (420 W ARTG and SRG-550) showed a natural break in numbers of General Purpose Heat Source's (GPHS) (12 in the ARTG design and 6 in the SRG-550 design) and block size. These two systems were then integrated into two versions of the KBOO and compared to one using the current 160W SRGs.

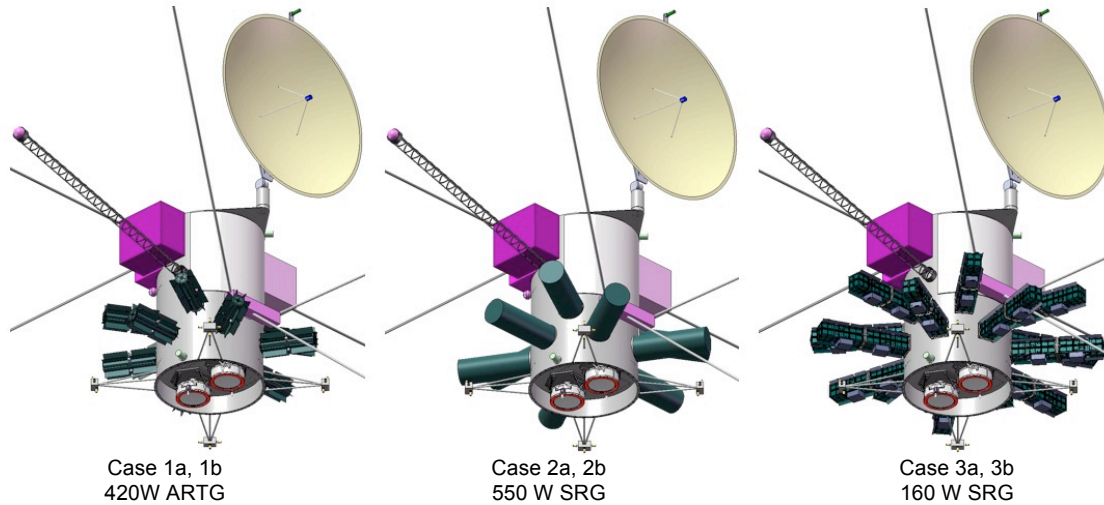


FIGURE 2—KBOO Spacecraft Options.

	Case number	1b	2b	3b
	GLIDE Case name		KBOO_Case2b (same mission as Case 1b)	KBOO_Case3b (same mission as Case 1b)
WBS	Main Subsystems	KBOO_Case1b Total Mass (kg)	Total Mass (kg)	Total Mass (kg)
06	<b>KBOO Spacecraft</b>	2801.0	2854.5	3033.3
06.1	Science Payload	130.0	130.0	130.0
06.2	Spacecraft Bus	2671.0	2724.5	2903.3
06.2.1	Attitude Determination and Control	30.2	30.2	30.2
06.2.2	Command and Data Handling	42.1	42.1	42.1
06.2.3	Communications and Tracking	71.4	71.4	71.4
06.2.4	Electrical Power Subsystem	718.5	766.3	925.5
06.2.5	Thermal Control (Non-Propellant)	64.0	64.0	64.0
06.2.6	Propulsion	191.7	202.1	202.1
06.2.7	Propellant	1283.9	1289.6	1289.7
06.2.8	Structures and Mechanisms	269.2	258.7	278.3
	Estimated Spacecraft Dry Mass	1517.1	1564.8	1743.6
	Estimated Spacecraft Wet Mass	2801	2854	3033
<b>System Level Growth Calculations</b>				
	Dry Mass Desired System Level Growth	1825.7	1882.7	2099.1
	Additional Growth (carried at system level)	309	318	355
	Total Wet Mass with Growth	3109.6	3172.2	3388.7
	Total Spacecraft Wet Mass	3109.6	3172.2	3388.7
	ELV Performance to C3 (kg)	3179.0	3179.0	3179.0
	ELV Launch Margin (kg)	69.4	6.8	-209.7
	ELV Launch Margin (%)	2.2	0.2	-6.6

FIGURE 3—KBOO Spacecraft Mass Breakdowns for Mission Option b.

A matrix of cases was run for this design session. They were divided into two families. In each family there were three different cases varying type of power system used to power the thrusters. The set of cases designated the “a” Cases target the primary choice of the KBO object QT322. The second set of cases, designated the “b” Cases, are targeting the KBO object XH255. A single trajectory to the target was run for each family of cases. The two chosen baseline cases both went to the secondary target. Due to space limitations only case 2b is shown in this report. It achieves the science requirements, within the time limitation and uses the least amount of plutonium compared to the other designs (the same amount as the Cassini mission). It should be noted that this last figure of merit, while of extreme importance in this decade, may not be critically constraining in the 2030 timeframe. The mass summary of the “b” cases is shown in Figure 3 and the mission summary of case 2b is shown in Table 1.

Table 1—Mission and S/C Summary: KBOO Baseline S/C (Case 2b)

Subsystem area	Details	Total mass with growth
<b>Top level system</b>	16 yr mission to KBO, Launch 2035	3172 kg
<b>Mission, operations, GN&amp;C</b>	Sun sensors, Reaction wheels, Star trackers, Inertial Measurement Unit	30 kg
<b>ACS</b>	ACS delta V using representative gravitational parameter of $0.943 \text{ km}^3/\text{sec}^2$ , $I_{sp} = 229 \text{ sec}$ .	
<b>Launch</b>	Modified heavy Delta IV H with Star 63f motor. Launch $C_3 = 69.56 \text{ km}^2/\text{sec}^2$ . Performance to $C_3 = 3179 \text{ kg}$	3179 kg
<b>Science</b>	Observe KBO for 1 yr. Ion Mass spectrometry, Penetrator.	130 kg
<b>Power</b>	Nine, SRG-550W	766 kg
<b>Propulsion</b>	1+1 NEXT ion thrusters with 65% efficiency and $I_{sp}$ of 3327 sec., ATK tank no. 80342-1, four clusters of four 229 sec RCS thrusters.	202 kg, 1289 kg propellant
<b>Structures and mechanisms</b>	Thrust tube design, Al 2090-T3. Separation mechanisms between probe and Star motor stage. Max 6g axial loading, 3.5 g lateral loading.	259 kg
<b>Communications</b>	X-band (7.2/7.4 GHz), Ka band High Gain Antenna, X/Ka band 3 m antenna	71 kg
<b>C&amp;DH</b>	2 flight computers, single fault tolerance, time generation unit, atomic clock, cabling	42 kg
<b>Thermal</b>	Multi-layer Insulation, Radiator with Louver, cold plates, and heat pipe, thermal paint, RHU	64 kg

## STUDY REQUIREMENTS AND ASSUMPTIONS

The goal of this design study was to utilize the COMPASS and the Team X Conceptual Design teams supported by RPS technologists to provide complete Flagship REP Reference Mission Designs for representative REP missions. The figure of merit was to determine the best physical size for a next generation RPS System (output power and specific mass) for the following potential missions: Neptune Orbiter with probes (Team X) and KBOO (COMPASS). An important groundrule was requiring the use of the current general purpose heat source (GPHS). This requirement limited the largest individual RPS system power level to around 500 We. Table 2 summarizes the study assumptions and requirements.

Table 2—Assumptions and Study Requirements

Subsystem area	Assumptions and study requirements	Critical trades
<b>Top-Level</b>	REP Orbiter to Orbit KBO (using Jupiter flyby). Orbit for 1 yr, science to include imaging and penetrators FOMs: Probe Mass, complexity, science	Solar electric propulsion (SEP) stage, SEP/Chemical mix, All Chemical
<b>System</b>	Off-the-shelf (OTS) equipment where possible, recommend TRL 3 or over technology for performance improvement, Mass Growth per updated ANSI/AIAA R-020A-1999 update AIAA (add growth to make system level 43%, per JPL practices)	
<b>Mission, Ops, GN&amp;C</b>	REP thrusting and a Jupiter flyby to orbit the KBO, 16 yr for probe to reach KBO	Earth Flyby (adds 2 yr) versus adding star upper stage (higher thrust level)
<b>Launch Vehicle</b>	Delta 4H with upper stage, $C_3$ 80-100 $\text{km}^2/\text{sec}^2$ , Adapter: 63 in. Launch Loads: 6 g's axial	
<b>Propulsion</b>	One active NEXT ion engine (run at 3 kW) with one cold spare, two PPU's (one is spare, single spherical Xe tank)	Existing Xe tanks or stretch existing design, Ion engine location
<b>Power</b>	~3800 W power required between Ion thruster, communications and housekeeping, 17 years of operations required	Trade 420 W ARTG, SRG-550W, and SRG-160W power modules
<b>Avionics/Comm.</b>	Rad 750 processors, 100 GB data storage, X/Ka band, 3 m antenna	Computer type, X band or Ka band
<b>Thermal &amp; Environment</b>	Body mounted radiator (main loads 500 Wth from PPU), Maintain propellant tank/line temperature, micrometeoroid environment, Radiation level	Tank heater from RPS waste heat or electric heaters
<b>Mechanisms</b>	Two-thruster gimbals, two-axis range of motion: $\pm 19^\circ$ , $\pm 17^\circ$ , Science deployments, Penetrator Separation System	Separation system: trade Light band
<b>Structures</b>	Primary: Thrust Tube 1.6 m diameter, Al-Li, secondary: 4% of probe components	Placement of RPS systems, loading of RPS systems

Table shows the matrix of cases run in the design study trade space. The matrix was determined by KBO target and power system used to run the thrusters. Due to space limitations, only case 2b is described in detail in this paper since it required the least number of GPHS (plutonium).

Table 3—Study Cases

Power System	Target: QT322	Target XH255
ARTG	Case 1a	Case 1b
SRG-550	Case 2a	Case 2b
SRG-160	Case 3a	Case 3b

## MISSION

This study’s goal was to design an REP spacecraft to send a science payload to orbit one of the KBOs. The targets were limited to KBO’s with periapsis >32 AU to ensure the surface ice has never been heated and modified from its primitive state. A single KBO will be taken as representative. The low thrust trajectory design was optimized using the Mission Analysis Low-thrust Trajectory Optimization (MALTO) tool. A single trajectory was found that fit the middle case (Cases 2a, 2b). For the primary target (“a” Cases), the LV is a future ELV, for the “b” target cases the LV is the Delta IV H with an upper stage. The trajectory was then applied to the first cases (1a, 1b) and third cases (3a, 3b) in order to provide equivalent comparison of the power systems.

The Kuiper belt is a region of the Solar System beyond the planets extending from the orbit of Neptune (at 30 AU) to approximately 55 AU from the Sun. It is similar to the main asteroid belt but much wider and containing much more mass. There are over 70,000 objects of greater than 100 km diameter to be found within the belt. Although similar to the asteroid belt, whose inhabitants are composed primarily of rock and metals, the KBOs are thought to be composed largely of frozen materials (termed “ices”), such as methane, ammonia and water.

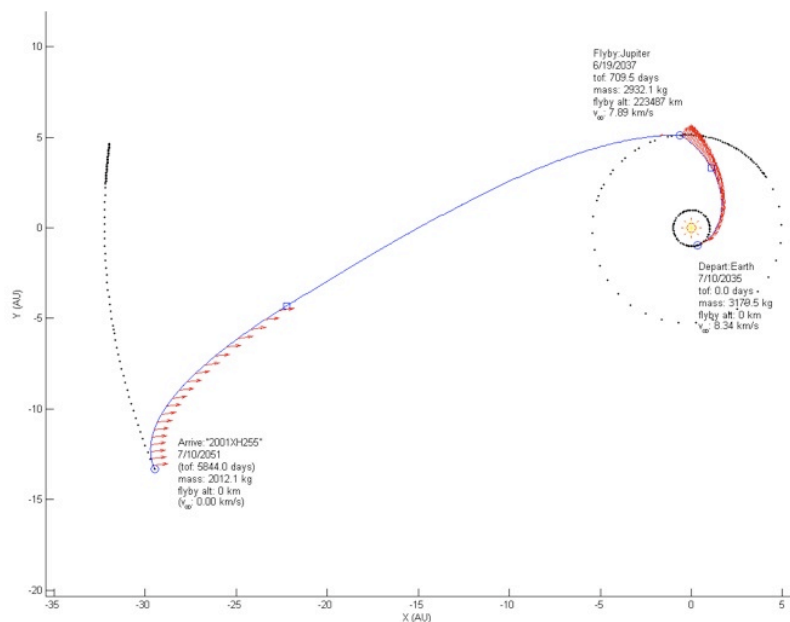


FIGURE 4—“b” Target Trajectory

Trajectories were optimized to a very high  $V_{inf}$ . Missions to the Centaur bodies are of the same class as those to the KBO because the S/C trajectory goes all the way out to Jupiter and then to the KBO. Initial calculations estimated an initial launch mass of 2,800 kg to a  $C_3$  of 100 km<sup>2</sup>/sec<sup>2</sup>. For this analysis, a single trajectory was run for all of the “a” cases and a single trajectory was run to cover all of the “b” cases. For the “b” cases in this trade space, a specialized Delta IV H LV performance curve was derived based on expected future technology advances of the heavy lift launcher by adding a Star 63F motor as an upper stage. Initially an Earth flyby was included in the trajectory, but it was deleted since it added 2 yr to the transit. All of the missions include a Jupiter flyby.

The “b” solution is a rendezvous with the trans-Neptunian Object 2001 XH255 and is shown in Figure 4. The object is in a near circular orbit with an eccentricity of 0.07 with a semi-major axis of 34.81 AU with a perihelion of 32.28 AU. The KBOO launches on July 10, 2035, with a launch mass of 3179.5 kg at a  $C_3$  of 69.56 km<sup>2</sup>/sec<sup>2</sup>. The thrusters operate continuously after launch, targeting the Jupiter gravity assist (at 1 million km) on June 19, 2037. Following the gravity assist there is a long coast period until the thrusters are used again to reshape the orbit and rendezvous with the target on July 10, 2051, 16 yr after launch.

## VEHICLE CONCEPT AND SUBSYSTEMS

The KBOO “b” cases concepts were designed for launch on a Delta IV-H LV within the 5-m payload fairing. The vehicle description is shown with the various subsystems called out in Figure 5.

**Science:** The science requirements determined that the spacecraft should observe KBO for 1 year while utilizing high power radar (possible given the reuse of the REP power) as well as in-situ investigation of the surface using penetrators. The science system is projected to have a mass of 130 kg with contingency, a power of 225 We and a data volume of 474 Gbits for full mapping in one month (worst case). The strawman instrument suite would require a data volume of 474Gbits and pointing control and stability of  $0.030^\circ$  with a pointing knowledge less than  $0.002^\circ$ .

**Communications:** The communication system consists of a 32 GHz Ka-band transmit-only system and a two-way X-band communication system. The communication system is single fault tolerant except for the antennas and diplexers. There is one dual X-band and Ka-band 3 m gimballed antenna, one medium gain (8 dBi) X-band antenna and three X-band dipole antenna (gain 1.5 dBi) on the S/C. Ranging and Doppler shift measurements can be done using either the X-band or Ka-band system.

**Command and Data Handling (C&DH):** The C&DH subsystem provides all telemetry acquisition and processing, and forwards telemetry to the command and telemetry subsystem for transmission to Earth at X-band. In addition, C&DH Avionics performs the GN&C calculations necessary to perform in-transit and rendezvous operations in concert with ground commanding. A RAD 750 set of processors and at 100 GB of data handling were assumed.

**Guidance, Navigation and Control (GN&C):** The GN&C design is based on the REP Neptune Orbiter design done by JPL in the Team X session portion of this joint design session study. The system has six sun sensors, four reaction wheels (75 Nms), two Star Trackers and one internally redundant inertial measurement unit.

**Mechanical:** The KBOO S/C structure must contain necessary hardware for instrumentation, avionics, communications, propulsion and power. This analysis assumed a maximum axial load of 6g. The main bus consists of a thrust tube design that provides the architecture for housing the power modules, thrusters, and various instruments for this study. A major challenge is integration of the large number of RPS systems through the shroud on the pad and needs to be addressed in future studies.

**Thermal:** The S/C utilized a multiple RPS-based power system. Each RPS unit has its own integrated radiator system and, therefore, did not require any cooling from the thermal control system. The thermal control system was used to maintain the temperature of the internal electronics and payload as well as the thruster PPUs. The maximum heat load to be rejected by the thermal system was 941 W. Internal heat was supplied by a series of RHUs (Radioisotope Heat Units) mounted near critical components within the vehicle. All outer surfaces were covered with either multi-layer insulation (MLI) or thermal control paint depending on their temperature requirements.

**Propulsion:** Upgraded NEXT ion engines were selected for this study due to their propellant throughput capability, high performance, and the maturity of the engine system.<sup>4</sup> Advances in the current NEXT ion system to provide longer lifetime and throughputs are assumed. The propellant throughput required for the ion propulsion system ranges from 1100 to 1400 kg including margin. Even throttled down to 3 kW the current NEXT molybdenum grids throughput lifetime is insufficient. The proposed solution to achieve the necessary throughput capability is to use pyrolytic graphite (PG) grids. The erosion rates for PG grids are an order of magnitude lower than the molybdenum option and the xenon throughput capability, limited by erosion, is expected to exceed the requirement of the Kuiper belt object orbiter mission. An additional concern of thruster life for the KBOO mission might be the neutralizer and discharge cathodes. Life tests have demonstrated greater than 30,000 hr of operation. Recent tests predict barium depletion or failure of the cathode is not likely to occur within 100,000 hr. It is recommended that additional analyses and testing on the expected life and wear-out mitigation plans for the discharge cathode be performed.

**Electrical Power:** Power requirements for the S/C are shown in Table 4. This power level is required for 16 years, with sufficient operational power for the 17<sup>th</sup> year required for everything but ion thruster. Three different RPSs were conceptually integrated into a S/C to quantify their impact on the S/C.

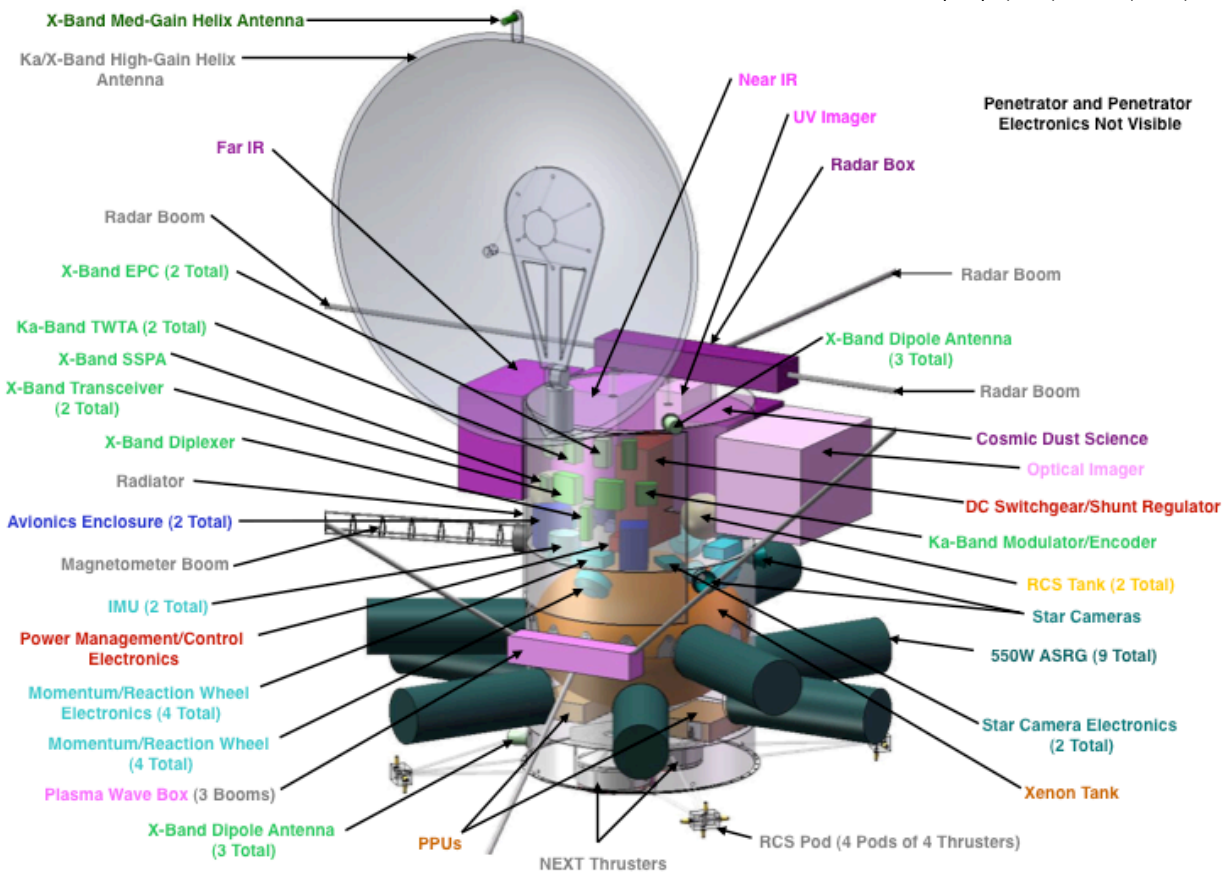


Figure 5—Component Callout of the ARTG Powered KBOO S/C (Case 2b)

Table 4—Bottoms-Up Power Requirements Assumptions

RCS Thrusters .....	60 W
Avionics .....	123 W
Communications.....	569 W
ACS .....	60 W
Power Into Thrusters .....	3000 W
<b>Total Power (note: science not used during EP).....</b>	<b>3812 W</b>

Three distinct RPS building blocks were modeled. Case 1 used an ARTG. The ARTG is similar in form to conventional General Purpose Heat Source (GPHS) RTGs (Galileo, Cassini, etc.); however, the thermoelectric converters have increased performance. Case 2 uses a conceptually designed advanced SRP-550W. This RPS uses 6 GPHS and a larger Stirling converter. Case 3 uses an advanced version of the current ASRG (Advanced Stirling Radioisotope Generator), termed SRG-160.

**ARTG:** Radioisotope Thermoelectric Generators (RTG) has been used for years as the power system for NASA’s deep space missions where sunlight is not available for a photovoltaic array. RTG’s depend on the decay of Pu-238 to provide heat to thermoelectric power converters. The most recent flights of RTGs came in the form of General Purpose Heat Source RTGs (GPHS-RTG). These were flown on the Cassini, Galileo, Ulysses and New Horizons S/C. The GPHS module is a standardized thermal source of 250 W using Pu-238 as the fuel. The ARTG proposed for this study is a higher performance RTG that is being studied by the JPL as a candidate high efficiency follow-on to the GPHS RTG.<sup>5</sup> Table 5 shows a comparison of the GPHS-RTG and the proposed ARTG.

Table 5—Comparison of GPHS RTG and ARTG

	GPHS RTG	ARTG
Power Output—BOL (W)	300	420
Mass (kg)	57	40
No. of GPHS	18	12
Efficiency	7%	14%
Degradation (%/yr)	1.6	1.6
Specific Power (w/kg)	5.3	10.5

**SRG-550:** A higher power output Stirling RPS is possible by using more GPHS modules than the SRG-160.<sup>6</sup> Advantages for a higher output RPS are fewer S/C-to-converter attachments and some scaling and performance advantages for Stirling converters as the power output increases. These converter advantages

are somewhat offset by the increased difficulty in integrating the GPHS with the Stirling and removing the heat from the converter. NASA GRC has developed sizing tools to estimate the performance of multi-GPHS Stirling systems. Hot end temperature for the Stirling was set to 850 °C, which is consistent with the current SRG-160, and cold end temperature was varied to look for changes in system mass and GPHS count. It was found that at 360 K bottom end temperature, a three GPHS per converter (six total for the dual opposed configuration) could provide 550 W of DC output at Beginning of Mission (BOM). Stirling vibration is addressed by having dual opposed systems and assuming the spacecraft could take the same sorts of vibrations that are generated by the ASRG. Isolators could also be used but better science package definition is required before they should be added. The SRG-550 Design Attributes compared to the SRG-160 are shown in Figure 6 and Table 6.

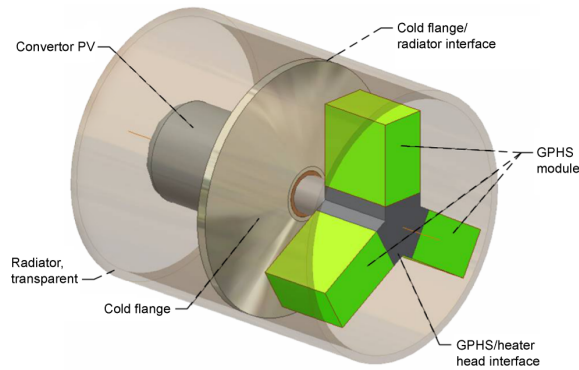


Table 6—Performance Details for SRGs

	SRG-160 (850 °C)	SRG-550 (850 °C)
System Life (yr)	14 +	14+
BOM Power (W)	160	550
Power at 5 yr	153	531
Power at 10 yr	146	512
Power at 14 yr	142	499
No. of GPHS Modules	2	6
Mass (kg)	22	54
BOM Efficiency (%)	~32%	~35%
BOM Specific Power (W/kg)	7.3	10.2
EOM Specific Power (W/kg)	6.4	9.2

FIGURE 6—SRG-550 Concept Design (one side)

Table 7 shows a comparison of the three power systems. Each system is sized to provide worst-case full power (EOM with thrusters running). For all of the systems an integer number of systems were required. Partially filled ARTG or Stirling systems were not allowed. For the Stirling system  $n + 1$  systems are assumed (to provide a spare) and the additional 550 and 160 W are **not** used for the S/C runs. Excess power from the round-up of power is used by the thrusters and is shown below in the “Excess Power” row of Table 7.

Table 7—Power per RPS System

	ARTG	SRG-550	SRG-160
Unit mass (kg)	40	54	22
BOL power (W)	420	550	160
EOL power (W)	331	448	142
Average power (W)	370	516	150
No. required	11	8+1=9	27+1=28
Excess power with 0 failures (W)	33	609	168
Excess power (W)	33	92	17
Total convertor mass (kg)	440	504	616

For the ARTG Cases (noted as “1”), 11 ARTG are required. It is important to note that a degradation of 1.6% per year was assumed, which it had a significant impact due to the 16-yr mission. This compares to 0.8% degradation (isotope decay only) for the Stirling systems.

Either the ARTG or the SRG-550 appear viable for the KBOO. The lower performance of the SRG-160 did not allow mission convergence due to its lower specific power and the penalty paid for integrating the 28 systems to the S/C. The SRG-550 offers the advantage of approximately 1/3 less GPHS modules (54 for the SRG-550 versus 132 for the ARTG) while the ARTG has the advantage of greater redundancy (parallel/series) string combinations and no vibration concerns.

## COST ESTIMATION

The following cost estimates are developed at the subsystem and component levels using mostly mass-based parametric estimates. Test hardware costs assume one-half units for subsystem/ component testing and one flight spare where appropriate. Quantitative risk analysis was performed on S/C cost using Monte Carlo simulation based

on mass and Cost Estimation Relationship (CER) uncertainties. The science instrument package and costs are based on Cassini instruments and their associated costs.

The major variation in the cost estimates is due to the difference in the Electric Power Subsystem. The advanced ARTG (Case 1b) and SRG-550 (Case 2b) cost are based on program office estimates for the MMRTG and ASRG, respectively. GPHS blocks are estimated at \$2M for each block in FY07\$M, while the fabrication and testing costs of the new systems is escalated based on their increase in mass. In both cases, the development cost of these systems is assumed to be covered by other programs and is not included in this cost estimate. Table 8 shows a Lifecycle Cost Comparison of these two options.

Table 8—Lifecycle Cost Comparison FY09\$M.

<b>KBOO Lifecycle Cost Comparison</b>	<b>Case 1b</b>	<b>Case 2b</b>
NASA Project Office/Technical Oversight	110	94
Phase A	74	59
Spacecraft	1,378	1,105
Spacecraft Prime Contractor Fee (10%)	110	83
Launch Services	519	519
Mission Operations	122	122
Reserves (25%)	449	366
<b>Lifecycle Cost</b>	<b>2,763</b>	<b>2,348</b>

The NASA project office estimate/technical oversight is based on 10% of mission cost. Phase A estimates are based on 5% of Phase B/C/D cost. The prime contractor fee for the S/C is 10% of the total S/C cost less the cost of the science instruments. The launch services cost is for a Delta IV H with an additional \$15M for services associated with handling nuclear materials. The mission operations costs are based on New Horizons with science operations time adjusted for this mission.

## CONCLUSIONS

The joint study for an REP Flagship-class vehicle to orbit a Kuiper Belt object evaluated two potential 500 W class RPS Unit designs capable of performing the 17 year mission: a conceptual 420W RTG based on past RTG designs using advanced thermoelectric convertors and 12 GPHS each, and a conceptual SRG-550W based on the current 140W ASRG design using Stirling generators and 6 GPHS each. The ARTG has an inherent reliability of no moving parts while the SRG-550 reduces the required GPHS count for the mission equal to that used by the Cassini flagship mission and may reduce life cycle cost by as much as 15%. Current production rates do not support <sup>238</sup>Pu loads at the Cassini level so they would have to be increased to enable the KBOO mission in the 2030 timeframe. Either approach would require on-pad installation of at least nine <sup>238</sup>Pu-fueled RPS system through the shroud. Other options using heat pipes and higher power stirling convertors would allow for more efficient grouping of GPHS heat sources, thus allowing higher power SRG units, which might increase efficiencies, simplify integration, and reduce mass.

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