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A Fission-Powered Interstellar Precursor Mission

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Abstract. An "interstellar precursor mission" lays the groundwork for eventual interstellar exploration by studying the interstellar medium and by stretching technologies that have potential application for eventual interstellar exploration. The numerous scientific goals for such a mission include generating a 3-D stellar map of our galaxy, studying Kuiper-belt and Oort cloud objects, and observing distant objects using the sun's gravitational lens as the primary of an enormous telescope. System equations are developed for a space tug which propels a 2500-kg scientific payload to 550 astronomical units in about 20 years. The tug to transport this payload uses electric propulsion with an Isp of 15,000 seconds and a fission reactor with a closed Brayton cycle to generate the electricity. The optimal configuration may be to thrust for only about 6 years and then coast for the remaining 14 years. This spacecraft does not require any physics breakthroughs or major advances in technology. The fission power system can be engineered and built by drawing upon known technologies developed for related systems over the past 40 years. The tug system would eventually reach 1000 a.u in 33 years, and would have adequate power to relay large amounts of data throughout its journey.

INTRODUCTION

NASA is interested in a deep-space probe which travels beyond the planets as preparation for eventual interstellar missions (West, 1998). There are numerous missions of high scientific interest for a spacecraft which journeys beyond 100 a.u. (Maccone, 1994). (An astronomical unit is the distance from the earth to the sun and is equal to about 150 million kilometers.) The Kuiper belt of comet nuclei begins at about 30 a.u. (orbit of Neptune) and extends outward from there, possibly for several hundred a.u. The Oort cloud of even more pristine comet nuclei begins at several hundred a.u. and extends out to over 100,000 a.u. A spacecraft with a telescope about a meter or more in diameter might be able to detect these objects during its outward journey and obtain information on the population density. It could possibly deflect its trajectory to obtain a close-up photo of one or more of these objects.

The measured distances to almost all astronomical objects are calibrated by a measurement of nearby stars via parallax as the earth travels around the sun at a distance of one a.u. These various measurement techniques include determining the distance to stars via spectral type and apparent magnitude, to globular clusters via the brightest stars and apparent size, to globular clusters via RR Lyrae-type variables, to galaxies via Cepheid variables, and ultimately to galaxies and quasars via redshifts. The accuracy of the parallax-calibration that is the foundation of all these measurements can be increased by over an order of magnitude by a long-range probe with a meter-class telescope on it. The greater baseline will increase the accuracy of the distance to the various astronomical "standard candles". In addition, there is an element of uncertainty in parallax measurements caused by the fact that the stars are traveling relative to the sun at various unknown velocities. This complication can be eliminated by having two simultaneous measurements at a large separation (one on earth and one on the probe). The net result would be a much improved 3-D map of our galaxy and the universe, as well as a more accurate measurement of the expansion rate and age of the universe (Hubble constant).

The solar system has a faint haze called zodiacal light. It prevents seeing very distant and faint galaxies even with space telescopes and long exposures. The zodiacal light at 3 a.u. is thirty times less than it is at 1 a.u., and is even further reduced farther out. Having a large telescope beyond 3 a.u., especially with infrared capability, would allow

seeing fainter objects than ever before. Potential items of interest are red-shifted galaxies at the edge of the observable universe, and brown dwarfs or other dark matter in our galactic neighborhood.

The heliopause is the boundary between the solar wind and the interstellar plasma. It occurs from 50 to 150 a.u. Small sensors on the probe could be used to measure the plasma density across the shock as the probe traversed it. After passing the shock, the probe could determine the density of interstellar matter. This has implications on the mass of the solar system and on the radiation environment and dust environments to which future interstellar missions would be exposed.

At about 550 a.u., the gravity of the sun focuses the light from distant galaxies which graze its edge to its nearest focus (Eshleman, 1979). The light-gathering power of this gravitational lens is enormous. Only a thin annulus near the edge of the sun is useful because the bending decreases inversely with the radial distance from the sun's center, but this is still a large area. It should be possible to make a very large effective telescope, called a "Solar Gravitational Telescope", by collecting this focused light. A gravitational lens is not a linear optic like those used in conventional telescopes, so the quality of the information and the algorithms for unfolding it need to be determined. In addition, only those objects which are aligned along the line of sight from the probe to the edge of the sun can be studied. But the density of deep-universe objects is high enough that there should be plenty of objects of interest in the field of view. Indeed, by planning the path of the probe to be aligned with a nearby object of interest (e.g., the Andromeda galaxy), we might obtain two sets of data as we pass through two different focal regimes ("infinity" and then nearer). In addition, finding a focus at 550 a.u. will be another verification of the general theory of relativity. The spacecraft might also provide a very long baseline with respect to earth for a gravity wave experiment.

SYSTEM EQUATIONS

In order to achieve distances of over 100 a.u. in times of 10 to 20 years, the velocity must be over 100 km/s. The rocket equation dictates that the total mass of fuel needed increases exponentially with the ratio of the desired velocity increase (ΔV) over the specific impulse of the fuel (I_{sp}) times the gravitational acceleration (g):

$$m_{fuel} = m_{nonfuel}\left(\exp(\Delta V/(gI_{sp})-1\right), \qquad (1)$$

where m_{fuel} is the mass of the propellant, $m_{nonfuel}$ is the mass of everything that is not propellant (scientific payload, communications, guidance, rocket engines, power supply, etc.). One of the best current chemical propellants is liquid oxygen/liquid hydrogen which has a specific impulse of 460 seconds. To achieve a final velocity of 100 km/s with a payload and structural mass ("non-fuel mass") of 1000 kg would required 4.2 billion tonnes of fuel. Clearly, chemical propellants cannot do the job. But NASA has recently developed very reliable electric propulsion units with a demonstrated specific impulse of 3300 s (Polk, 1998). An even higher Isp can be achieved either by using a larger voltage on the grids or by using a lighter gas. To reach 100 km/s with a specific impulse of 5000 seconds and 1000 kg of payload and structure requires only 7.7 tonnes of propellant. This is much more reasonable.

Electric propulsion requires very large amounts of electrical energy. Nuclear fission, in the form of a small research-sized reactor, is the only credible near-term means for obtaining this energy, especially in deep space. A fission reactor and power conversion system for space (excluding the radiator) would be about the size of an automobile and similar in power to reactors found at many universities. A scoping study of the required performance will better define the power and weight requirements for the system.

The system analysis is based on the following assumptions: (1) The design point goal is 550 a.u., the closest gravitational focal point of the sun, (2) the reactor operates at steady power for a fixed duration (typically many years), (3) the tug takes some time and fuel consumption to escape the earth's and sun's gravitational pull before it begins an "outward burn" to start acquiring speed in interstellar space, (4) after several years of propulsion, the tug coasts at the final velocity to reach 550 a.u, (5) the reactor switches to low-power mode during the coast period, and (6) some propellant is reserved until the tug reaches 550 a.u., at which time the reactor returns to higher power and the propellant is used to produce a transverse velocity perpendicular to the line of sight from the tug to the sun. This allows the telescope to view more objects during its mission. In deference to historical rockets, the propulsion duration will be called a "burn," even though the propellant is not actually burned.

We shall choose to set the tug electric power and the duration of the outward burn as input parameters. Then the mass of fuel needed for the outward burn (m_{fo}) is:

$$m_{fo} = \frac{2\varepsilon_f P t_{bo}}{(gI_{sp})^2}, \tag{2}$$

where ε_f is the efficiency in converting electric power to fuel exhaust power, P is the electric power of the tug, t_{bo} is the scheduled duration of the outward burn, and I_{sp} is the specific impulse of the fuel. The fuel needed for the tug to escape the gravitational pull of the earth and the sun is

$$m_{fese} = (m_{tug} + m_{tel} + m_{ft} + m_{fo})\left\{\exp\left(\frac{(\Delta V_{ee} + \Delta V_{se})}{gI_{sp}}\right) - 1\right\}, \tag{3}$$

where m_{tug} is the mass of the tug system (including reactor, shield, power conversion system, radiator, structures, empty propellant tank, and control systems), m_{tel} is the mass of the telescope and other scientific equipment and communication equipment, m_{ft} is the mass of fuel reserved for achieving the final transverse velocity, ΔV_{ee} is the velocity needed to escape the pull of the earth, and ΔV_{se} is the velocity needed to escape the pull of the sun once the tug is free from earth. Because the acceleration of the tug is so small, it must follow a spiral orbit to escape the earth's pull, so ΔV_{ee} is about 7.8 km/s. But fortunately the acceleration is large enough that it can achieve escape velocity from the solar system in less than half a year, so the burn is effectively a single impulse and approximately follows the equations for a Hohmann orbit transfer. Thus ΔV_{se} is less than for a spiral orbit and is about 12.3 km/s.

Once the total mass of fuel needed to escape the earth and sun is known, the time needed to accomplish this is simply determined from the fuel consumption rate, which depends on the Isp, and the electric power:

$$t_{se} = \frac{m_{fese}(gI_{isp})^2}{2\varepsilon_f P}. \tag{4}$$

The time it takes to reach solar-system escape velocity is fairly short, so the tug does not have time to travel very far from the sun before the start of the outward burn. Typically, it is only about 2 a.u. at this point. The tug has the velocity needed to escape the sun but this will soon be reduced by the sun's gravity. So, for computational purposes, the tug is essentially starting from zero velocity as it begins the outward burn. Thus the final velocity in interstellar space may be determined to be:

$$v_{fis} = gI_{sp}\ln(m_{rat}), \tag{5}$$

where

$$m_{rat} = \frac{m_{tug} + m_{tel} + m_{ft} + m_{fo} - m_{fese}}{m_{tug} + m_{tel} + m_{ft}}. \tag{6}$$

The total distance traveled in time t_t is the sum of the distance traveled by the time solar-system escape velocity is reached (d_{se}, which, as mentioned previously, is usually about 2 a.u.) plus the distance traveled during the remainder of the burn, plus the distance traveled during coasting:

$$d_t = d_{se} + \frac{(m_{tug} + m_{tel} + m_{ft} + m_{fo} - m_{fese})(\mathrm{gI}_{\mathrm{sp2}})^3}{2\varepsilon_f P}\left(1 - \frac{1 + \ln(m_{rat})}{m_{rat}}\right) + v_{fis}(t_t - t_{bo}). \tag{7}$$

PERFORMANCE CHARTS

Figure 1 shows the distance from the sun achieved by the spacecraft for four representative systems. In all four cases, the tug electric power is 2000 kWe, the tug mass is 10,000 kg, the telescope and other scientific payload is 2500 kg, and the fuel reserved for cross-track propulsion when the tug reaches 550 a.u. is 500 kg. The specific impulse is 15,000 seconds. The durations of the outward burns are 3, 4, 6, and 10 years respectively for the four cases presented. The amount of fuel loaded onto the spacecraft initially is different for the four cases since only enough fuel to last the specified burn duration is loaded. At the end of the outward burn the tug coasts at the final interstellar velocity. This velocity is indicated in the figure at the end of each curve.

The time it takes to reach escape velocity from the earth and sun is typically about a year, with about 0.5 years required for the solar-escape burn (which barely meets the Hohmann approximation criterion). The main differences between the cases is that those with shorter burn times reach high speeds faster (because of the lower initial fuel loading) and then have more time to coast at this higher speed after the fuel is all consumed. The short-burn options reach new frontiers (>30 a.u.) sooner. The 6-year burn option reaches the desired 550 a.u. only two years later than the 10-year burn option. A tug which is required to operate at full power for only 5 years, rather than 10, might need less development time and proof-testing, and might be lower risk than a 10-year tug. In addition, it would obtain better parallax and other data earlier in its mission than a 10-year tug. Thus it may be better to opt for a 6-year burn rather than a 10-year burn.

To see whether Isp = 15,000 s is indeed optimum, Figure 2 shows the final distance from the sun for a 20-year mission with various values for Isp. Two options are shown: 6-year burn and 10-year burn. A range of Isps from 10,000 s to 15,000 s is close to optimum for a 6-year burn, but this optimal range is higher for a 10-year burn. Figure 2 also shows the initial mass in low-earth orbit (LEO) vs. Isp. This is an important consideration. The initial mass in LEO is dominated by the propellant mass. If Isp is too low, the required mass of fuel makes the cost of the mission prohibitive. At Isp = 15,000 s, the initial mass in orbit is about 45 metric tons (tonnes) for a 6-year burn, but 68 tonnes for a 10-year burn. Both of these options are acceptable, but the 6-year burn might be more affordable.

Figure 3 shows the distance from the sun vs. time for two sets of curves. The thick curves are for 2000 kWe and the thin ones are for 4000 kWe. Three different specific masses (kg/kWe), designated by α, are also shown. The distance achieved by the tug is very insensitive to total power, but it is very sensitive to the specific mass. Design experience shows that specific mass decreases with increasing power. So, because of that, higher-power systems end up having a shorter delivery time.

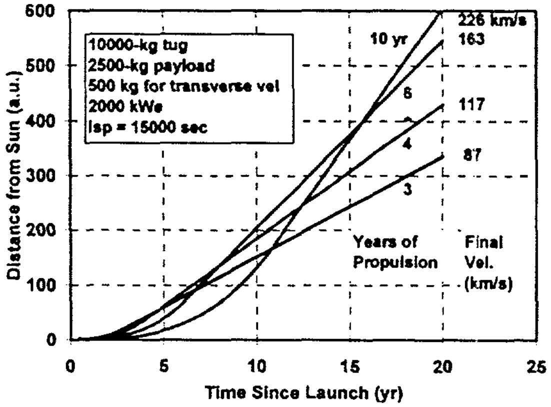

FIGURE 1. Distance from sun vs. time for various cases.

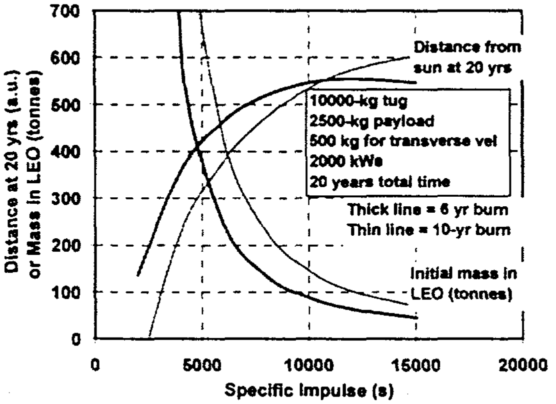

FIGURE 2. Distance at 20 years vs. specific impulse (Isp).

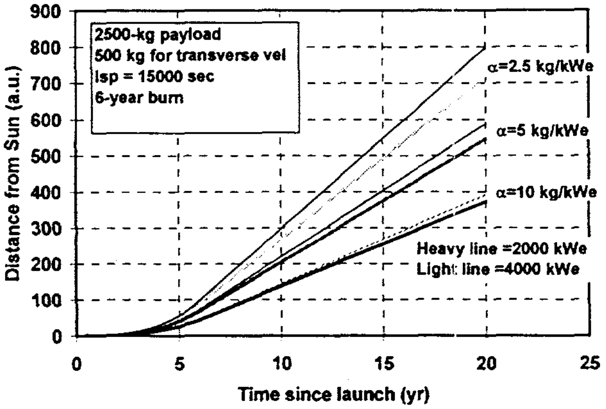

FIGURE 3. Distance vs time for different kg/kWe.

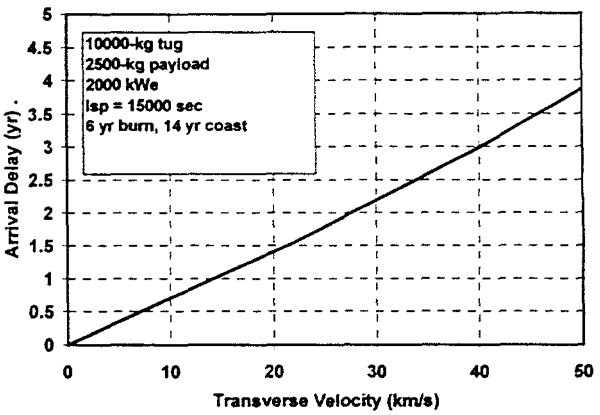

FIGURE 4. Arrival delay vs. final transverse velocity.

After reaching the gravitational lens position at 550 a.u., we have a very large effective telescope with the sun as the primary lens and the spacecraft telescope as the eyepiece. The only way we can steer this telescope is by moving the eyepiece perpendicularly to the line from the spacecraft to the sun with a transverse velocity. This allows mapping out a good image and imaging a variety of objects behind the sun's limb. An object at the edge of the seeable universe would be about 10 billion light years distant. At that distance, a transverse motion of 1 km by the tug at 550 a.u. from the sun would sweep out 0.12 light years. To scan across a typical 60,000-light-year diameter galaxy at 10 billion light years distance would take 10.6 hours at 5 km/s. So a transverse speed of about 5 km/s should give a comfortable rate of data collection.

To obtain a transverse velocity, some propellant must be saved for the end of the trip. Alternatively, one could add a transverse velocity just before coasting begins, but this velocity would be diminished by geometry effects as the distance from the sun increased; the loss would be almost 90% for a 6-year burn. Figure 4 shows the amount of delay in arrival time vs. the amount of transverse velocity desired. Reserving fuel for a 5-km/s transverse velocity causes a 0.4-year delay in arrival time for a 6-year burn with 15,000-s Isp. This is probably an acceptable delay.

Table 1 gives the key parameters for two reference missions. All assume a 2000-kWe 10,000-kg tug, with 15,000 s of Isp and a 6-year burn time, and the payload varies from 1000 kg to 4000 kg. They all reach 550 a.u. in about 20 years and require similar amounts of initial mass in LEO. They also reach 1000 a.u. in about 30-35 years. The reason for the similarity in performance is because it takes an alpha of about 5 kg/kWe to reach 550 a.u. in 20 years, and to get alpha down that low requires a high total power (2000 kWe), which results in a tug mass of 10,000 kg, so any payload below about 4000 kg is small compared to the tug itself.

TUG DESIGN

The proposed design consists of a gas-cooled fission reactor with a closed Brayton cycle for power conversion at 2000 MWe and ion thrusters using xenon or argon as the propellant at Isp = 15,000 s. The thruster is a derivative of the NASA NSTAR engine, which has been demonstrated at 2.3 kW with an Isp of 3300 s in a continuous ground test for 8000 hours in a simulated space environment at JPL.[4] The researchers have identified the primary wear modes (erosion of the acceleration grids) and have developed new materials (carbon-carbon) in which early tests suggest lifetimes of greater than 50,000 hours (5.7 years). To achieve Isp = 15,000 s, either the voltage is increased from 1100 V to 23 kV, or the propellant is changed from xenon to argon, and the applied voltage is increased from 1100 V to 6600 V. Use of liquid xenon as a propellant keeps the tankage volume and pressure low and the total empty tank mass to about 300 kg. Alternatively, lithium could be used as a non-cryogenic propellant. Since power increases with the square of Isp, the nominal power of each thruster is about 50 kW, making them lightweight. The high voltage needed would be obtained by a direct tap off the generator.

TABLE 1. Reference mission configurations.

Parameter	Case 1	Case 2	Case 3
Power in tug (kW)	2000	2000	2000
Mass of the tug (kg)	10000	10000	10000
Mass of the telescope & science payload (kg)	1000	2500	4000
Mass of the transverse fuel (kg)	500	500	500
Specific impulse (s)	15000	15000	15000
Efficiency of converting electrical to exhaust power	0.9	0.9	0.9
Propulsion duration (yr)	6	6	6
Initial system mass in low earth orbit (kg)	43272	44992	46712
Final vel. in inter-stellar space (km/s)	174.85	162.55	152.00
Distance from sun after burn (au)	75.17	71.07	67.43
Final transverse velocity (km/s)	6.54	5.77	5.16
Total time to reach 550 a.u. (yr)	18.96	20.10	21.23
Total time to reach 1000 a.u. (yr)	31.20	33.26	35.30

The fission-based electric power source utilizes many of the technologies and insights from the SP-100 program (Mondt, 1994). The main difference is replacement of the 4.2% efficient thermoelectric conversion system with a closed Brayton cycle and generator to obtain about 50% conversion efficiency. The thermal radiator is also much larger, which allows a lower thermal sink temperature. There is a very extensive industrial data base and fabrication experience for open-cycle Brayton units: they form the basis for commercial and military jet engines as well as helicopter engines. Brayton conversion systems have one moving part: a single shaft connected to the turbine, the electrical generator rotor, and the compressor. In closed systems, this single shaft floats on a gas bearing bled off from the main gas flow and returned to it. Space Brayton units would be weightless and at constant power. They should easily last for many years without any maintenance. A 52,000-hr ground test of a 10.7-kWe closed Brayton unit at NASA/LeRC in 1965 supports these expectations.

The reactor is gas cooled (30/70 mole-% He/Xe) to couple better with the Brayton system. The fuel is uranium nitride (UN), which is the same fuel extensively tested for longevity in the SP-100 program. The active core is 0.60 m in diameter and 0.5 m long. The radial reflector is 0.15-m thick beryllium, and the axial reflector is 0.10-m thick BeO. The fuel rods are held in a lattice of BeO with a 2.0-mm thick flow channel around each rod for the gas coolant. The BeO provides a small amount of moderation. There is a strong negative thermal feedback which allows the reactor power to naturally follow variations in load without needing adjustment of the control elements. There is a thick radiation shield on top of the reactor to shield the payload from the reactor neutron and gamma radiation. There also is a thin radial shield to reduce the amount of reflected radiation from the thermal radiators.

Figure 5 shows a schematic of the Brayton cycle and the associated state points. The reference design produces 2002 kWe with 48.8% total thermal efficiency and has a specific mass of about 5.1 kg/kWe. A key feature is the heat exchanger which recuperates some heat from the turbine exit and uses it to preheat the gas returning from the heat sink before it re-enters the reactor. This recuperation step gives the cycle a greater conversion efficiency than a "non-recuperated" Brayton cycle. The radiator is opened out flat to radiate from two sides and is very large (about 1250 m^2 per side). This allows a low heat-sink temperature and enables the high electrical conversion efficiency. Figure 6 shows one possible vehicle system configuration.

The radiator consists of an array of tubes sandwiched between carbon-carbon panels. This protects them from micrometeors and tiny debris particles as the tug escapes earth orbit. The tubes are cooled with liquid NaK (56%Na, 44%K) which has a melting point of 262 K. An electromagnetic pump forces the coolant flow through the radiator and requires 7 kWe. Because of the small diameters of the tube manifolds (3 cm), the radiator can be folded for launch and then deployed in space. There are a total of 500 tubes, and each set of 10 tubes has a close-off valve at each end in case there is a leak.

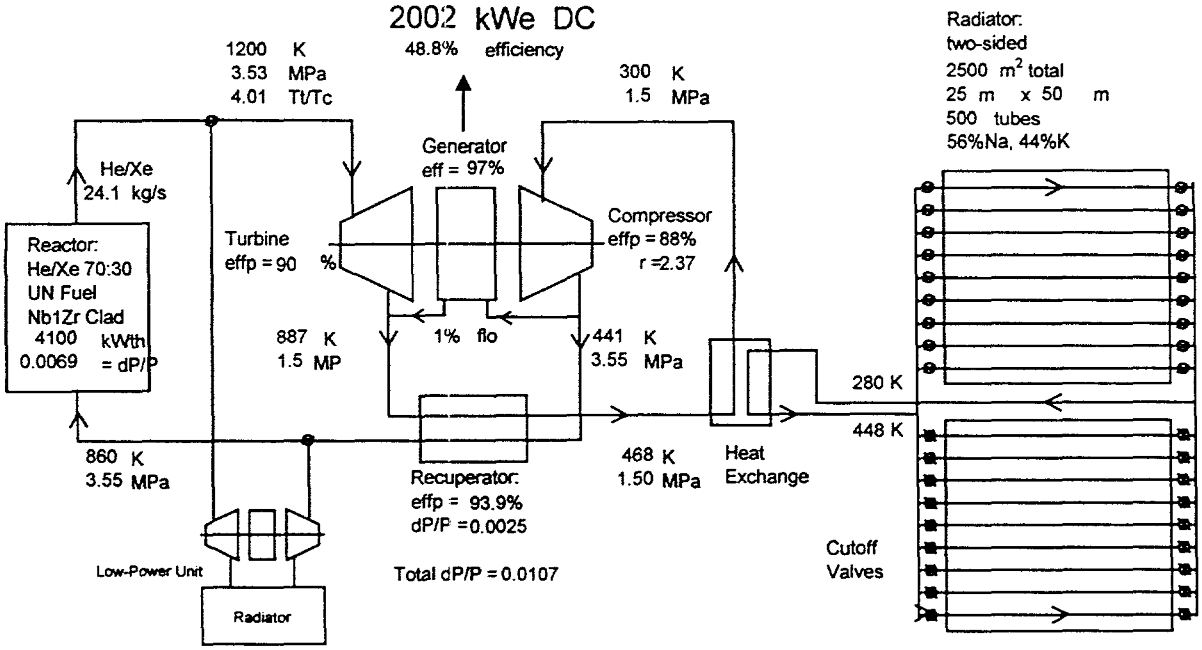

FIGURE 5. Brayton cycle schematic and associated statepoints.

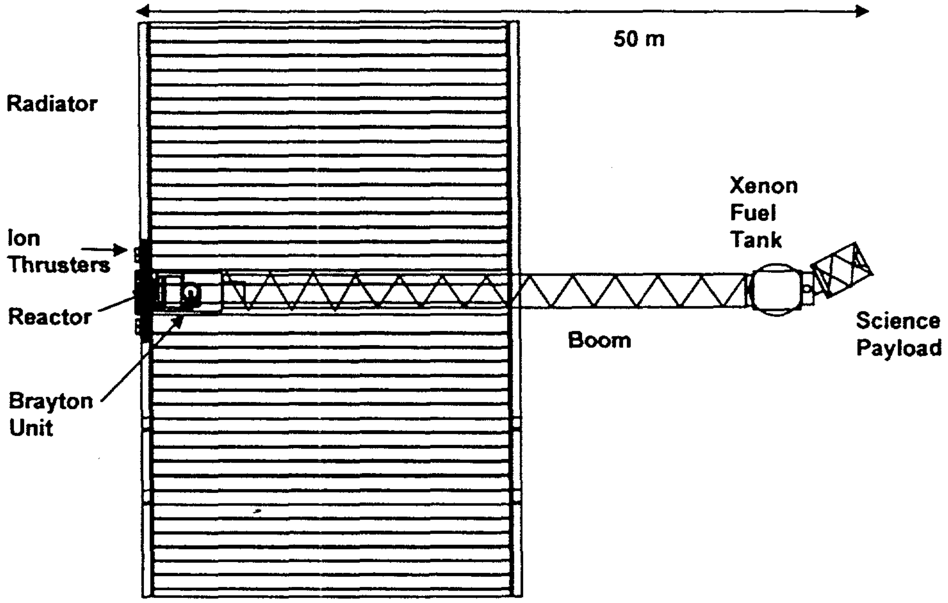

FIGURE 6. Conceptual vehicle system configuration.

LAUNCH APPROVAL

There is a precedent for operating small research-sized reactors in space. There are presently over 30 shut-down nuclear reactors orbiting earth at about 600 km altitude. All but one of these are Russian reactors from Rorsat high-power radar satellites. The one U.S. reactor is SNAP-10A, launched in 1965. Every U.S. launch of a payload involving nuclear material must be reviewed by an Interagency Nuclear Safety Review Panel (INSRP) (Sholtis, 1994). The INSRP reviews the sponsors assessment of the risk and reports to the Office of Science and Technology Policy under the Executive Branch. The President or his designee (usually the Science Advisor) then decides whether to grant launch approval. This process has been followed for 25 launches of nuclear materials over the past 40 years and approval has always been granted. All but one of these launches have involved radioisotopic power sources, but a space reactor would follow the same process.

One key safety feature of a fission reactor is that it is barely radioactive before it is used. The radiological inventory in the fresh fuel is about the same as a truckload of uranium ore, with which uranium miners work safely in nations around the world. The space reactor can be tested prior to launch at essentially zero power to prevent any inventory buildup, so the primary concern for launch safety will be to assure that the reactor will not turn on for any conceivable launch accident scenario. This requires solid engineering, but is not difficult. In addition, once the reactor begins operation in space, it should be assured that it cannot reenter the earth's atmosphere. With high circular orbits and low-thrust ion-propulsion, this should be fairly straightforward. Once it is on its way away from earth, the safety issues vanish, and waste disposal is automatic.

SUMMARY

The propulsion requirements for an interstellar precursor mission that reaches 550 a.u. in 20 years are derived. A 2000-Mwe fission-powered space tug with electric propulsion at 15,000 s Isp can meet the mission requirements if the specific mass is about 5 kg/kWe. A recuperated Brayton cycle will give the high efficiency needed to meet the low weight requirements. The reactor is comparable in power to many research reactors operating at universities throughout the U.S. Based on over 40 years of world-wide experience in design, construction, and operation of terrestrial reactors, we have high confidence that such a space tug can be constructed in the very near term.

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