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Direct Energy Conversion for Low Specific Mass In-Space Power and Propulsion

John H. Scott[1], Jeffrey A. George[2], Alfonso G. Tarditi[3]

[1]*NASA Lyndon B. Johnson Space Center, Code EP3, Houston, TX 77058*
[2]*NASA Lyndon B. Johnson Space Center, Code EP3, Houston, TX 77058*
[3]*Electric Power Research Institute, 942 Corridor Park Boulevard, Knoxville, TN 37932*

Abstract. "Changing the game" in space exploration involves changing the paradigm for the human exploration of the Solar System, e.g, changing the human exploration of Mars from a three-year epic event to an annual expedition. For the purposes of this assessment an "annual expedition" capability is defined as an in-space power & propulsion system which, with launch mass limits as defined in NASA's Mars Architecture 5.0, enables sending a crew to Mars and returning them after a 30-day surface stay within one year, irrespective of planetary alignment. In this work the authors intend to show that obtaining this capability requires the development of an in-space power & propulsion system with an end-to-end specific mass considerably less than 3 kg/kW_e. A first order energy balance analysis reveals that the technologies required to create a system with this specific mass include direct energy conversion and nuclear sources that release energy in the form of charged particle beams. This paper lays out this first order approximation and details these conclusions.

Keywords: Direct Energy Conversion, Rankine Cycle Conversion, Nuclear Fission, Aneutronic Nuclear Fusion

INTRODUCTION

For many decades, NASA's paradigm for the human exploration of Mars has centered on the conjunction class mission, an example of which is described in NASA's Mars Architecture 5.0 study [Drake 2009]. In this class of mission, the crew is sent to Mars on a ~200 day transit near the time of an Earth-Mars conjunction, remains on Mars for approximately 500 days until the next conjunction approaches, and then returns on another ~200 day transit. The crew is thus in space for approximately two and half years, with all the health risks that such exposure entails. In the Mars Architecture 5.0 study, nuclear thermal propulsion on a vehicle with an initial mass to low Earth orbit (IMLEO) of ~350 mT is identified as the reference propulsion technology for accomplishing this mission. Other studies indicate that nuclear-electric propulsion (NEP) [George 1993] and solar-electric propulsion (SEP) [Donahue 2010] systems could also accomplish this mission architecture with similar IMLEO requirements.

However, replacing this paradigm of human Mars exploration with one built around rapid access to Mars on annual expeditions would truly "change the game" for exploration of the Solar System. Such a mission capability can be attained with high thrust, low specific impulse (I_{sp} < 1000 sec), short burn technologies such as chemical or nuclear thermal propulsion but only at the expense of very large (> 1000 mT) IMLEO for the mission, which is most likely unaffordable given current and projected launch vehicle technology and NASA budgets. However, such mission capability may also be attained within the 350 mT IMLEO limit of Mars Architecture 5.0 through the application of low thrust, high I_{sp} (> 2000 sec), continuous burn electric propulsion technologies. The parametric study of Earth-Mars transit times shown in Fig. 1 reveals that, holding to the same IMLEO limits identified in Mars Architecture 5.0 and applying such electric propulsion, getting a crew to Mars and back within one year around the optimal 2018 Earth-Mars opposition (and with a 30 day surface stay) would require an in-space power and propulsion system with specific mass (α) of under 5 kg/kW and a delivered power of approximately 20 MW. Enabling such a mission over a broader range of Earth-Mars opportunities would require an α of 3 kg/kW, and the capability to carry out such a mission during any one-year period, regardless of Earth-Mars alignment would require α closer to 1 kg/kW.

A first order assessment of the range of in-space power and electric propulsion systems can identify what technologies must be advanced in order to deliver a sufficiently low total power & propulsion system α. Simple but revealing estimates of system total α can be built by selecting a system power output requirement from Fig. 1, identifying an efficiency (η) and α for each of the subsystems involved based on a consistent set of assumptions for technology capability, and then calculating the mass of each major subsystem required to handle the power that must pass through it.

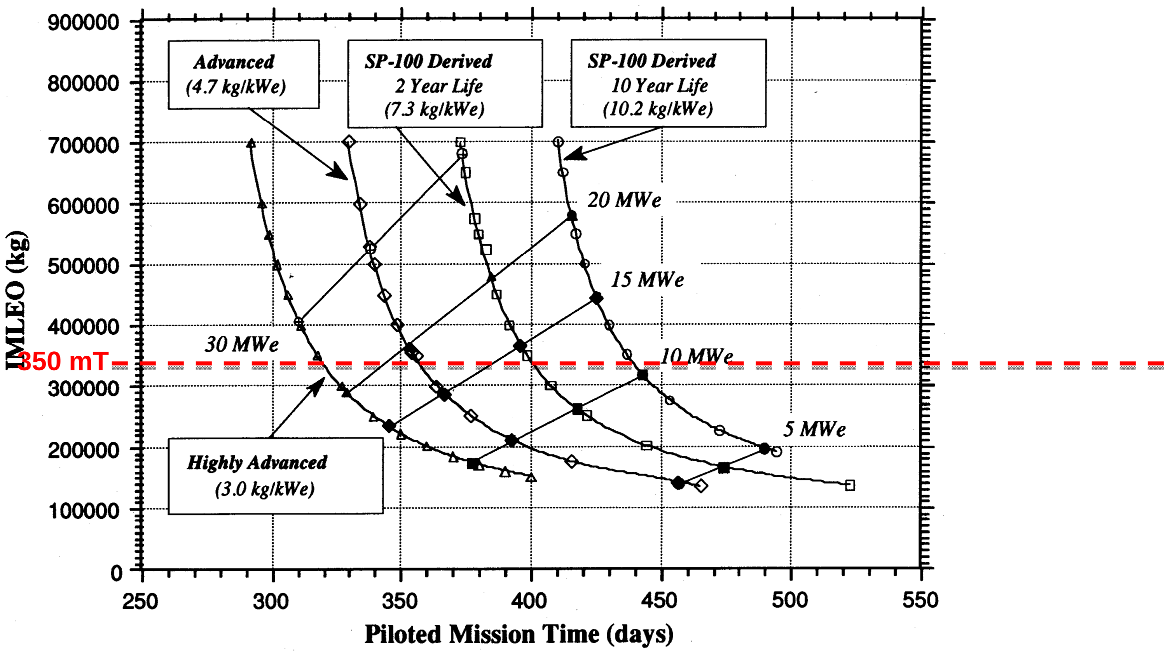

FIGURE 1. Round-trip Earth-Mars mission times to/from High Earth Orbit (HEO) as a function of specific mass, power, and IMLEO. Mission times assume Earth-Mars opposition, a 30-day crewed surface stay, a 40 mT habitat carried outbound, an Earth Crew Capture Vehicle returned, and lander & surface habitat delivered separately. [George 1993].

SUBSYSTEM SPECIFIC MASS ESTIMATES

When viewing a basic energy balance, any in-space electric power & propulsion (EPP) system can be seen to consist of five basic subsystems: energy source, energy conversion subsystem, waste heat rejection subsystem, power management and distribution (PMAD) subsystem, and the electric propulsion subsystem itself. There are different technology solutions, with different α and η figures of merit, for each. The figures of merit used for each subsystem technology in the present analysis represent the author team's assessment, based on cited literature, of the most aggressive achievable α and η. These are listed in Table 1. The basis of each of these assessments follows below. In each case, a simplifying assumption is made that α will remain constant over a range of 100 kW to 10's of MW. This is a conservative assumption made for purposes of this paper, as the parameter α would usually decrease as power is greatly increased in such subsystems. It should also be noted that, for purposes of the energy balance analysis in this paper, the α denominator is defined as the power passing in or out (as specified) of the subsystem and not that generated by the total EPP power subsystem.

Energy Sources

Energy sources considered in this paper are photovoltaic (solar) arrays, solid core, vapor core, and "thin" core nuclear fission, and aneutronic nuclear fusion.

Photovoltaic Arrays

Human Mars mission architectures utilizing SEP have been developed in some detail [Donahue 2010]. A relatively near term array concept is the DARPA/Boeing FAST array. With the solar intensity at 1 A.U. and with 33% efficient photovoltaic cells, this array concept is projected to achieve an α of 8 kg/kW_{out}. However, the efficiency of triple-junction photovoltaic concentrator cells, such as would be used in the FAST array, is projected to approach 50% in the 2020's [NREL 2012]. Thus, array α at 1 A.U. might be projected to reach 5 kg/kW_{out}. Accounting for the decrease in solar intensity with the square of the distance from Earth to Mars, the effective α for an Earth-Mars mission increases to 7.5 kg/kW_{out}.

TABLE 1. Figures of Merit η and α for Advanced Electric Power and Propulsion (EPP) Subsystems.

Subsystem: Technology	**α**	**η**	**Reference**
Energy Source: Photovoltaic Array	7.5 kg/kW_{out}	-	Donahue 2010, NREL 2012
Energy Source: Solid Core Fission	0.15 kg/kW_{out}	-	George 1991
Energy Source: Vapor Core Fission	0.04 kg/kW_{out}	-	Knight 2004
Energy Source: "Thin Core Fission"	0.15 kg/kW_{out}	-	Authors' estimate
Energy Source: Aneutronic Fusion	0.2 kg/kW_{out}	-	Authors' estimate
Fission Neutron Shield	1.0 kg/kW_{in}	-	Mason 2012
Energy Conversion: Rankine heat engine	0.14 kg/kW_{in}	0.18	George 1991
Energy Conversion: MHD	0.03 kg/kW_{in}	0.20	Knight 2004
Energy Conversion: TWDEC	0.14 kg/kW_{in}	0.70	Momota 1992
PMAD	1.0 kg/kW_{in}	0.99	George 1991
Heat Rejection: Condensing Radiator (1100 K)	0.12 kg/kW_{in}	-	George 1991
Heat Rejection: Condensing Radiator (1500 K)	0.10 kg/kW_{in}	-	Knight 2004
Heat Rejection: Single Phase Radiator (600 K)	0.98 kg/kW_{in}	-	Mason 2012
Electric Propulsion (Hall or Plasma)	1.0 kg/kW_{in}	0.6	Brown 2009
Electric Propulsion (Direct Conversion Plasma)	0.4 kg/kW_{in}	0.6	Tarditi 2012

Solid Core Nuclear Fission

Human Mars mission architectures utilizing solid core fission nuclear-electric propulsion have been developed in some detail as well. As this energy source puts out its power as heat, it is desirable to run such a reactor at the highest temperature that the materials can stand. This is estimated in George [1991] to be 2000 K for gas cooled reactors, for which Brayton cycle conversion would be optimal, and 1500 K for liquid cooled reactors, for which Rankine cycle conversion would be optimal. These studies have also shown that, due to the lower mass of Rankine "constant temperature," condensing radiators, the latter would yield the lower α for an NEP-based EPP system. For the mission length under consideration in this study, a reactor with sufficient fuel for two years of operation is appropriate, and George [1991] estimates α for such a reactor designed for 1500 K operation to be 0.15 kg/kW_{out}.

Most concepts for crewed NEP missions assume a shadow shield placed at 50 to 100 m from the crew habitat. The mass required of such a shield is proportional to the neutron flux, and thus to the thermal power output, of the fission core. Mason [2012] estimates an effective α for such a shield, which would expose the habitat to 50 rem/year located 50 m from the habitat, at 1 kg/kW_{in}.

Vapor Core Nuclear Fission

Another fission concept that has received attention for space applications is the vapor core fission reactor. In this concept, fission fuel in the form of uranium tetrafluoride (UF_4) gas is made critical by a shock wave, and the resulting hot (~2500 K) partially ionized gas is passed through a magnetohydrodynamic (MHD) power convertor. While the physics of such a reactor are understood, none has ever been made to go critical experimentally. The total α of an EPP system based on vapor core technology has been estimated in published studies [Knight 2004]. The present analysis presents a modified estimate, in which PMAD and propulsion subsystem α's are those used in the other EPP system α estimates developed herein. Based on the Knight 2004 estimate, the α of a vapor core reactor is estimated to be as low as 0.04 kg/kW_{out}.

"Thin" Core Nuclear Fission

Yet another fission concept to consider is known as "thin" core fission. In this long known concept, uranium fission fuel is deposited in a very thin layer (e.g., 6 x 10^{-3} g/cm^2 [Safanov 1954]), allowing fission product fragments to fly free and be collimated through a direct energy conversion device, thus avoiding the Carnot limits of heat engine conversion. As with vapor core fission, the physics of such a reactor are understood, but none has ever been made to go critical experimentally. Analytical research continues [Slutz 2000]. No published estimates have been made of the α of such a reactor intended for space applications, thus the present analysis assumes an α equivalent to that of a full solid core fission reactor: 0.15 kg/kW_{out}. It is also important to note that cooling the magnets necessary to collimate fission product ions into a direct conversion subsystem, as well as cooling the core itself may take a substantial amount of power. Of the cited references only Safonov mentions the escaped or absorbed neutron flux associated with such a reactor and then only speculates that only a small fraction of the source neutrons would support fission. Thus, for conservatism, the present study conjectures that 10% of the reactor thermal output power would be required to run heat pumps for cooling the superconducting, collimating magnets and that neutron shielding requirements would be the same as for a solid core.

Aneutronic Nuclear Fusion

The harnessing of a range of fusion reactions has been studied, both analytically and experimentally, for many decades. The key figure of merit for any fusion reactor concept is "Q", defined as the ration between the gross thermal power emitted by fusion reactions (P_{gross}) and the power required to be fed into the reactor to maintain confinement of the fusion plasma (P_{drive}). No effort has yet experimentally produced a Q greater than 1 for any reactor concept. Most of the U.S. and international focus in this field has been on harnessing the Deuterium-Tritium (D-T) reaction in an ignited plasma. The D-T reaction emits most of its energy as high-energy neutrons, thus functioning as a heat source in a system requiring heat engine conversion. The primary program pursuing a D-T reactor, the International Tokamak Experimental Reactor (ITER), is not expected to yield a reactor with α anywhere close to that suitable for spacecraft power [ITER 2012]. In any case, such a reactor would function as a heat source, just as would a solid core fission reactor, and face the limitations of heat engine conversion. There have been studies of using D-T fusion plasmas directly for propulsion [Williams 2005], but these are projected to yield an α that would be attractive for a human Solar System mission context only at a gigawatt scale, requiring IMLEO far in excess of the limit assumed for the present study.

Another set of fusion reactions under study are the so-called aneutronic reactions: Deuterium-^{3}Helium and Hydrogen-^{11}Boron (D-^{3}He, p-^{11}B). These reactions release their energy in the form of charged particles, enabling direct conversion not subject to Carnot limitations. However, the ion collision energy required for these reactions to take place in conditions near the peak of the fusion cross section is so high that the radiation losses in any equilibrium plasma heated to the required temperature would exceed the fusion power output, making $Q > 1$ effectively impossible [Dawson 1981]. For these reactions $Q > 1$ can only obtained by confinement of a non-equilibrium plasma. Various such confinement concepts have been proposed [e.g., Rostoker 2003, Krall 1991]. It should be noted that such plasmas do not ignite, thus the possible Q may be quite low. However, studies indicate that Q up to 8 may be possible [Burton 2003]. The driving power is required to replace energy losses in the confined plasma. A fraction of these loses (those from plasma collision with structure) must be rejected with 600 K radiators, but the majority could be radiated directly into space. There are few published estimates of α for these reactors, but claims range from 0.01 kg/kW_{out} [Bussard 2006] to 0.1 kg/kW_{out} [Burton 2003]. The uncertainties in these estimates lead to the author's assumption of $\alpha = 0.2$ kg/kW_{out} for the present study.

It is important to note at this point that, though the potential for successful physics proof of a $Q > 1$ reactor is uncertain, the aneutronic fusion energy source offers certain key advantages over the other nuclear options identified above. The aneutronic nature of the reactions means not only that a flight EPP system will avoid heavy neutron shielding, but also that the development program will most likely avoid the challenges of managing radioactive material (i.e., nuclear waste). Thus, not only would the overall EPP system α be improved over fission options, but the overall design, development, testing, and evaluation (DDT&E) program would be significantly cheaper than that for any fission-based EPP system. Pursuing a $Q > 1$ physics proof for aneutronic fusion would involve investing in the development of multiple confinement concepts, any one of which might only have a less than even chance of success. However, many such "bets" could be placed for the price of the ground development effort for even a well understood solid core fission reactor.

Energy Conversion Subsystems

Energy conversion options considered in the present analysis include two heat engines (Rankine cycle and Magnetohydrodynamic – MHD) and one particular direct conversion engine (the so-called Traveling Wave Direct Energy Convertor - TWDEC).

The Rankine engine is selected for consideration with solid core fission, because its constant temperature heat rejection enables the lowest mass heat rejection radiators (which condense two phase flow). Previous studies [George 1991] estimate α for such an engine and its coolant piping at a 1500 K topping temperature to be 0.14 kg/kW_{in}. Note that the optimal η for such an engine at 1500 K topping is shown to be only 18%, well less than might be possible with a deep space heat sink. Such an η setting optimizes between higher heat rejection temperature, which greatly lowers α for radiators, and lower reactor mass.

MHD conversion is considered as the optimal way in which to take advantage of the high (~2500 K) source temperature of a UF_4 vapor core reactor. Previous studies [Knight 2004] estimate MHD subsystem (including UF4 flow channels, pumps, nozzles, and diffusers) α at 0.07 kg/kW_{in}.

The TWDEC is suggested by the authors for discussion as the optimal way to draw energy from the ion beams produced by "thin core" fission and aneutronic fusion. The TWDEC functions by decelerating ions with an electric field and thus converting the kinetic energy of these ions into high (RF) frequency AC electric power. Previous studies [Momota 1992] predict η of 70% and also note that, in a space application, only a fraction of the losses from the TWDEC (those from ion collisions with structure and electrodes) must be rejected as heat, thus even the relatively low temperature (600 K) radiators required can be relatively small. The remaining energy losses are rejected by simply allowing the remaining ion kinetic energy to radiate into space. An estimate of α for a space TWDEC of 0.14 kg/kW_{in} is derived from Momota 1992.

Heat Rejection Subsystems

Heat rejection radiators are an important contributor to the α of in-space power & propulsion systems. In some cases, in which heat rejection temperatures are relatively low, they can dominate the system α. For single phase flow heat rejection, as is encountered when cooling PMAD and system structural components with single phase fluids, the present analysis takes the projected advanced radiator α from a previous study [Mason 2012], as adjusted for temperature via the Stephan-Boltzman equation. For two phase flow, condensing radiators, as are encountered with a Rankine cycle, the projected advanced radiator from an earlier study [George 1991] is applied for 1100 K heat rejection and from a more recent vapor core fission study [Knight 2004] for ultra-high temperature 1500 K heat rejection. Selected values for α are in Table 1.

Power Management and Distribution (PMAD)

In the context of the present study, the basic function of PMAD is to convert electric power from the voltage and current (AC or DC) at which it is generated to that which is required by the electric propulsion subsystem. The degree of voltage change and inversion/rectification required drives the α of these subsystems, but only as a second-order effect. Previous studies [George 1991] predict that, with high voltage (5000 V) and high frequency (kHz) electronics and transformers, advanced PMAD subsystems can be highly efficient (η >95%) and have α approaching 1 kg/kW_{in}.

Electric Thruster

While there are widely different approaches to electric thrusters, which are variables in the present study, those considered scalable to the multi-MW power level include Hall thrusters and plasma engines. Even given this variety of concepts, previous studies [George 1991, Brown 2009] generally assume achievable α in a range of 0.5 to 1.5 kg/kW_{in} and η of ~60%. An α of 1.0 kg/kW_{in} is chosen for the present analysis for each case save one. It should be noted that a plasma engine, which accelerates its propellant plasma via, for example, RF wave heating and a magnetic nozzle, may offer a special α advantage when combined with TWDEC conversion. A TWDEC can conceivably be engineered to tune its power output to the frequency used in the plasma engine's RF frequency, in which case the PMAD subsystem would not be required to condition the power going into the propulsion subsystem. It will be shown below that this can enable a significant decrease in EPP system mass.

There is also one special case of a thruster that will be considered in the present analysis. Recent studies [Tarditi 2012] indicate the possibility of accelerating the propellant plasma in a plasma engine via direct interaction with the ions emanating from an ion beam energy source (e.g., aneutronic fusion, thin core fission). This would enable an EPP system than avoids even converting energy from the source into electricity, for an even greater system mass savings. This will be considered in one of the system cases assessed below.

EPP SYSTEM ENERGY FLOW ANALYSIS

A comparison, based on subsystem α and η identified in Table 1, of achievable α for a complete, EPP system is presented in Table 2. Figure 2 provides energy flow diagrams of each system option. As the mission capability goal is an annual Mars visit capability with 350 mT IMLEO for a single mission, a comparison basis of 30 MW is inferred from Fig. 1. Each case in Table 2 is described below:

Case 1 - Photovoltaic Power with Plasma or Hall Propulsion: This α estimate is only valid out to Mars orbit. The α would increase rapidly for missions further away from the Sun.

Case 2 – Solid Core Fission Power with Plasma or Hall Propulsion: This cases exemplifies the capability limits of Nuclear Electric Propulsion (NEP) as described in George [1991] and Mason [2012].

Case 3 – Vapor Core Fission Power: The present analysis reveals a significantly higher α_{power} than the 1.4 kg/kW_e estimated by Knight (2004). This is due to the present analysis assuming less aggressive α's for neutron shielding and PMAD.

Case 4 – "Thin" Core Fission: The α and collimating power estimates for this case are particularly speculative. It can also be seen per Fig. 2, Case 4 that propulsion options to obtain this α are limited to plasma engines that accelerate propellant via an RF antenna which can be powered by TWDEC conversion without intermediate power conditioning by a PMAD subsystem.

Case 5 – Aneutronic Fusion: This case is highly sensitive to the Q of the fusion reactor assumed. As can be seen in Fig. 3, α rapidly increases as Q drops below 3 and decreases only slowly as Q exceeds 6. This is the primary consideration in the development of aneutronic fusion for spacecraft power applications.

Case 6 – Aneutronic Fusion with Direct Conversion to Thrust: The case is also highly sensitive to the fusion reactor Q as shown in Fig. 3. Further, this system concept channels the fusion product ion beam through a TWDEC only to produce drive power and to condition the beam to go on directly into the plasma engine. The propellant is accelerated through direct interaction with the ion beam in the manner proposed by Tarditi [2012]. While this thruster concept offers the most attractive α assessed in the present study, it is somewhat speculative relative to Cases 1 through 5.

TABLE 2. Figure of Merit α for Electric Power and Propulsion (EPP) Systems

Photovoltaic (Case 1)				Solid Core Fission (Case 2)				Vapor Core Fission (Case 3)			
Subsystem	**MW**	**mT**	**α**	**Subsystem**	**MW**	**mT**	**α**	**Subsystem**	**MW**	**mT**	**α**
PV Concentrator Array	30	227		1500 K Fission Reactor	168	26		2500 K Fission Reactor	152	6	
				Fission Shadow Shield	168	169		Fission Shadow Shield	152	152	
				Rankine Engine	168	23		MHD Engine	152	4	
				1100 K Condensing Radiators	138	16		1500 K Condensing Radiators	121	12	
PMAD	30	30		PMAD	30	30		PMAD	30	30	
600 K Single Phase Radiators	0	0		600 K Single Phase Radiators	0	0		600 K Single Phase Radiators	0	0	
Power Total	30	258		Power Total	30	265		Power Total	30	205	
Power α ($mT/MW_{e,out}$)			8.6	**Power α ($mT/MW_{e,out}$)**			8.8	**Power α ($mT/MW_{e,out}$)**			6.8
EP Thruster	30	30		EP Thruster				EP Thruster	30	30	
Power & Prop Combined α ($mT/MW_{e,in}$)			**9.6**	**Power & Prop Combined α ($mT/MW_{e,in}$)**			**9.8**	**Power & Prop Combined α ($mT/MW_{e,in}$)**			**7.8**

"Thin Core" Fission (Case 4)				Aneutronic Fusion (Case 5)				Aneutronic Fusion (Direct-to-Thrust) (Case 6)			
Subsystem	**MW**	**mT**	**α**	**Subsystem**	**MW**	**mT**	**α**	**Subsystem**	**MW**	**mT**	**α**
Thin Core Fission Reactor	50	8		Fusion Reactor	67	13		Fusion Reactor	47	9	
Collumating power	5	0		Driving power (Q=4)	17	0		Driving power (Q=4)	12	0	
600 K Single Phase Radiators	5	5		600 K Single Phase Radiators	9	9		600 K Single Phase Radiators	7	2	
Fission Shadow Shield	50	50									
TWDEC	50	7		TWDEC	67	9		TWDEC (only for driving powe	17	2	
600 K Single Phase Radiators	8	7		600 K Single Phase Radiators	10	10		600 K Single Phase Radiators	5	1	
PMAD	5	5		PMAD	17	17		PMAD	12	12	
600 K Single Phase Radiators	0	0		600 K Single Phase Radiators	0	0		600 K Single Phase Radiators	0	0	
Power Total	30	82		Power Total	30	59		Power Total	30	27	
Power α ($mT/MW_{e,out}$)			2.7	**Power α ($mT/MW_{e,out}$)**			2.0	**Power α ($mT/MW_{e,out}$)**			0.9
EP Thruster	30	30		EP Thruster	30	30		EP Thruster	30	12	
Power & Prop Combined α ($mT/MW_{e,in}$)			**3.7**	**Power & Prop Combined α ($mT/MW_{e,in}$)**			**3.0**	**Power & Prop Combined α ($mT/MW_{e,in}$)**			**1.3**

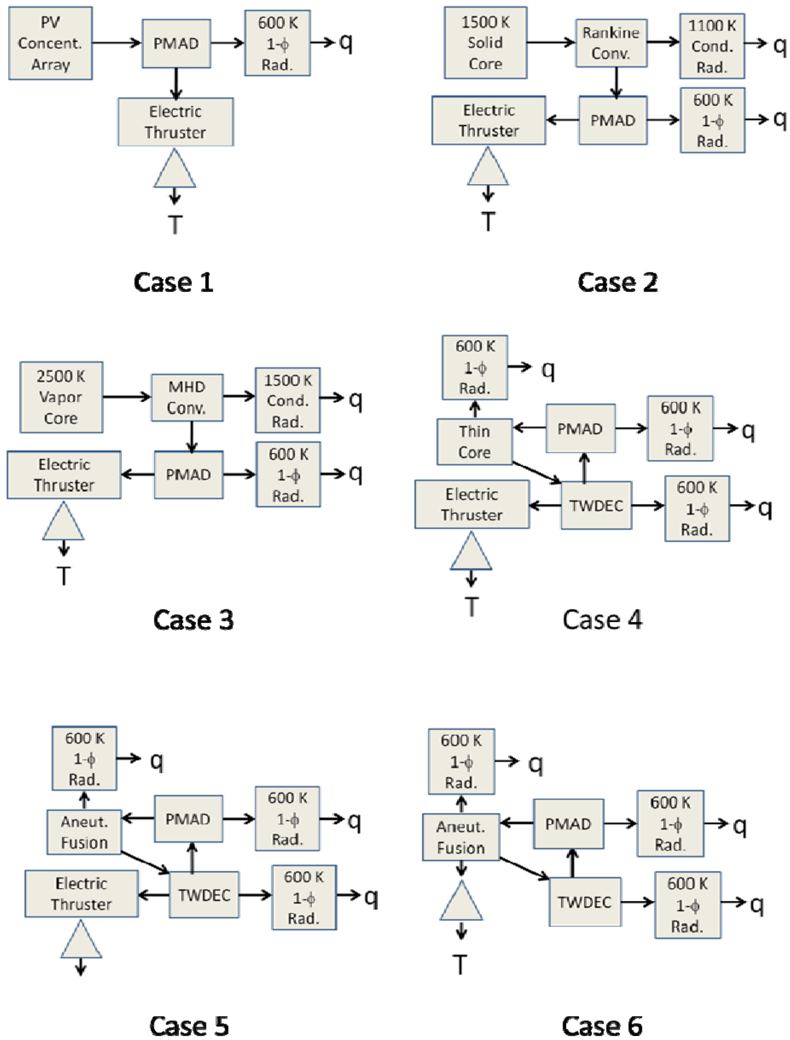

FIGURE 2. Functional block diagrams of propulsion & power analysis cases identified in Table 2

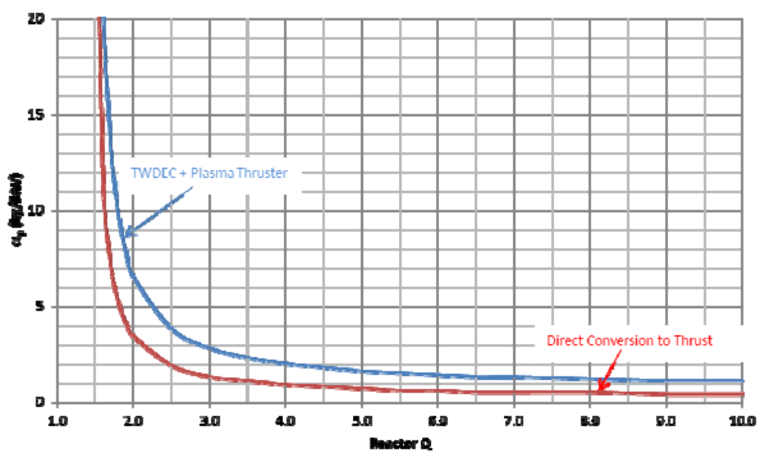

Figure 3. Sensitivity of total power subsystem α to aneutronic fusion reactor Q.

CONCLUSION

A quick assessment of Table 2 reveals that the cases described Cases 1 through 3 do not offer an α low enough to enable annual Mars expeditions under the constraints identified at the beginning of this paper, while those of Cases 4 through 6 do. The energy sources of these last three cases (Cases 4-6) involve substantially greater development risk than those of the first three (Cases 1-3), but the total α of the EPP system is not particularly sensitive to that of the sources. The engineering that enables this major reduction in system α involves the removal of energy conversion steps. The combination of ion beam energy sources and the TWDEC not only avoids the massive heat rejection subsystems associated with heat engine conversion, but it also, when used with a plasma engine thruster, enables the bulk of the system energy flow to bypass high-α PMAD subsystems. The next step in this direction, exemplified by the case of Case 6, effectively removes another conversion step along the energy flow from source to thruster. In this last case, even conversion of source energy to electricity is for the most part avoided.

Another inference from the present parametric study is that obtaining the desired low system α via direct conversion requires aggressive development of energy sources that release their energy as charged particle beams rather than neutrons/heat. The two such options assessed present very different development paradigms. The physics of a fission reactor are well understood, and, while no "thin" reactor core has been made critical in test, there is some justifiable confidence that it could be done. However, developing a fission reactor concept so radically different from that now used would require extensive nuclear testing involving the production of activated material. The development program going forward would be prohibitively expensive. The means by which to overcome the engineering challenges of the other option, aneutronic fusion, are less well understood, and $Q > 1$ has yet to be experimentally achieved for any fusion concept. However, as the aneutronic reactions would not produce activated material in test, many different confinement concepts could be examined and, if successful, developed to $Q > 1$ perhaps far more economically than a fission-based system development program.

NOMENCLATURE

α = specific mass (kg/kW). For propulsion & power system, α is defined as $kg_{(total\ system)}/kW_{(from\ power\ into\ thruster)}$
η = Thermodynamic efficiency
Q = For a nuclear fusion reactor: P_{gross}/P_{drive}
q = Heat rejected (kW)
T = Thrust (N)
P_{gross} = Total fusion power (kW) output from a fusion reactor core
P_{drive} = Power (kW) required to maintain plasma confinement in a fusion reactor core.

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