THE NEED FOR FUSION PROPULSION RESEARCH

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Fusion propulsion is inevitable if the human race remains dedicated to exploration of the solar system, and it must be pursued by NASA if the President's vision for U.S. space exploration is to be upheld. There are fundamental reasons why fusion surpasses more traditional approaches to routine crewed missions to Mars, crewed missions to the outer planets, and deep space high speed robotic missions, assuming that reduced trip times, increased payloads, and higher available power are desired. A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. We compiled a sufficient set of arguments for utilizing fusion in space. If the U.S. is to lead the effort and produce a working system in a reasonable amount of time, NASA must take the initiative, relying on, but not waiting for, DOE guidance. Arguments for fusion propulsion are presented, along with fusion enabled mission examples, fusion technology trade space, and a proposed outline for future efforts.

"Like the explorers of the past and the pioneers of flight in the last century, we cannot today identify all that we will gain from space exploration; we are confident, nonetheless, that the eventual return will be great. Like their efforts, the success of future U.S. space exploration will unfold over generations." – President George W. Bush, January 14, 2004

INTRODUCTION

The goals of the President's vision for space exploration include implementing a sustained and affordable human and robotic program to explore the solar system and beyond and extending human presence across the solar system. To implement this vision, NASA must develop and demonstrate power generation and propulsion required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. In order to successfully fulfill this vision, there must be a long term strategy to develop propulsion systems that enable routine manned trips to Mars and manned missions to the outer solar system. Technology to reach Mars is within near term reach in the form of chemical, nuclear thermal, and perhaps nuclear electric propulsion (NEP). NASA has recently proposed to develop shuttle-derived technologies for near term lunar and Martian missions, <u>relying on chemical propulsion</u> for both. This is a logical, economic first step for getting humans out of low earth orbit. However, if fast Mars trip times of the order of 3-4 months are desirable, if humans are to explore beyond Mars, and if fast, power-rich robotic missions at the edge of the solar system and beyond are to be pursued, then alternatives that enable high specific impulse (>5000 s) and high specific power (~10 kW/kg) are required. These constraints exclude chemical propulsion, so alternative propulsion technologies must be pursued. Only fusion and perhaps other, more exotic systems like antimatter or possibly solar sails can meet the performance criteria. We will demonstrate a historical imperative for fusion research to begin immediately to be ready when needed in the decades to come.

In order to utilize fusion energy for propulsion or power production, scientists and engineers must endeavor to overcome a host of technical challenges. Temperatures must reach 10 to 100 keV. The plasma must hold together with a density and residence time sufficient to yield more power from fusion reactions than supplied to the system and lost by radiation and thermal conduction. The energy from the reactions must be converted into a usable form of energy, such as electricity or directed plasma jet exhaust. The entire cycle must be repeatable and affordable.

Fusion research has taken many paths, but the landscape is dominated by two schemes, inertial confinement fusion (ICF)(Weynants 2002) and magnetic fusion energy (MFE)(Weynants 2002). MFE devices confine plasmas with a magnetic field. The magnetic field pressure ($B^2/2\mu_0$) must be higher than the plasma pressure, thus requiring strong magnetic fields and relatively low densities. Reactor size scales with the inverse of density, thus MFE devices, of which tokamaks are the most actively pursued, need to be rather large. The development of the International Tokamak Experimental Reactor (ITER), a concept designed to demonstrate fusion breakeven, has a multibillion dollar pricetag. ICF overcomes this by using plasma at densities typically ten to twelve orders of magnitude higher. At this density, the size of the reacting volume (of less than a mm in diameter) is inconsequential. The approach requires extremely high power drivers (lasers, particle beams), and reactor chambers for containing the relatively large explosive yields. Both of these requirements tend to drive up the cost of conventional inertial fusion energy approaches. As stated by Siemon et al., a more timely and economical approach to fusion may require a different physics regime and technological approach(Siemon, Lindemuth et al. 1999). Regardless of the path chosen, if fusion is to ever be used for in-space propulsion, then the time to start working on the effort is now.

A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. In this paper, we discuss the arguments for utilizing fusion in space, based on those discussions. We then explain why NASA must take the initiative, relying on, but not waiting for, guidance from the Department of Energy (DOE). We present a summary of some fusion propulsion approaches that have been investigated, as well as some mission examples. Finally, we propose an outline for a sustained fusion program at NASA.

ADVANTAGES OF FUSION PROPULSION

There are a great number of reasons for utilizing fusion power in space, mostly due to the high specific power (1-100 kW/kg), high thrust (10 to 100's of kN), and variable to high specific impulse (up to ~100,000 s). It is important to explain why fusion is fundamentally a high specific power system, especially compared with nuclear electric propulsion (NEP), which has recently been deemphasized by NASA due to the technology limitations needed to reach performance criteria for manned missions to Mars. Electric power requires *energy conversion* from a reactor or other source. *Thermal/electric conversion*, required for NEP, is about 30% efficient limited by Carnot cycle (2nd Law) efficiency. Thus, much of the energy has to be rejected by heavy radiators. The primary reason fusion propulsion systems have theoretically much higher specific powers compared with NEP is because thermal/electric inefficiencies can be offset in a high gain fusion system(Bussard 1990). Further, large propulsion system masses are offset by added jet power. Direct conversion of the plasma exhaust energy, a viable approach for fusion, can approach 70% efficiency of the total fusion reaction, making thermal/electric conversion unnecessary.

As a consequence of the high power (~GW) performance, fusion power in space provides tremendous capabilities and advantages. First, it reduces trip times, making the trip safer for astronauts by lowering the radiation dose from cosmic rays and solar events. Shorter trip times lessen the psychological impact of long term space travel and reduces the skeletal and muscle tissue atrophy. Second, high specific powers at high specific impulse increase the payload mass fraction, enabling new missions, permitting more science in shorter mission times. Finally, fusion permits significant mission flexibility because of the very high mission ΔV capability.

THE INCENTIVES FOR A NASA-LED FUSION PROGRAM

A common knee-jerk reaction to the suggestion of a NASA-sponsored program is to 'wait for DOE to do it, and then leverage the technology'. Norman Schulze was among the first to state why this was not the most logical approach, by explaining the NASA-DOE relationship(Schulze 1991). The Space Act of 1958 has a mandate that states, "… the improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical space vehicles." DOE's mandate is primarily to develop terrestrial power generation. A premium at DOE is placed on cost effective (i.e. fuel efficient, high containment) power generation, not mass limitation. NASA requires a lightweight propulsion system with high exhaust velocities. Electrical power generation is of secondary importance. Therefore, a fusion reactor for propulsion may not necessarily look like, or operate in the same physics regime as, a power plant. A comparison between chemical rockets and coal burning power plants is a good example. Nevertheless, DOE is actively pursuing tokamak research for terrestrial power production. DOE sponsored investment in fusion terrestrial power generation has generated a substantial database of basic physics and engineering knowledge relating to fusion physics. NASA can leverage the basic research being developed by DOE to develop fusion propulsion technologies, but NASA would benefit substantially from initiating its own program.

NASA must seed technologies so they are in the maturation pipeline. An internal fusion science and engineering capability is necessary to properly evaluate usefulness of technologies coming from industry, academia, and other government agencies. A sustained and steady development program is required now to generate usable results in the near future.

NASA can leverage efforts in other areas which overlap with the fusion program. High voltage and power distribution and management are common elements in NEP and fusion. Neutron and gamma shielding are necessary for all nuclear approaches and as shielding from cosmic rays and solar flares. Fusion reactions with a gain less than unity can be used at an intermediate stage in the development program to increase specific impulse of certain electric thruster concepts. Fission ignited fusion, both steady state (UF_4 gas entrained in fusion plasma to increase temperature and pressure) and pulsed (fission explosion to confine fusion plasma to very high densities) may also be considered. Finally, lunar and outer planet abundance of ^3He gives further impetus for exploration(Santarius 1992) and provides a key motivation for sustained lunar missions and infrastructure development.

A historical perspective indicates advanced propulsion systems require long lead times for development, giving further merit to beginning now. Flight-weight aircraft engines took about 15 years to develop(Anderson 1999). In the late 1800's it was accepted that a flight-weight reciprocating engine was required to enable human flight. Wright brothers developed a barely adequate engine (12 hp/140 lb), but combined with adequate aerodynamics and phenomenal propellant efficiencies (70%), the flight was a success(Anderson 1999). The jet engine also took about 15 years(Anderson 1995). Frank Whittle proposed turbofan engine in 1928 and it received little interest. The Messerschmitt Me 262 started mass production in 1942(Anderson 1995). Liquid propellant rocket engines, however, required about 30-45 years(Sutton and Bilbarz 2001). Theorized by Tsiolkovsky in late 1890's, the first test flight was performed by Goddard in 1929, and not used until 1944 in V-2 rockets(Sutton and Bilbarz 2001). Electric propulsion thrusters required about 40 years of development time. First proposed in the 1950's by several authors(Choueiri 2004), the first flight of an ion thruster for main propulsion was Deep Space 1 in 1990's. Given the development times, if NASA begins NOW, it may be able to utilize fusion in 40-50 years. If NASA fulfills the shorter term goals of sustained lunar and Martian exploration, then the timing may be 'just right' for deeper space manned exploration, taking advantage of existing lunar and Martian infrastructure.

FUSION TECHNOLOGY TRADE SPACE

If NASA begins now with a fusion propulsion program, the following questions should be asked:

1. What has already been done?
2. What missions can be accomplished with fusion?
3. What is an appropriate plan for a development program?

Perhaps the most important answer to question 1 is that there was a 20 year program at NASA-Lewis on fusion energy for space power and propulsion from 1958 to 1978(Maslen 1959; Schulze 1991). Some of the fusion-related accomplishments and program areas covered included (Schulze and Roth 1991) basic research on MFE fusion confinement, the first superconducting magnet facility to be used in fusion, steady state neutron production, studies of direct conversion of plasma enthalpy to thrust for a fusion rocket, power and propulsion system studies, high-field superconducting and cryogenic magnet technology, and mission analysis and system studies of fusion propulsion systems for interplanetary missions. More progress was made between 1978 and 1991, mostly in the form of conceptual studies by plasma physics researchers in the field. Much of that work is detailed in a comprehensive technical memorandum by Norman Schulze(Schulze 1991). Other studies have been carried out since then, and some performance results from that work are summarized below in Table 1. In a future work, we may elaborate on these concepts, or other authors may use this as a starting point.

Below Table 1, we map fusion technologies of interest in a 4D parameter space of density, confinement time, vehicle mass, and specific power in an attempt to show the vast parameter space that must be explored in order to determine interesting concepts for propulsion. The confinement time is calculated using a Lawson criteria for T = 10keV DT plasma. Because each fusion concept represented on the chart reflects the bias of the authors in each study, there is much difficulty in assessing which concepts are better for propulsion. It shows that there needs to be a common set of tools to objectively assess the merits of all of these concepts. Once this is done, mission analysis can be performed using some of the more promising concepts.

Table 1. Summary of recent fusion propulsion approaches, including specific power (α), confinement particle number density (n), pulse frequency if applicable, vehicle mass, and author. To the authors' knowledge, the values in this table reflect the most recent paper for each concept.

Concept	α (kW/kg)	n (#/m^3)	Freq. (Hz)	Mass (mT)	Source
Steady State					
Quiet Electric Discharge (QED)	12	n/a	n/a	500	(Bussard and Jameson 1994)
Inertial Electrostatic Confinement (IEC)	0.02	n/a	n/a	300	(Miley, Satsangi et al. 1994)
Gas Dynamic Mirror (GDM)	10	1.0×10^{22}	n/a	1225	(Emrich 2003)
Tandem Mirror (SOAR)	1.2	5.0×10^{19}	n/a	1220	(J.F. Santarius 1998)
Spheromak	5.75	8.0×10^{20}	n/a	1050	(Borowski 1994)
Field Reversed Configuration (FRC)	1	1.0×10^{21}	n/a	1100	(H. Nakashima 1994)
Colliding Beam FRC	1.5	5.0×10^{20}	n/a	33	(Cheung, Binderbauer et al. 2004)
Dipole	1	1.0×10^{19}	n/a	1300	(Teller, Glass et al. 1992)
Spherical Torus	8.7	5.0×10^{20}	n/a	1630	(Williams, Dudzinski et al. 2001)
Pulsed					
Inertial Fusion Rocket (IFR)	70	1.0×10^{25}	100	760	(Borowski 1994)
Inertial Confinement Fusion (ICF)	3.4	1.0×10^{25}	30	5800	(Orth and al. 1987)
Magnetized Target Fusion (MTF)	1.12	1.0×10^{26}	20	890	(Thio, Freeze et al. 1999; G. Statham 2003)
Magneto-Kinetic Expansion (MKE)	2.2	1.0×10^{24}	10	67	(Slough 2001)

MISSION ANALYSIS

Figure 2 illustrates the different mission regimes by category. It is expected that fusion propulsion will be overpowered for the closer missions to LEO and Lunar space. However there are good reasons to believe that fusion will enhance missions to the inner planets. In fact, for continuous exploration of Mars (such as the case if we establish a Martian base) fusion propulsion will be required to give access to Mars at non-optimal departure and arrival points.

Beyond Mars fusion propulsion is essential for crewed exploration. Defense of this assumption is given in Adams et al. 2003. The referenced study considered crewed missions to Jupiter's moon Callisto. Non fusion options were marginal to achieve this mission and trip times exceeded 5 years. The long duration mission made limiting crew radiation exposure problematic. Figure 3 illustrates the vehicle trajectory for a Callisto vehicle using Magnetized Target Fusion. Here the entire mission is accomplished in 654 days. An illustration of the MTF Callisto vehicle is given in Figure 4.

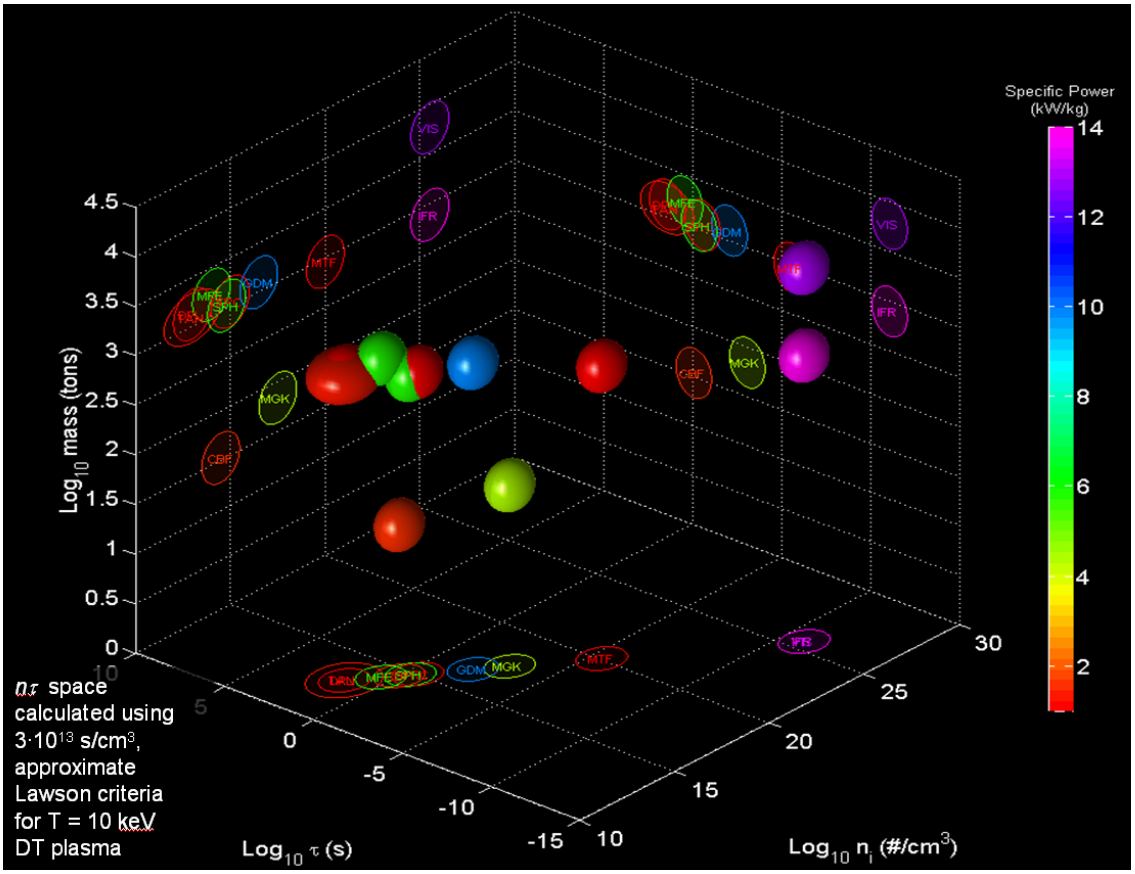

Fig. 1. Map of fusion propulsion concepts in a 4D parameter space of density, confinement time, vehicle mass, and specific power. Performance values can be referenced in Table 1 above. The confinement time is calculated using a Lawson criteria for T = 10keV DT plasma.

PROPOSED OUTLINE FOR FUTURE EFFORTS

Definition of actual funding levels were suggested in our series of discussions last fall, but were considered premature at this time. However, to sustain a research program, funding levels for the next few years are expected to be in the 2-10 million dollar range. Initial objectives should include deeper research into DOE efforts and how they can be adapted for NASA's purposes, research announcements soliciting ideas for developing benchmark experiments, periodic workshops with the fusion community to create a fusion propulsion system development roadmap, review of research developments, development/enhancement of analytical codes to further system design and development, emphasis on coordinating code and experimental work to be broadly applicable to the wide range of fusion propulsion concepts, and coordinated efforts with common technology requirements for other propulsion systems (NTP, NEP, etc.). Funding should be ramped up as appropriate, with comparatively low levels in the first decade so as to not have deleterious effects on more near term programs such as lunar and Martian exploration, and significant funding increases once fusion technologies are understood well enough for development of a working prototype for space propulsion. One item unanimously agreed upon during the discussions: NASA must start now!

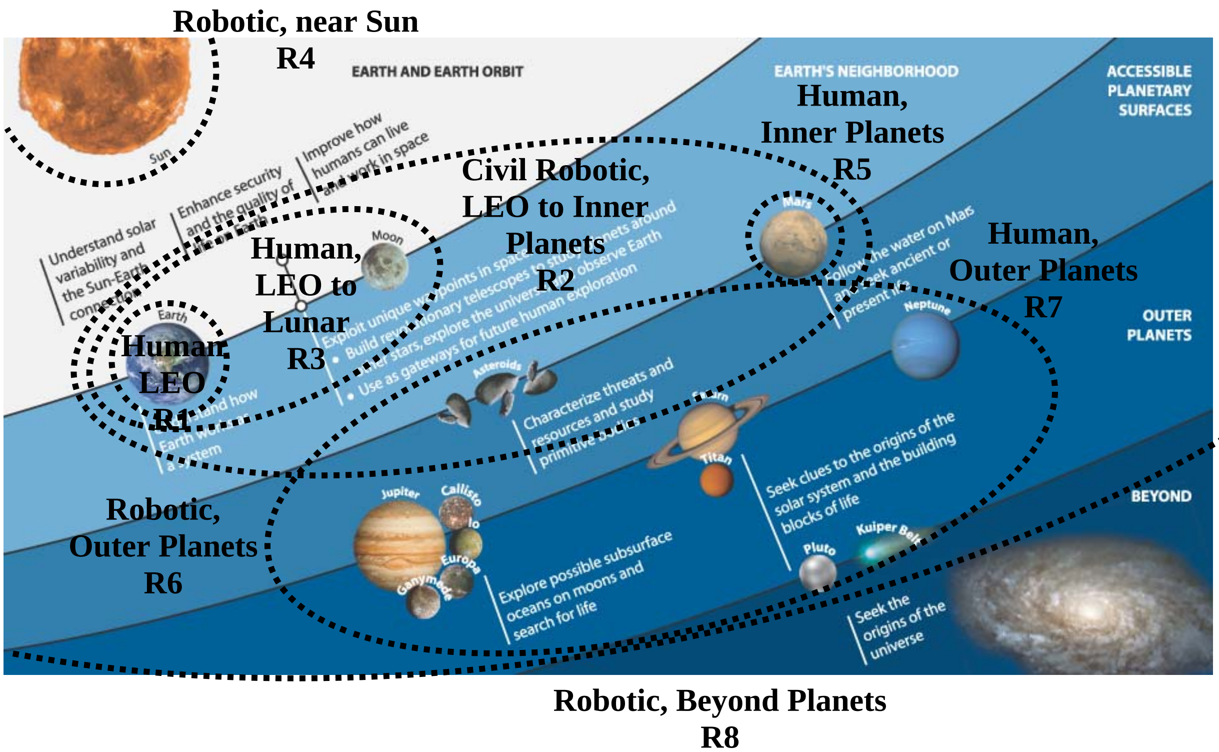

Fig. 2. Categorization of crewed and robotic missions of interest to NASA.

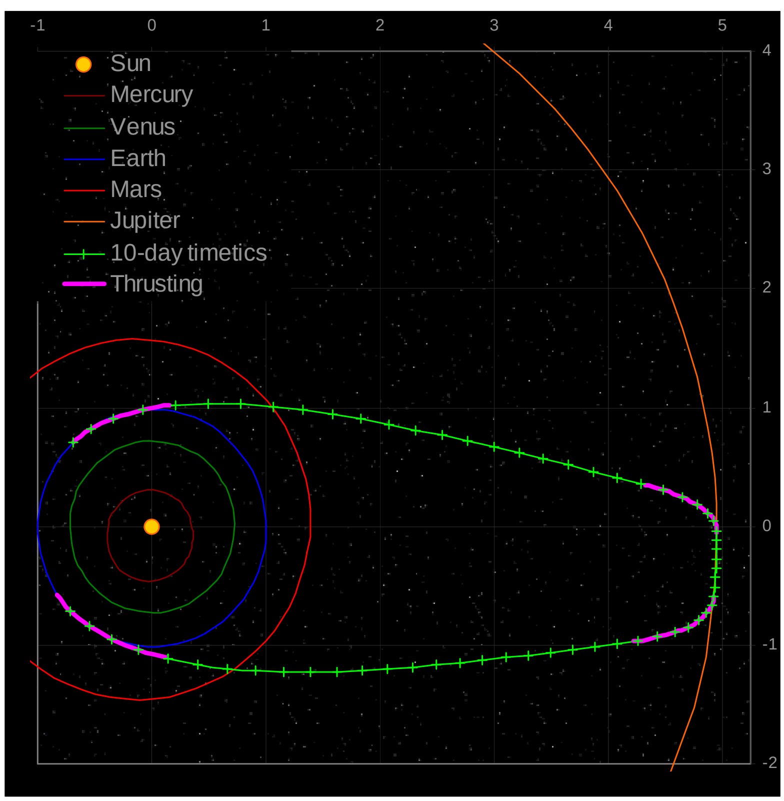

Fig. 3. Trajectory plot of representative crewed mission to Jupiter's moon Callisto using MTF. Pink lines indicate thrusting times and green lines indicate coasting times.

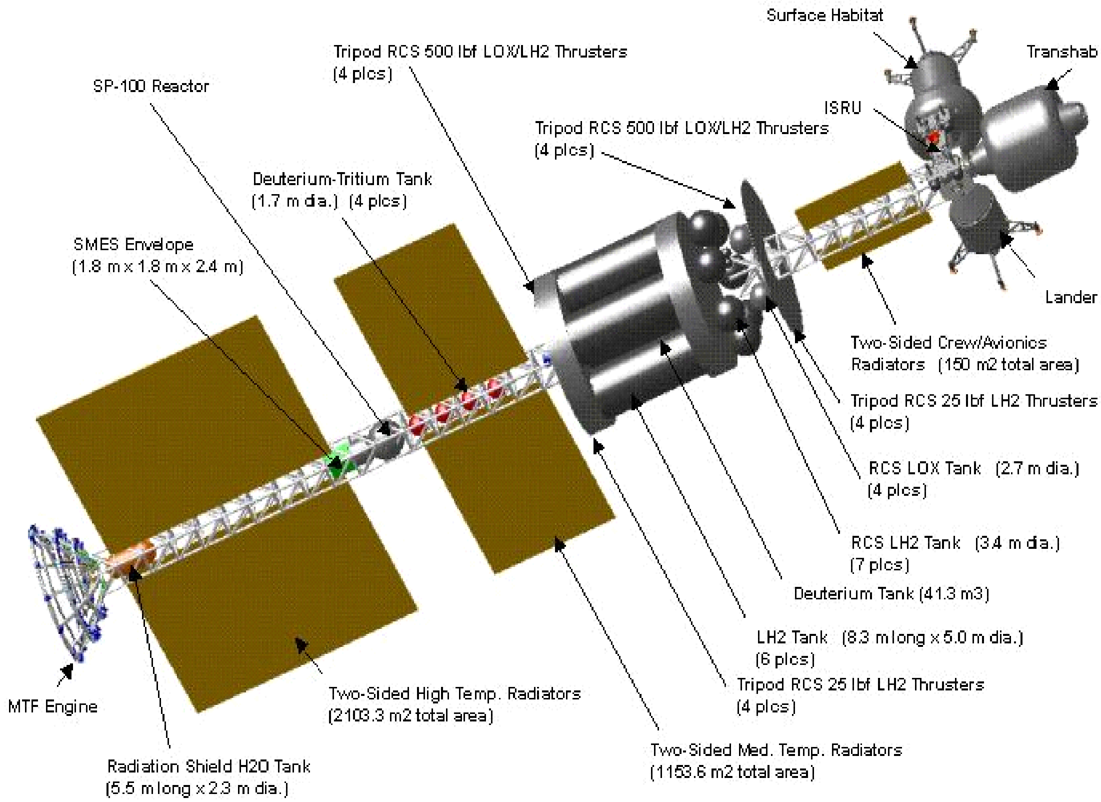

Fig. 4. Layout of the MTF crewed vehicle for a round trip mission to Callisto. Vehicle is self contained with crew transhab, lander, ISRU plant and surface habitat on vehicle.

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