ISTS 2006-k-35
MISSIONS TO THE EDGE OF THE SOLAR SYSTEM USING A NEW ADVANCED DUAL-STAGE GRIDDED ION THRUSTER WITH VERY HIGH SPECIFIC IMPULSE

R. Walker [1], D. Izzo [1], D. Fearn [2]

[1] Advanced Concepts Team, European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
E-mail: Roger.Walker@esa.int, Dario.Izzo@esa.int

[2] EP Solutions, 23 Bowenhurst Road, Church Crookham, Fleet, Hants, GU52 6HS, United Kingdom
E-mail: dg.fearn@virgin.net

Abstract

A new and innovative type of gridded ion thruster, the "Dual-Stage 4-Grid" or DS4G concept, has been proposed and its predicted high performance validated under an ESA research, development and test programme. The DS4G concept is able to operate at very high specific impulse and thrust density values well in excess of conventional 3-grid ion thrusters at the expense of a higher power-to-thrust ratio. This makes it suitable for ambitious missions requiring very high delta-V capability and high power. Such missions include sub-100 kilowatt multi-ton probes based on nuclear electric propulsion to distant Kuiper Belt Object and inner Oort cloud objects, and to the Local Interstellar medium. In this paper, the DS4G concept is introduced and its application to this mission class is investigated. Benefits of using the DS4G over conventional thrusters include reduced transfer time and increased payload mass, if suitably advanced lightweight nuclear reactor technologies are developed.

A mission-level optimisation is performed (launch, spacecraft system design and low-thrust trajectory combined) in order to find design solutions with minimum transfer time, maximum scientific payload mass, and to explore the influence of power system specific mass. It is found that the DS4G enables an 8-ton spacecraft with a payload mass of 400 kg, equipped with a 65 kW nuclear reactor with specific mass 25 kg/kW (eg. Topaz-type with Brayton cycle conversion) to reach 200 AU in 23 years after an Earth escape launch by Ariane 5. In this scenario, the optimum specific impulse for the mission is over 10,000 seconds, which is well within the capabilities of a single 65 kW DS4G thruster.

1. Introduction

In recent years, very intruiging and exciting data has been gathered by ground-based and space-based telescopes and deep space probes on the objects and environments at the edge of our solar system. Such data has placed important constraints on theories of the formation of the solar system and given tantalising hints on the dimensions of the heliosphere with the interstellar medium. Although some questions have been answered, the many new ones posed have established the very outer solar system as a high priority for exploration.

As optical and IR imaging telescopes have become ever more sensitive and image processing ever more powerful, the existence of the Edgeworth-Kuiper Belt (EKB) has been truly confirmed with the discovery of over 500 Kuiper Belt Objects (KBOs) between 30 and 50 AU distance in the last decade, including the largest of these, "Quaoar" (2002 LM60), a 1300 km diameter icy body about half the size of Pluto [1] and 2003 UB313, a 2700 km body about 20% larger than Pluto [2]. A population of over 70,000 KBOs larger than 100 km are predicted to exist and contain primitive accretion disk material from the early solar system.

The discovery in 2004 of a new object of 1200-1800 km diameter called Sedna at 90 AU distance and with an orbit well beyond the EKB has, for the first time, given a possible glimpse at the inner part of the hypothesised Oort cloud, a predicted shell of billions of icy proto-comets extending halfway to the nearest star. Sedna is currently the most distant known object and is near the 76 AU perihelion of its highly eccentric orbit. Its bright red colour does not fit with observations of icy bodies such as Pluto and other KBOs and so its composition is completely unknown [3].

As such, these extremely interesting minor planets represent prime targets for in-situ characterisation by interplanetary spacecraft. However, the delta-V requirements are high for reasonable mission durations. This is provided by a combination of launcher escape velocity and on-board propulsion. The NASA New

Horizons Pluto/KBO flyby mission will be the first to attempt this challenge when it reaches Pluto in 2015 and proceeds to encounter other KBOs in 2016-2020 [4]. Recent technology assessment studies have indicated that missions to rendezvous with Pluto or other members of the KBO family are within the propulsive capabilities of humankind using a combination of a powerful launcher giving a high escape velocity and a 1kW-class RTG-powered spacecraft with conventional gridded ion propulsion to accomplish the mission within 12-17 years from launch [5,6]. However, to flyby or rendezvous with Sedna at more than double the distance of Pluto and a higher ecliptic declination within a reasonable mission duration is even more challenging. A flyby could be achieved within 21 years, assuming a small RTG-powered probe with minimal on-board propulsion, and launched at a high escape velocity of 9.3 km /s on a ballistic trajectory with multiple swings (Earth-Venus-Venus-Earth-Jupiter). In the case of a Sedna rendezvous mission, the delta-V requirements and hence desired specific impulse may be on the boundary of performance of current ion propulsion systems.

At the end of 2004 after 28 years, the Voyager 1 spacecraft reached a distance of 94 AU from the Sun and sent back data indicating that it had reached a crossing of the "termination shock" of the solar wind at the edge of the Sun's magnetosphere. Beyond the shock is the heliopause, the pressure balance interface between the plasma of the solar wind and that of the Very Local Interstellar Medium (VLISM). Despite this data, models of the heliopause distance are still open to large uncertainty and precise properties of the interstellar medium remain very unclear. The only way to determine these properties and truly understand the nature of interstellar space is again by in-situ measurements, particularly of the magnetic field and low-energy cosmic rays, *beyond the heliopause*. This is at the boundary of technological capability on many mission elements such as launcher escape velocity, power, propulsion, communications, on-board autonomy and extremely long-duration component/system reliability. Nonetheless, recent studies on an Innovative Interstellar Explorer [7] have indicated that it could be feasible with certain technology developments and aggressive mass savings to reach the predicted closest VSLIM at a distance of 200 AU within 30 years from launch (foreseen as the maximum "scientific career lifetime"). The approach again uses very high escape velocity (over 11 km/s) provided by a heavy launcher with multiple solid boost stages, and a 1000 kg, 1 kW-class RTG-powered spacecraft with current ion propulsion performance (4,000 s specific impulse) and small scientific payload in order to meet the high delta-V requirements of over 17 km/s.

A new concept for an advanced 'dual-stage' gridded ion thruster has been developed which has significant potential to deliver substantial improvements in propulsive performance over the current state-of-the-art [8,9]. Four grids are used instead of the usual three-grid arrangement in order to separate the ion extraction and acceleration processes (done simultaneously in current systems). This enables very high ion beam potentials to be put on the grids in the acceleration stage, thereby significantly increasing exhaust velocity, specific impulse, power density and thrust density. Operating at a beam potential of 30kV with Xenon propellant (as opposed to a maximum of 5 kV in present ion engines), the predicted performance of this advanced thruster is a specific impulse of 19,000 s, power density of over 600 W/cm^2, thrust density of over 6 mN/cm^2, and beam divergence <5°. This high performance comes at the expense of a high power-to-thrust ratio, which at this operating point is approximately 110 W/mN. Thus, the thruster is foreseen to be compatible with lightweight power systems only.

The very high specific impulse and thrust density make the DS4G concept ideal for use on very high delta-V missions such as those discussed above, with potential pay-offs in transfer time, scientific payload mass and relaxed Earth escape launch requirements. In order to prove this new thruster concept, a small experimental laboratory model has been developed and built to ESA requirements by Australian National University, and its performance was measured during an extensive test campaign in ESA's Electric Propulsion Test Facility at ESTEC during November 2005 and May 2006 [10]. The experimental thruster is operated in the 1-2 kW power range, though due to the high power density it is ultimately scaleable to power levels of nearly 1 MW (50 cm diameter), and hence also suitable for advanced human Mars missions using electric propulsion.

2. Mission Scenario

The focus of this paper is on the technical assessment of the DS4G thruster concept for Nuclear Electric Propulsion (NEP) missions to the local interstellar medium at 200 AU, since this represents the most demanding scenario for both the power and propulsion technologies, as well as many others, in terms of performance and reliability. It is noted that the results of this paper are also applicable to shorter duration flyby missions of KBOs and inner Oort cloud objects such as Sedna. Rendezvous missions for these objects, as well as high power Solar Electric Propulsion (SEP) missions will be the subject of future work on DS4G assessment. We assume that the NEP spacecraft starts its mission from an Earth escape launch by the Ariane 5 ECB launcher, and then thrusts continuously until propellant burnout, at which point it then coasts with a fixed solar system escape velocity until 200 AU. No gravity assist manoeuvres are considered, thus giving a wide launch window. The direct injection capability of the Ariane 5 ECB for an escape launch energy C3 of 16 km^2/s^2 is predicted in [11] to be 8200 kg (assuming an Earth escape declination of 0°), 10900 kg at 1 km^2/s^2, and 4200 kg at 50 km^2/s^2 respectively.

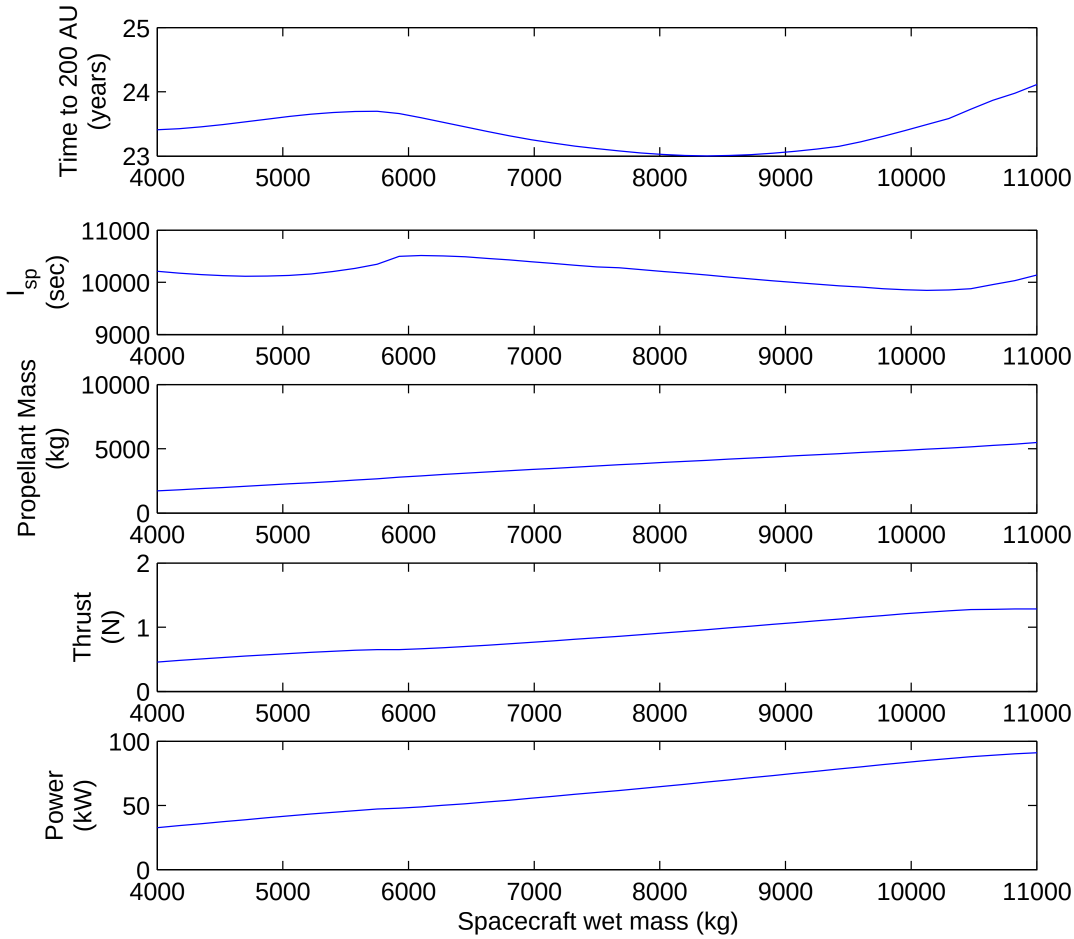

Figure 1. Variation of optimum mission design parameters with spacecraft mass (assuming power system specific mass of 25 kg/kW and payload mass of 400 kg)

3. Mission Optimisation

The main objective of the analysis is to find the optimum launch energy, spacecraft system design (payload, power, propellant), DS4G thruster performance (optimum specific impulse) and trajectory (thrust vectors) that gives the minimum time to reach 200 AU. A simple analytical model is used in order to derive the main spacecraft parameters of interest to the trajectory optimisation software, namely the power generated and the thrust produced. The power generated by the power subsystem for NEP can be expressed by the formula:

$$P = \frac{M_{p+p}}{\left(\alpha_{thr}\eta_{ppu} + \alpha_{ppu}\right) + \alpha_{pow}} \tag{1}$$

where α_{thr}, α_{ppu}, and α_{pow} are the specific masses (kg/kW) of the thruster, PPU (thruster Power Processing Unit) and power system respectively. η_{ppu} is the efficiency of the PPU. M_{p+p} is the power and propulsion system mass available after accounting for the propellant, payload and other subsystem masses, and is given by:

$$M_{p+p} = \left(M_{wet} - M_f\right)\left(1 - m_{s/s} - m_{p/l}\right) - m_{\tan} M_f \tag{2}$$

where M_{wet} is the spacecraft wet mass, $m_{s/s}$ is the mass fraction of other subsystems (ADCS, structure, avionics etc), $m_{p/l}$ is the scientific payload mass fraction, and m_{tan} is the tank mass fraction. Finally, M_f is the fuel mass varied by the trajectory optimisation code. Once the power has been calculated, then the thrust produced by the DS4G thruster can be determined by:

$$T = \frac{2\eta_{thr}}{g_o I_{sp}} \eta_{ppu} P \tag{3}$$

where η_{thr} is the thrust efficiency, which (as the PPU efficiency) we assume to be constant. g_o is specific gravity at Earth surface. Hence, the thrust is entirely

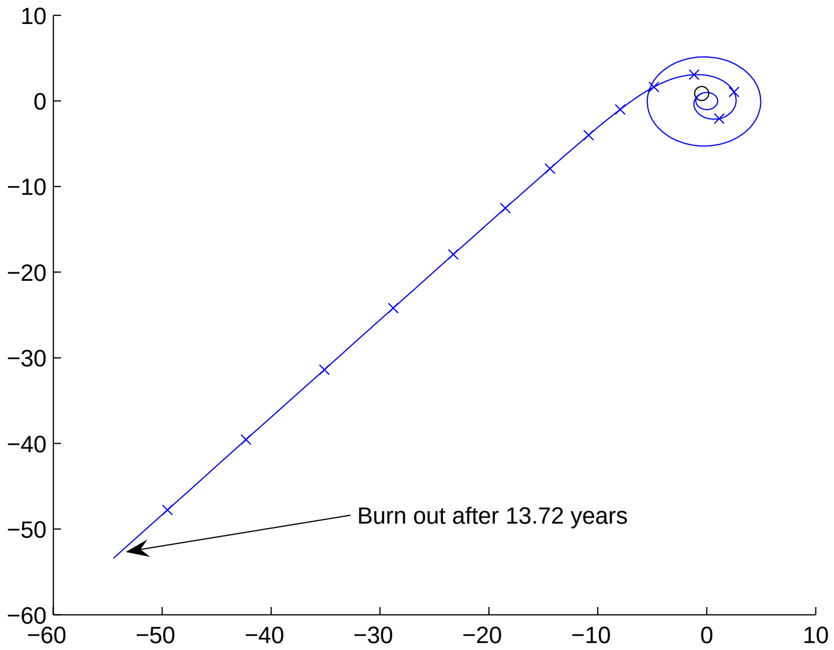

Figure 2. The optimal trajectory is shown up to the burnout, after that it is basically straight. The crosses are per year.

dependent on power available and the specific impulse of the thruster (varied by the trajectory optimisation code). The thrust, propellant mass and specific impulse are used to determine the trajectory during the continuous thrust phase until the burnout condition, and then the trajectory is propagated to 200 AU. Together they determine the transfer time. These parameters are varied (for a specific spacecraft design) to find the optimum specific impulse and fuel mass fraction that gives the minimum transfer time. Here, the subsystem specific masses are α_{thr} = 0.25 kg/kW, α_{ppu} = 5 kg/kW, and α_{pow} is an input parameter variable. EP system efficiencies are η_{ppu} = 0.95 and η_{thr} = 0.7 respectively. Subsystem mass fractions are $m_{s/s}$ = 0.28, m_{tan} = 0.15, and $m_{p/l}$ is another input parameter in the analysis.

The results of the mission optimisation can be seen in Figures 1-4. Figure 1 shows the time to 200 AU and related optimised values as a function of spacecraft mass for a power system specific mass of 25 kg/kW, and payload mass of 400 kg. The power specific mass is quite an optimistic assumption, but is achievable if high efficiency power conversion technologies such as Brayton cycle turbines are developed with over 20-30% efficiency. Initial conditions for the trajectory, ie. the C3 launch energy vary according to the spacecraft mass due to Ariane 5 ECB capabilities. We can see that all spacecraft wet masses between 4000 and 11000 kg give similar times to 200 AU of 23-24 years, with 8000 kg being the optimum. The optimum values at this point are Isp= 10212 s, time to 200 AU = 23.03 years, propellant mass = 3914 kg, T = 0.9 N, Power = 64.64 kW. The trajectory for this optimum is presented in Figure 2.

Figure 3 provides the variation of minimum time to 200 AU with the scientific payload mass on a spacecraft of 8000 kg wet mass. As we might imagine, this has non-negligible impact on the time to 200 AU. Increasing the payload to 1400 kg still allows the mission to completed within 30 years, 7 years longer than with 400 kg payload. Reducing the payload to 200 kg only reduces the transfer time by 1 year. For larger payloads, the optimum specific impulse increases towards 12000 seconds, still well within the capabilities of the DS4G.

Finally, Figure 4 displays the variation of minimum time to 200 AU and optimum specific impulse with the power system specific mass for an 8000 kg spacecraft with 400 kg payload. Specific mass has a strong impact on both the transfer time and Isp. For heavier nuclear reactors with values approaching 50 kg/kW (present day performance), we see that time to 200 AU increases to 32 years and optimum Isp down to below 8000 seconds (within the upper limits of 3-grid thrusters). This is also the reason why the DS4G is not compatible with smaller RTG-powered missions, since RTGs have a specific mass of the order 212 kg/kW. If specific masses of order 10 kg/kW are used (very optimistic), then the trip time would reduce to as low as 18 years and optimum Isp rises to over 12000 seconds. Hence, nuclear reactor technology development would be warranted for interstellar probe missions.

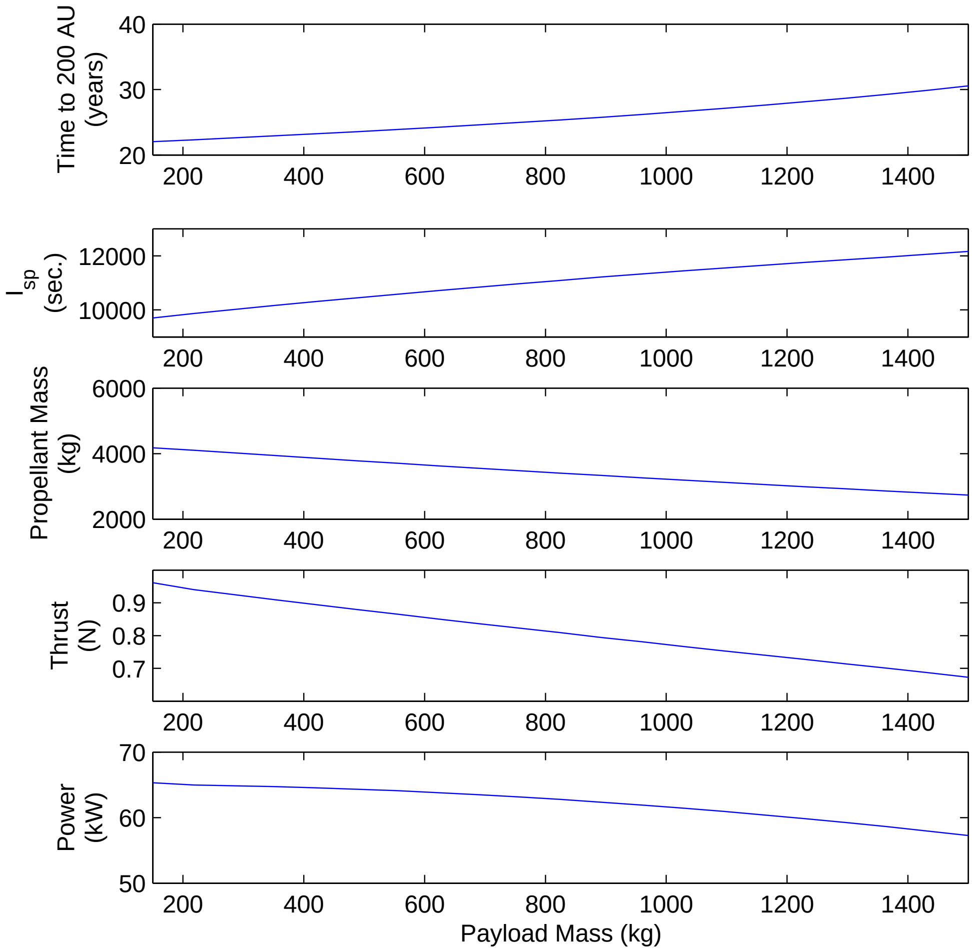

Figure 3. Variation of optimum mission design parameters with payload mass (assuming power system specific mass of 25 kg/kW and spacecraft mass of 8000 kg)

4. Conclusions

Preliminary technology assessment and mission optimisation studies suggest that significant benefits for local interstellar probe missions to 200 AU and KBOs or inner Oort cloud objects can be obtained by employing the Dual-Stage 4-Grid ion thruster concept. Such benefits include reduced trip time (7 years compared to previous studies), increased payload mass (several hundreds of kg may be available), lower C3 launch energy (16 instead of 140 km^2/s^2 delivered by Ariane 5), and wider launch windows/lower radiation dose (no close Jupiter swingby needed). However, the development of a low specific mass space nuclear reactor would be required. An optimum design solution was found for an 8000 kg spacecraft wet mass, 400 kg payload, with 65 kW reactor and DS4G operating at 10200 seconds specific impulse and thrust of 0.9 N. A single 25 cm diameter DS4G thruster with a beam potential of 13000 Volts may be sufficient for these requirements.

References

[1] Brown M.E., Trujillo C.A., “Direct measurement of the size of the large Kuiper belt object (50000) Quaoar”, Astron. J., 127, 2413-2417, 2004.

[2] Brown M.E., Trujillo C.A., Rabinowitz D.L. (2005), “Discovery of a planetary-sized object in the scattered Kuiper belt”, Astrophysical Journal Letters, submitted.

[3] Brown M.E., Trujillo C.A., Rabinowitz D., “Discovery of a candidate inner Oort cloud planetoid”, Astrophys. J., 617, 645, 2004.

[4] Gou Y., Farquhar W., “New Horizons Pluto–Kuiper Belt mission: design and simulation of the Pluto–Charon encounter”, Acta Astronautica 56 (2005) 421 – 429.

[5] Fiehler D., Oleson S., “Radioisotope electric propulsion missions utilizing a common spacecraft design”, Acta Astronautica 57 (2005) 444 – 454.

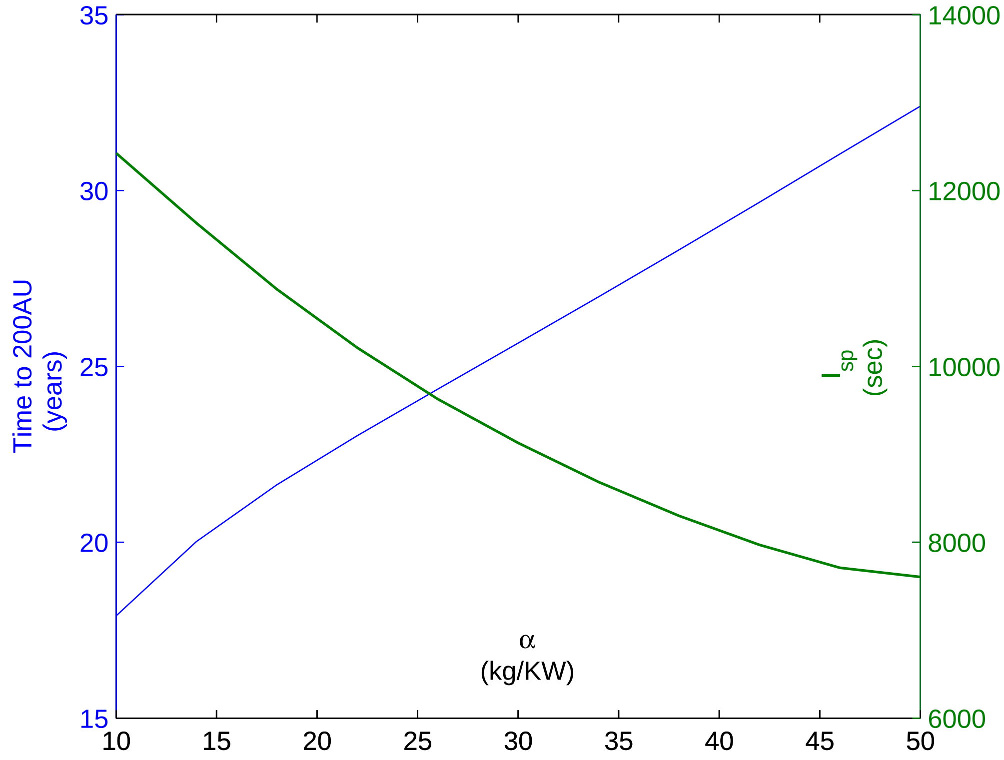

Figure 4. Variation of time to 200 AU and optimum specific impulse with power system specific mass (assuming payload mass of 400 kg and spacecraft mass of 8000 kg)

[6] Bondo, T., Walker, R., Willig, A., Rathke, A., Izzo, D., Ayre, M., "Preliminary Design of an Advanced Mission to Pluto", paper ISTS 2004-k-10, 24th International Symposium on Space Technology and Science, Miyazaki, Japan, June 2004.

[7] McNutt R.L., Leary J.C., Gold R.E., Krimigis S.M., Roelof E.C., Gruntman M., Gloeckler G., Koehn P.L., Kurth W.S., Oleson S., Fiehler D.I., "Innovative Interstellar Explorer: Radioisotope Propulsion to the Interstellar Medium", paper AIAA 2005-4272, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson Arizona, 10-13 July 2005.

[8] Fearn, D., "The Prospects for MW Power Level Gridded Ion Thrusters", Tenth International Workshop on Combustion and Propulsion: IN-SPACE PROPULSION, Lerici, La Spezia, Italy, 21-25 September 2003.

[9] Fearn, D., "The Application of Gridded Ion Thrusters to High Thrust, High Specific Impulse Nuclear-Electric Missions", Journal of the British Interplanetary Society, Vol. 58, No. 7/8, pp. 257-267, 2005.

[10] Walker R., Bramanti, C., Sutherland O., Fearn D., Frigot, P.-E., Orlandi, M., Gonzalez del Amo, J., Boswell R., Charles C., "Initial Experiments On An Advanced Dual-Stage Gridded Ion Thruster For Very High Specific Impulse, Power And Thrust Density", abstract accepted to the 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Sacramento California, July 2006.

[11] Biesbroek, R.G.J., Ancorola, B.P., "Optimisation Of Launcher Performance And Interplanetary Trajectories For Pre-Assessment Studies", paper IAC-02-A.6.07, 53rd International Astronautical Congress, The World Space Congress, Houston, Texas, 10-19 Oct 2002.