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INTERPLANETARY PROPULSION USING INERTIAL FUSION

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ABSTRACT

Inertial fusion can be used to power spacecraft within the solar system and beyond. Such spacecraft have the potential for short-duration manned-mission performance exceeding other technologies. We are conducting a study to assess the systems aspects of inertial fusion as applied to such missions, based on the conceptual engine design of Hyde (1983). We describe the required systems for an entirely new spacecraft design called VISTA that is based on the use of DT fuel. We give preliminary design details for the power conversion and power conditioning systems for manned missions to Mars of total duration of about 100 days. Specific mission performance results will be published elsewhere, after the study has been completed.

INTRODUCTION

An inertial fusion rocket (IFR) powered by fusion microexplosions using DT fuel has the potential for short-duration manned missions within the solar system and beyond. A high-performance IFR utilizes driver beams focused on a fusion fuel pellet to initiate small fusion microexplosions inside a thrust chamber created in space by the magnetic field generated from a single superconducting coil. The fusion reactions convert the pellet, which includes a surrounding mass of added hydrogen expellant, into an expanding plasma debris cloud. The magnetic field diverts about two-thirds of this debris and causes it to exit the thrust chamber in one direction, thus providing thrust as well as protection for spacecraft components that the debris might otherwise strike. The large neutron and x-ray emissions from the DT microexplosions dictate an overall conical design for the spacecraft, with all subsystems placed along the cone in the shadow of the neutron shielding already required for the cryogenic magnet coil. With this geometry, nearly all of the neutron and x-ray emissions exit without striking any spacecraft components.

This paper describes some preliminary results for the assessment of the IFR performance capabilities, long-term mission benefits, and technological challenges associated with missions employing technologies in existence by A.D. 2020. Although the systems concept is similar to that of Hyde (1983), the results represent a more in-depth study of the systems issues, and the spacecraft design concept (called VISTA: a Vehicle for Interplanetary Space Transport Applications) is entirely new. Because VISTA incorporates DT fuel and thereby emits neutrons which represent a significant hazard for unprotected personnel in nearby spacecraft, VISTA may be considered a high-orbit to high-orbit transport vehicle. Typical results include a manned-Mars mission with a 100-tonne payload and a round-trip travel time (including a 10-day stay on the planet) of about 100 days. Such mission times represent a significant advance over other technologies, such as chemical or nuclear-electric. Final results will be presented elsewhere after our study group completes its systems assessment.

SPACECRAFT DESIGN

The neutron and x-ray emissions from the DT pellet represent losses and add to vehicle heating wherever they impinge on component surfaces. We cannot avoid having such heating for the interior face of the magnet coil, so a thick neutron coil shield is required there to insulate the cryogenic fluid for the magnet. The shield uses liquid lithium to facilitate heat transfer and to generate extra tritium by reactions of the neutrons on lithium.

We have chosen a hollow-cone geometry for the spacecraft, with the pellet located at the cone apex, to exclude other surfaces from the neutron and x-ray bombardment, and for mechanical reasons (see Figure 1). The relative positioning of the pellet and coil determines the cone half-angle to be about 50 degrees. All components, including the driver systems, waste-heat radiators, fuel tanks, and manned areas, lie along the conical surface in the shadow of the coil shield. Pellet debris expanding spherically from the pellet position is deflected after a few meters of travel into a plume exiting on the other side of the apex from the coil. The spacecraft is thus propelled with its blunt end forward.

The most notable aspect of the artist's concept of the spacecraft shown in Figure 1 is that the radiators, whose designs are based on heat-pipe technology, actually form the conical structure. Because the radiators nearest the apex experience high loads following each microexplosion, a NASTRAN model was used to help estimate the radiator thickness required for structural support. Assuming a titanium-foil surface is used to cover interior heat-pipe radiators, we calculate that a specific mass of about 14 kg/m^2 would be required, which indicates an effective radiator specific mass of 0.2 kg/kWt at 900 K. Alternate mechanical packaging designs are being considered for the heat pipes, with the main (core) heat pipe feeders suitably protected from micrometeroid bombardment and stiffened to form the main conical structure. With these more advanced designs, we hope to achieve our baseline goal of 0.1 kg/kWt (or less) for the radiators. In general, our study considered the entire range of specific radiator masses from 0.03 to 0.23 kg/kWt.

FUSION DRIVER SYSTEM

The energy required to ignite an inertial fusion pellet must be supplied by a driver. All drivers currently under development for terrestrial fusion applications (heavy ions, light ions, free-electron lasers, solid-state lasers, or KrF lasers) appear to have limitations that necessitate further driver development before they would be suitable for an IFR. The system with the most promise of realizing the required high efficiency at high operating temperature (to minimize waste heat rejection) is some sort of gaseous excimer laser. We have assumed such a system can be developed by A.D 2020 with an efficiency of at least 6% and a rejection temperature of at least 900 K. The efficiency developed may be twice this, but even so, the waste heat rejection system for the driver will still represent a significant fraction of the total driver mass. At 6% and an output of 2 MJ, 33 MJ must be supplied to the input of the driver, of which about 31 MJ must be radiated as waste heat using heat pipe radiators at a rate of 1 to 30 Hz (that is, about 30 to 940 MWt). The driver would be modular, with perhaps 100 modules located along the conical radiator shell of the spacecraft.

FUSION PELLET SYSTEMS

An onboard pellet assembly system will fill prefabricated pellets with deuterium-tritium (DT) cryogenic fuel, add the required surrounding mass of liquid-hydrogen expellant (with holes for the laser light to shine through to the target), and transfer the filled pellet assemblies to an accelerator-injection system that positions the pellets at the center of the magnetic thrust chamber. At the moment each pellet arrives at the center of the chamber, driver beams will ignite the pellet, producing a microexplosion. This sequence repeats at a rate of about 1 to 30 Hz. Each microexplosion produces an energy gain (that is, the ratio of nuclear energy produced to driver energy delivered to the pellet) anywhere between about 50 and 2000, depending on the driver energy E_D and the pellet technology. Pellet gains near 50 to 100 correspond to current DT technology, which permits gains described by the approximate relationship $G_{DT} \simeq (1000\ E_D - 1000)^{0.53}$ (Lindl 1986). The most important feature of a pellet, however, is the amount of fusion energy that ends up in the plasma debris. This energy depends on the product of the fusion pellet gain, and the fraction of the total energy that ends up in the debris plasma (and not in neutrons or x rays). Advanced fuels like DD or DHe^3 ignited by a DT core permit higher fractions of the total energy in debris plasma (essentially unity for DHe^3, about two-thirds for DD, but significantly less for DT). On the other hand, DD and DHe^3 provide energy gains that are smaller than the corresponding DT gain by factors ranging from 4 to 6. When the products of the gains and the debris fractions are considered, it is possible for DD and DHe^3 to compete with and perhaps even surpass DT fuel in performance, but only for very advanced pellet technologies. The advanced technologies required to use DD and

DHe^3 fuels will not exist in the near term, and the use of DHe^3 requires mining the lunar surface or the Jovian atmosphere to obtain sufficient quantities of He^3. We therefore consider DT fuel to be the more viable fuel choice for the near term. The only disadvantage for DT is the tritium radioactive-decay waste-heat generation of about 1/3 W/g. This necessitates storage of the tritium as a gas, with subsequent liquefaction using a cryogenic refrigerator having a mass of about 50 tonnes.

Advanced DT technologies exist that permit energy gains, according to speculation in the pellet design community, in excess of 1,000 for driver energies near or above 2 MJ. The corresponding gains for DD and DHe^3 are expected to be near 200. We do not expect technology developed by A.D. 2020 to permit DD gains of 1,000 for driver energies near 2 MJ, as reported by Hyde (1983). The additional expellant mass placed around the pellet enhances the debris fraction and increases the mass ejection rate per pulse (and hence the thrust). The added expellant mass can be varied, but is typically 50 g per pellet. With this expellant mass, the optimum driver energy is larger than 2 MJ (perhaps 4 or 5 MJ), and the corresponding advanced-technology pellet gains are greater than 1,000 (scaling approximately as the cube-root of E_D).

THRUST CHAMBER DESIGN

The debris plasma can be directed by a simple dipole magnetic field (one current loop) to form an exhaust with high specific impulse (30,000 s is typical). We are considering a 12-T magnet of radius 13 m using warm superconductors in a rotationally symmetric geometry, where the stored magnetic energy is at least 5 times the pellet kinetic energy. Although this configuration can convert 42% of the debris kinetic energy into exhaust (Hyde 1983), we have lowered the jet efficiency to 36% to account for such things as the nonzero resistivity of the cooling pellet plasma.

Thrust-chamber operation depends on the positioning of the pellet explosions on the axis of the magnet coil but displaced to the rear of the coil plane, so the interaction of the magnetic pressure with the kinetic energy of the expanding plasma can collimate the debris into an exhaust as it is expelled from the thrust chamber. Maximal efficiency for debris deflection in the magnetic field requires a certain axial positioning of the pellet relative to the coil. This positioning determines the 50-degree half-angle spacecraft geometry.

The above engine concept allows a power-to-mass ratio near 20 for a driver energy $E_D = 5$ MJ, operation at 30 Hz, and a highly speculative pellet gain of $G_{DT} = 1500$. Engine thrust would be over 2×10^5 N at a mass flow rate of 1.5 kg/s. Maximum onboard acceleration would be less than 0.02 g.

Disposing of the heat generated by the 3% of the x rays and neutrons striking the coil shield degrades the rocket's power to mass ratio, and necessitates the use of a cryogenic refrigeration/heat-rejection system. Even though the heat-rejection system can operate at 1500 K (Hyde 1983), the coil-shield radiators represent a significant contribution to the total spacecraft mass when operating at high engine power. Some of the x-ray and neutron energy intercepted by the coil shield can be converted to electricity with a Rankine thermal cycle to run the driver and auxiliary equipment by flowing liquid lithium from the coil shield through a shell and tube heat exchanger (see below).

Design refinements which have been considered for the thrust chamber include magnetic field shaping with additional coils to avoid plasma flowing back along closed field lines, and practical methods to detach the exiting plasma from the downstream field in order to reduce magnetic drag.

POWER SUPPLY SYSTEMS

The power supply systems must be capable of supplying approximately 1 MW of auxiliary DC power plus at least 10^8 pulses with about 600 kV for 400 ns or more at a rate of typically 1 to 30 Hz to operate the laser driver. Several overall systems concepts are being considered. The original baseline design was a power conversion system consisting of a 20%-efficient Rankine power cycle utilizing the neutron deposition in the superconducting magnet coil shield as a heat source, with the Rankine system feeding a power conditioning system employing a high-frequency turbo-alternator with capacitative storage. The relatively low efficiency used here for the Rankine system is based on minimum-mass rather than maximum-efficiency considerations. Driver pulses would be formed through either resonant capacitor discharge, or by the discharge of charged transmission lines.

The large mass of the Rankine system greatly restricts mission performance, so studies are in progress to use an inductor-coil power-conversion system as suggested by Hyde (1983) as the baseline design for VISTA. The inductor-coil system would employ structure acting as a pickup coil placed interior to the large superconducting-magnet coil to produce electricity through magnetic induction when the expanding plasma from one fusion microexplosion causes magnetic field lines to cross through the pickup coil and generate e.m.f. for the next driver pulse. The inductor-coil system greatly reduces system masses and thus improves engine performance, because it essentially eliminates the equipment mass and the radiator mass associated with the 80%-inefficient Rankine system. In addition, advanced concepts are under study to figure out how to delay or store the pulses from such an inductor coil with only minor conditioning to compress the 100-microsecond inductor pulses to the 400-ns pulses needed for the driver. Such an advanced system would improve engine performance even more.

Power Conversion System

The Rankine power cycle utilizes saturated potassium vapor as the working fluid, in a design similar to one presented for a fusion-based power study (Meier 1986). A flow sheet for the power cycle is shown in Figure 2 (specific thermodynamic details will be published elsewhere). Fusion neutron energy is deposited as heat in a 1-m thick shield of liquid lithium encased in a refractory metal sheet and located in front of the superconducting coil. The lithium is pumped out of the shield and through a counterflow tube and shell boiler, transferring the heat to boiling potassium inside the tubes. Potassium vapor exits the boiler and flows to the main turbine inlet, with a side stream flowing to an auxiliary turbine that drives the centrifugal feed pump. Fluid entering the boiler is preheated by one or more shell and tube regenerative feed heaters. In the figure, only one feed heater is shown. Additional heaters utilize turbine extraction vapor. The temperature of the potassium leaving the boiler was selected as 1390 K (2500 R); this is compatible with high-temperature components made of Astar-811C and low-temperature components made of Nb-1%Zr.

The mass of the Rankine power subsystem was determined for one preliminary case: a fusion engine having a driver energy of 2 MJ, a pellet gain of 1000, a frequency of 8 Hz, a total fusion power of 16,000 MWt, and a jet power of 4200 MW. In this case, 267 MWe of power are required for a 6%-efficient fusion driver, although design refinements will change this power requirement slightly. This case assumes 19% of the total fusion energy is present in the neutrons (Hyde 1983).

The minimum Rankine subsystem mass for this case was found by varying the temperature at the turbine exit and calculating the mass of each component in the conversion cycle, in order to find the temperature corresponding to the minimum total mass. The computer program ALKACYCL (Moyers 1985) was used to determine cycle efficiency for various values of radiator temperature. The program also outputed the energy balance, line sizes, and masses for the piping and feed heaters. The masses of the major components were determined separately from the program. Individual components, and the scaling laws used for each, are discussed in the following paragraphs.

The lithium coil shield was expanded in size to form a blanket to collect enough energy from depositing neutrons to power the driver. The first wall distance assumed here is 7.9 m, based on a superconducting coil radius of only 6.5 m (which was the value used by Hyde 1983, and for a preliminary VISTA design, but not for the final VISTA design). The blanket is enclosed by Nb-1%Zr walls; the thickness of the walls was estimated for a 99% survivability on an 80-day mission in an interplanetary micrometeoroid environment.

The lithium piping of the primary heat transport loop was sized to provide steady-state heat removal from the lithium blanket. A 100 K temperature drop through the boiler and a flow velocity of 6.1 m/s were assumed. Like the lithium shield, the piping wall thickness was selected for protection from micrometeoroid damage.

An EM pump is used to circulate the lithium through the boiler. The pump mass is a function of both the volumetric flow rate and the pressure drop through the lithium piping. The flow rate increases directly with system thermal power. For a fixed length of piping, the pressure drop decreases slightly as the flow rate increases, due to increased pipe size. As a result, pump mass scales very closely with system thermal power.

The turbine is an axial flow type with nine stages and two interstage moisture separators. The stage efficiency is equal to the dry stage efficiency (0.85) degraded by stage moisture. Turbine size depends largely on the total volumetric flow through the turbine. Based on a previous study (Yoder and Graves 1986), a specific mass of 70 kg/(m^3/s) of turbine outlet flow was calculated for a turbine of 100 kWe output. The scaling of turbine size with power is difficult to determine, because potassium vapor turbines of megawatt size have not been built. As the turbine size increases, its efficiency increases, suggesting a scaling exponent less than 1.0. However, the wall thickness must also increase as power goes up due to the large component size. A scaling exponent of 0.9 was found by comparing the turbine masses of a 350-kWe and a 10-MWe potassium Rankine power cycle design with approximately the same temperature conditions (Pitts and Jester 1968 and Pitts and Walter 1970).

The generator mass was assumed to scale as a transformer, that is, to the 0.75 power (Sercel and Krauthamer 1986). At 5 MWe output, the generator was assumed to have a specific mass of 0.1 kg/kWe. The number of boiler tubes, and thus the total tube mass, is directly proportional to the thermal power absorbed by the shield. The boiler shell diameter and shell thickness both increase with the square root of the thermal power; thus the total scaling factor is a direct function of thermal power. A boiler specific mass of 0.025 kg/kWt was obtained based on an overall heat transfer coefficient of 8500 W/m^2K (Pitts and Walter 1970), a tube-to-shell temperature difference of 111 K, and a factor of 1.5 to account for shell mass.

Secondary loop sizes and feedheater masses were obtained from the computer program. The secondary piping also has micrometeoroid-protective shielding. The heat pipe radiator considered for these calculations, however, is not shielded; the wall thickness is sized to accommodate internal pressure only. It is assumed that excess heat pipes are installed at the beginning so that 10% can be lost to micrometeoroid damage during operation.

The radiator was assumed to be an array of heat pipes of Nb-1%Zr construction using sodium as a working fluid. Potassium vapor leaving the turbine condenses as it comes in contact with the evaporating sections of several heat pipes embedded in the turbine outlet piping. The piping tapers as the potassium condenses and subcools before entering the feed pump. The radiating temperature is assumed to be 100 K less than the turbine outlet temperature. The radiator design has an assumed specific mass of 0.13 kg/kW of reject heat at 900 K and scales with radiator temperature to the fourth power. More advanced radiator designs are under study.

The resulting component masses are plotted versus radiator temperature in Figure 3. The total mass is also plotted, and a minimum total mass of 450,000 kg occurs at a radiator temperature of 900 K. Of this mass, 14,000 kg is due to the alternator that is included below in the power-conditioner system. Thus, the total Rankine-system mass is 436,000 kg. At 900 K, the lithium shield, in which the energy is collected, is the heaviest component. It increases with temperature because the cycle efficiency decreases, and a greater thermal power is necessary to output the required electric power.

The turbine mass decreases with radiator temperature. As the radiator temperature increases, the mass flow rate increases to provide the same power output at a lower efficiency. However, a higher radiator temperature corresponds to a higher saturated liquid pressure, which has the effect of reducing volumetric flow rate even though the mass flow rate is increasing. The turbine curve turns upward at higher temperatures when the mass flow increase dominates the volumetric flow decrease. The generator mass remains constant as the radiator temperature increases, since electric power output is held constant.

A minimum radiator mass occurs because specific mass decreases with radiator temperature while the amount of heat rejection increases due to the decreasing cycle efficiency. A minimum mass of 130,000 kg occurs at 1000 K although the curve is very flat between 950 K and 1025 K.

The boiler mass increases with radiator temperature as the efficiency decreases. Primary piping and EM pump masses both increase in order to accommodate the larger flow rate due to a higher thermal power. Secondary piping mass decreases because although the flow rates are increasing, the turbine outlet pressure also increases with temperature, keeping the piping sizes small.

The high-frequency turbo-alternator delivers 3-phase AC current at 1,500 Hz and typically 15 kV. The 3-phase output allows acceptable low voltage ripple on the DC bus, requires a modest rectifier parts count, gives adequate rectifier utilization, and simplifies alternator and transformer design.

Power Conditioner System

The purpose of the power conditioner is to accept alternator output voltage and convert this AC source of power into high-energy short-duration pulses used to drive the fusion driver. (Our design for the power conditioner is easily modified for use with the inductor-coil conversion system, but is presented here under the assumption of the use of a Rankine system with a turbo-alternator.) In order to optimize system mass and efficiency, the power conditioner uses a single multimegawatt 3-phase transformer to perform primary AC voltage stepup and electrical isolation. The transformer output is processed with a 3-phase solid-state bridge silicon-controlled rectifier/voltage regulator, and an inductor to provide signal filtering and current limiting in the case of driver fault. The processor is assumed to incorporate high-efficiency, low-mass, moderate-to-fast fault interruption. The output of the processor feeds a capacitor-storage network. We selected capacitor storage to obtain a system with high specific energy, low specific mass, and rapid rise-time discharge. The driver is powered from the capacitor bank through a pulse-forming network and a load switch. The capacitors can be resonantly discharged into the load, or perhaps even better, through the discharge of charged transmission lines. Distribution to other systems would be through conditioners that would provide the correct potential and modulation for each subsystem.

The masses and efficiencies associated with the power conditioning system are shown in Table 1 for the preliminary case of a 280-MWe unit for a 10%-efficient 2-MJ driver and a specific capacitor design. The combined specific mass of the Power Conditioning/Processing Unit (PPU) has been found to be 0.37 kg/kWe exclusive of radiators. The design of the buffer capacitors was based on both the solid dielectric capacitor technology developed by Maxwell Labs (funded by the Defense Nuclear Agency), and state of the art polypropylene film technology (developed by Sandia National Laboratories, G.W. Mauldin principal investigator). The total specific energy will be between 400 J/kg and 4000 J/kg. The specific volume is between 0.6 and 0.8 J/cm^3, with 2 MV/cm, and the plate material is aluminum.

The mass of the capacitor network can vary from 5 to 55 tonnes at 20 MJ, using the above parameters. The total mass of the power conditioning system for minimum driver input requirements (6%-efficient driver with 2-MJ illumination on the fusion pellet, and hence 33 MJ of driver input--not 20 MJ) is correspondingly between 65 and 170 tonnes exclusive of radiators. Total system efficiency is 97.5%. New device developments assumed include improved semi-conductor switches (high-voltage and high-current, and very fast deep-impurity double-doped silicon devices), capacitors (new materials and new cooling techniques with objective of high energy density and low loss for pulsed operation), and high-frequency magnetic materials for transformer size reduction and efficiency improvement.

MISSION PERFORMANCE

Only preliminary mission performance can be presented at this time because our study has not yet been completed. The development options required for optimal performance include the use of the inductor-coil pickup in place of the Rankine system (whether or not any advance signal processing can be developed for direct inductor-pulse utilization), because the Rankine system is excessively massive (it doubles the total spacecraft mass for short-duration missions). The options also include the development of waste-heat radiators with the least specific mass consistent with the mechanical constraints for the conical spacecraft geometry. Any driver improvement towards efficiencies above 6% would of course alleviate this development option.

Using the inductor-coil option, round-trip transit times for a manned-Mars mission are under about 100 days for a vehicle of total mass near 6000 tonnes. The total mass includes approximately 4400 tonnes of propellant (fuel, expellant, refrigeration, tankage), a 500-tonne laser driver, a 500-tonne thrust chamber, 240 tonnes of payload and crew systems, and 100 tonnes in power systems. Past mission studies based on highly advanced chemical propulsion or nuclear thermal propulsion systems of minimum mass suggest comparable trip times of 2 to 3 years. Direct fission propulsion, such as the solid-core and particle-bed concepts, cannot do much better because they are limited by thermal constraints. A recent study using technology projected to the A.D. 2020 time frame suggests that advanced nuclear-electric propulsion systems might achieve a minimum trip time of about two-thirds of a year with a launch mass of 1500 tonnes (Sercel and Krauthamer 1986). We presume that much of the IFR technology will already be developed for terrestrial applications. An IFR system thus represents a significant advancement.

CONCLUSIONS

We have outlined the preliminary results of an ongoing study to define a design concept of an interplanetary spacecraft powered by inertial fusion using DT fuel. Emphasis has been placed on obtaining a realistic design based on technology extrapolated to A.D. 2020. Assuming significant technological developments for the driver, pellet, thrust-chamber, and radiator subsystems in particular, we find that manned missions to Mars are possible with total mission durations of about 100 days. Such performance surpasses that for any other viable engine concept, based on minimum-mass configurations.

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TABLE AND FIGURE CAPTIONS

Table 1: 280-MWe Power Conditioner Unit Preliminary Point Design for a 2-MJ Driver with 10% Efficiency.

Figure 1: Artist's Concept of the Spacecraft Configuration.

Figure 2: Schematic of Rankine Cycle Subsystem.

Figure 3: Power Conversion System Masses as a function of Radiator Temperature.

Table 1: 280-MWe Power Conditioner Unit Preliminary Point Design for a 2-MJ Driver with 10% Efficiency.

ITEM	MASS (Tonnes)	SPECIFIC MASS	VOLUME (m^3)	SPECIFIC VOLUME	DISSIPATION (kW)	EFFICIENCY	REJECTION TEMPERATURE (K)	RADIATOR	
								Area (m^2)	Mass (Tonnes)
Turbo Alternator	14.55	Alternator .048 kg/kW @ 304 MW	20		Alternator 3.0	99.5%	175	1847	9.23
Transformer	14.55	.048 kg/kW @ 304 MW	20		950	99.66%	175	577	2.89
SCR Regulator/ Rectifier	3.40		6		730	99.73%	100	1121	5.61
Filter Inductor	4.88		5		180	99.94%	175	109	0.55
Capacitor Bank	50.00	400 J/kg	25	0.8 J/cm^3	2960*	98.94%	100	4548	22.74
Output Switch	3.64		8		180	99.94%	100	277	1.38
Low Voltage Bus	1.82		1.0		305	99.89%	175	185	0.93
High Voltage Bus	1.82		1.0		305	99.89%	175	185	0.93
Support Structure	7.64								
TOTAL	102.3		86			97.5%		8849	44.3

*(at 6×10^{-6} second pulse)

Figure 1: Artist's Concept of the Spacecraft Configuration

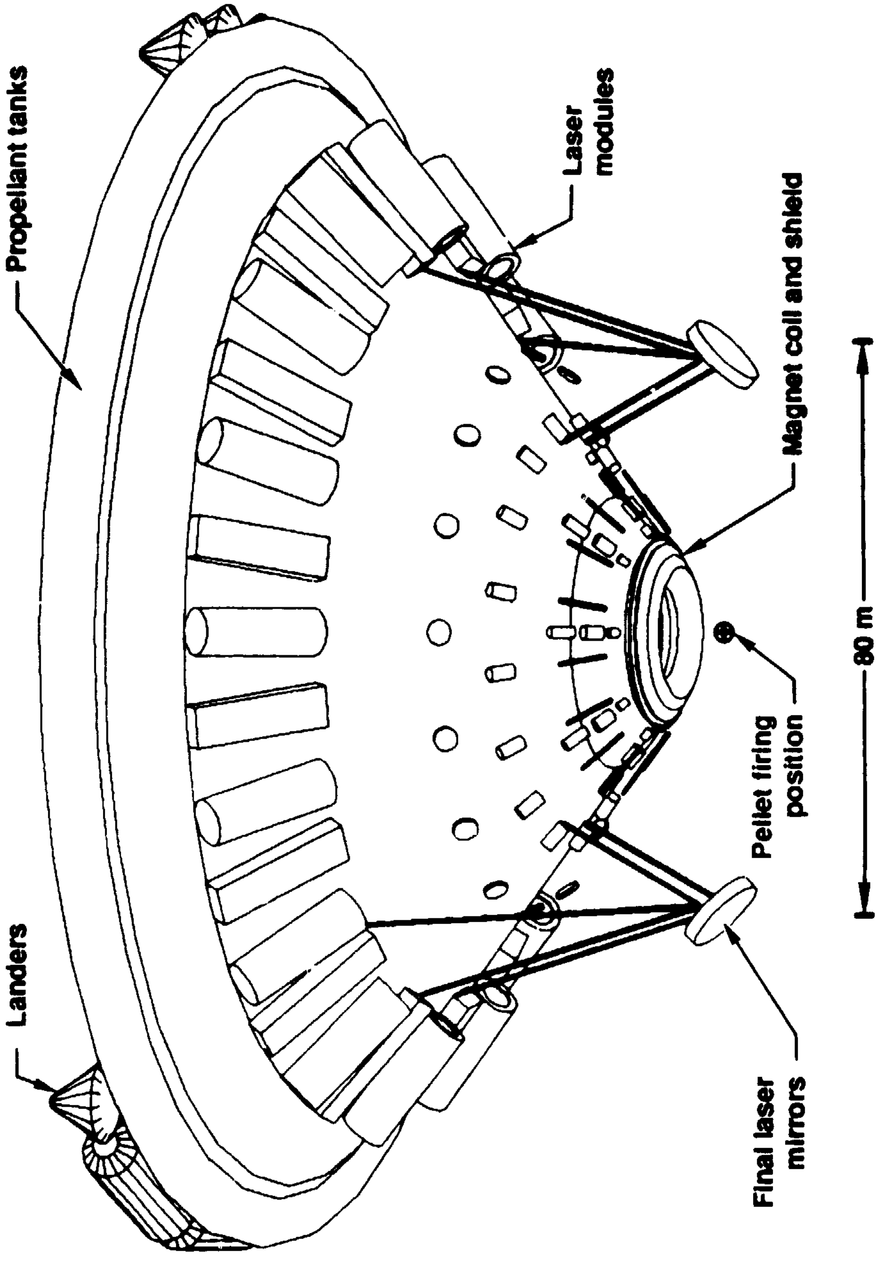

Figure 2: Schematic of Rankine Cycle Subsystem

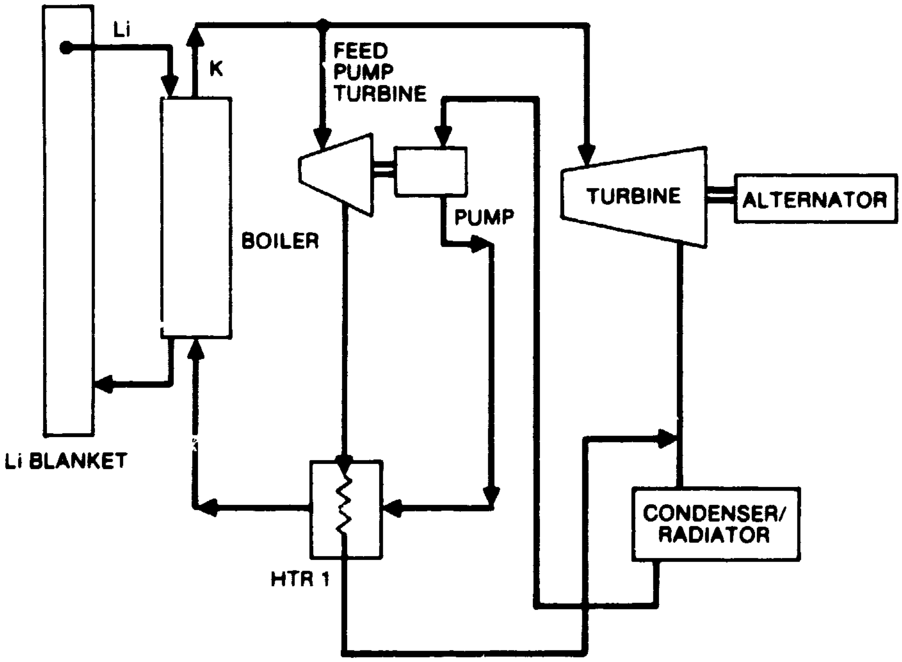

Figure 3: Power Conversion System Masses
as a function of Radiator Temperature