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Direct Fusion Drive for a Human Mars Orbital Mission

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The Direct Fusion Drive (DFD) is a nuclear fusion engine that produces both thrust and electric power. It employs a field reversed configuration with an odd-parity rotating magnetic field heating system to heat the plasma to fusion temperatures. The engine uses deuterium and helium-3 as fuel and additional deuterium that is heated in the scrape-off layer for thrust augmentation. In this way variable exhaust velocity and thrust is obtained.

This paper presents the design of an engine for a human mission to orbit Mars. The mission uses NASA's Deep Space Habitat to house the crew. The spacecraft starts in Earth orbit and reaches escape velocity using the DFD. Transfer to Mars is done with two burns and a coasting period in between. The process is repeated on the return flight. Aerodynamic braking is not required at Mars or on the return to the Earth. The vehicle could be used for multiple missions and could support human landings on Mars. The total mission duration is 310 days with 30 days in Mars orbit. The Mars orbital mission will require one NASA Evolved Configuration Space Launch System launch with an additional launch to bring the crew up to the Mars vehicle in an Orion spacecraft.

The paper includes a detailed design of the Direct Fusion Drive engine. The engine startup/restart system and shielding are discussed. The computation of the specific power for the engine is presented along with a full mass budget for the engine. The paper includes the trajectory design and mission simulations.

I. INTRODUCTION

Human missions to the planets have been planned since before the engine of the Apollo program in the early 1970's. At that time the most advanced propulsion option was nuclear fission thermal rockets which heat hydrogen flowing through a reactor core. Several of these engines were tested in the late 1960's and early 1970's, before the fission engine programs were canceled.

Recent work reports that the radiation data the Curiosity rover collected on its way to Mars found "astronauts traveling to and from Mars would be bombarded with as much radiation as they'd get from a full-body CT scan about once a week for a year." [1]. Add to that the harmful effects of muscle atrophy from long-term low-gravity, the mission speed becomes a clear priority to ensure the crew's health. Consequently, chemical or nuclear thermal rocket transfers would not be sufficient for human exploration to Mars and more distant destinations. A DFD-powered transfer stage could get astronauts to Mars in months, significantly reducing radiation exposure and atrophy effects.

To demonstrate the potential of DFD technology, we developed a concept for a Mars orbital mission that uses NASA's Deep Space Habitat to house the crew [2]. Previous work demonstrated its capability for asteroid deflection [3], robotic missions [4, 5], missions to the outer planets [6] and interstellar missions [7].

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With a variable thrust augmentation system, the DFD is ideal for interplanetary exploration. The Orion spacecraft would launch the astronauts into low Earth orbit where it would dock with the DFD transfer vehicle. The baseline vehicle is shown in Figure 1 docked with the Orion. It has six 11.5 MW engines. This provides redundancy and an abort capability in case of an engine failure. The engines provide both propulsion and electric power during the mission.

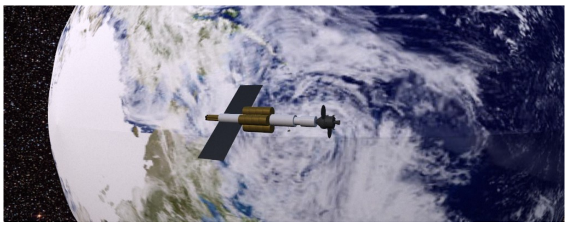

Figure 1: Orion spacecraft docked with the Deep Space Habitat on the DFD transfer vehicle.

II. DIRECT FUSION ENGINE DESIGN

Overview

The Princeton Field-Reversed Configuration Reactor (PFRC-R) would be a 2 m diameter, 10 m long, steady-state plasma device heated by a novel radio-frequency (RF) plasma-heating system, enabling the achievement of sufficiently high plasma temperatures for D–^{3}He fusion reactions. An FRC employs a linear solenoidal magnetic-coil array for plasma confinement and operates at higher plasma pressures, hence higher fusion power density for a given magnetic field strength than other magnetic-confinement plasma devices. A linear solenoid is well-suited for producing a collimated directed exhaust stream that may be used for propulsion. A rocket engine based on the PFRC is designed to operate with a D–^{3}He fuel mixture though, for decade-long missions, it may be operated with a tritium-suppressed D–D fuel cycle. Both fuels produce much lower levels of neutrons than deuterium-tritium, reducing shielding mass as well as waste energy unavailable for propulsion. In the PFRC-R, waste heat generated from bremsstrahlung and synchrotron radiation will be recycled through the RF system to maintain the fusion temperature. The features of this design are:

1. Odd-parity rotating magnetic field (RMF) heating for high stability and efficient heating
2. Can operate with D–^{3}He or tritium-suppressed D–D
3. Combined thrust and electric power generation
4. Variable specific impulse and thrust through deuterium augmentation in the scrape-off layer
5. High temperature superconductors for plasma confinement and the magnetic nozzle that result in drastically reduced cooling requirements
6. Engines are an ideal power range for space power and propulsion
7. Multiple engines can be combined to produce higher levels of thrust and power

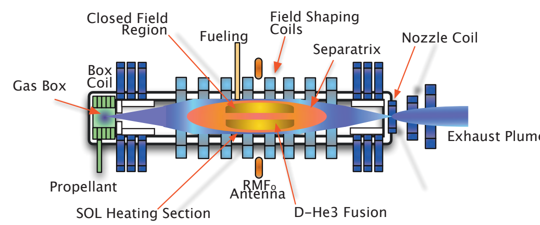

Figure 2: Schematic of the DFD core. Deuterium gas, introduced in the gas box, is ionized there. This newly formed plasma flows to the right in the scrape-off layer (SOL) where the electrons are heated as they pass over the FRC region. This gas-feed process augments the mass flow and increases the thrust, at the cost of reduced specific impulse. The white region is neutron shielding, predominantly for the coils.

Reactor

An important figure-of-merit for fusion reactors is β, the ratio of the plasma pressure to the magnetic energy density. Of all candidate magnetic-confinement fusion reactors, FRCs have the highest β, see [8] for a review of early FRC research. Accordingly, FRC magnets would be less massive than those for a tokamak of comparable power. High β is essential for burning aneutronic fuels, such as D–^{3}He, because they require higher ion energies to achieve the same fusion reactivity as D–T. FRC plasma-confinement devices have at least two other attractive features, notably, a linear magnet geometry [8] and a natural divertor. This structure provides an ideal attachment point for a magnetic nozzle, allowing for the control of the plasma exhaust and its plume angle, for use as a propulsive or power-producing device. The FRC is unique among quasi-toroidal, closed-field-line magnetic confinement devices in that it is simply connected. FRCs also have zero toroidal magnetic field, no internal conductors, and a line of zero magnetic field strength within the plasma encircling its major axis, termed the O-point null line. This O-point null line proves essential for our proposed method of RF plasma heating. Figure 2 shows the FRC's magnetic-field structure and the linear coil array. A separatrix divides a closed-field region (CFR) from the open-field region (OFR). Field-shaping coils that are magnetic flux conservers surround the plasma. The O-point null line, not shown, is a ring, co-axial to the magnetic axis and located on the midplane of the nearly elliptical CFR.

The reactor design we propose differs from that of Cheung [9] in size, heating method, and fuel. Cheung *et al.* selected p–^{11}B, which requires five-times higher ion energies and produces far less fusion power *per* reaction. Cheung *et al.* selected neutral beams for heating, requiring a plasma volume that is one hundred times larger, and is therefore more costly and less stable. The heating technique selected in Miller [10] is called an even-parity rotating magnetic fields (RMF_e) [11], a method that has shown poor energy confinement, and requires larger FRCs. FRCs where the plasma radius is more than 10 times their ion Larmor radius are prone to magnetohydrodynamic (MHD) instabilities. To achieve better energy confinement, we instead invented odd-parity RMF, RMF_o, allowing for smaller, more stable reactors.

Many physics challenges remain before the RMF_o-heated FRC can be developed into a practical reactor. The predictions of excellent energy confinement and stability and of efficient electron and ion heating to fusion-relevant temperatures, must be validated. Substantial progress has occurred in the first three areas. In 2010 and 2012, TriAlpha Energy Corp reported near-classical energy confinement time in their FRC [12, 13]. (Classical confinement time occurs for Coulomb-collision-driven diffusion only. The confinement time of real plasma is often far less than the classical limit [14].) Our reactor needs energy confinement only $1/5$ as large as the classical. In 2007, an RMF_o-heated FRC [15] achieved stable plasma durations 3,000 times longer than predicted by MHD theory [16]; by 2012 that record was extended to over 10^5 times longer. Finally, theoretical studies [17, 18, 19] indicate that RMF_o will be able to heat plasma electrons and ions to fusion relevant temperatures. These are promising starts, but much research is needed at higher plasma temperatures and densities, and with burning, *i.e.* fusing, plasmas.

Based on $1/5$-classical-confinement, a plasma radius of 30 cm is adequate for confining the high energy plasma needed to produce 11.5 MW of fusion power. This radius matches criteria set by the RMF_o heating method.

Figure 3 shows the central vacuum vessel section of the PFRC-2 experiment at PPPL. This vessel section vessel is made of Lexan. The BN-covered superconducting flux conserving coils are visible in the interior. The experiment is shown in operation in Figure 4. No shielding is needed for the PFRC-2 as it forms hydrogen plasmas, hence does not produce neutrons.

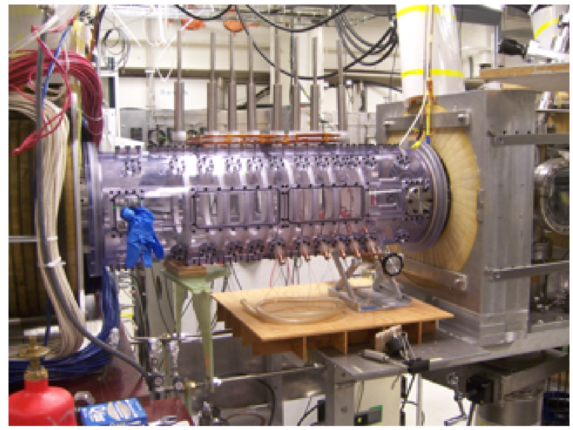

Figure 3: PFRC-2 device during assembly.

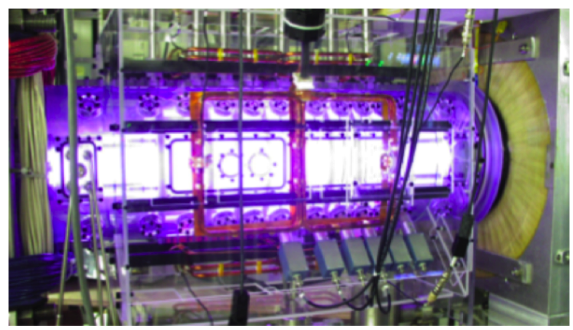

Figure 4: PFRC-2 device during operation.

Engine Design

Figure 5 on the following page gives the major subsystems of the engine. On the left is the gas box. The gas box is for the thrust augmentation. The amount of gas put is there is, atom-for atom, about 10,000 to 100,000 times larger than the ^{3}He burn up rate. The D and ^{3}He injectors are shown above the gas box. On the right is the reactor core consisting of the field-reversed configuration plasma confined by superconducting coils. It also includes the RMF_o system and the shielding and cooling systems. On the right of the FRC are the coils for the magnetic nozzle which directs the flow and allows plasma detachment from the field lines for directed thrust. The high temperature superconducting coil blanket is cooled by a refrigeration system that only handles residual heat from the reactor. Below the reactor is the helium coolant stream that drives the heat engine. The heat engine powers a generator that produces electricity for the engine subsystems.

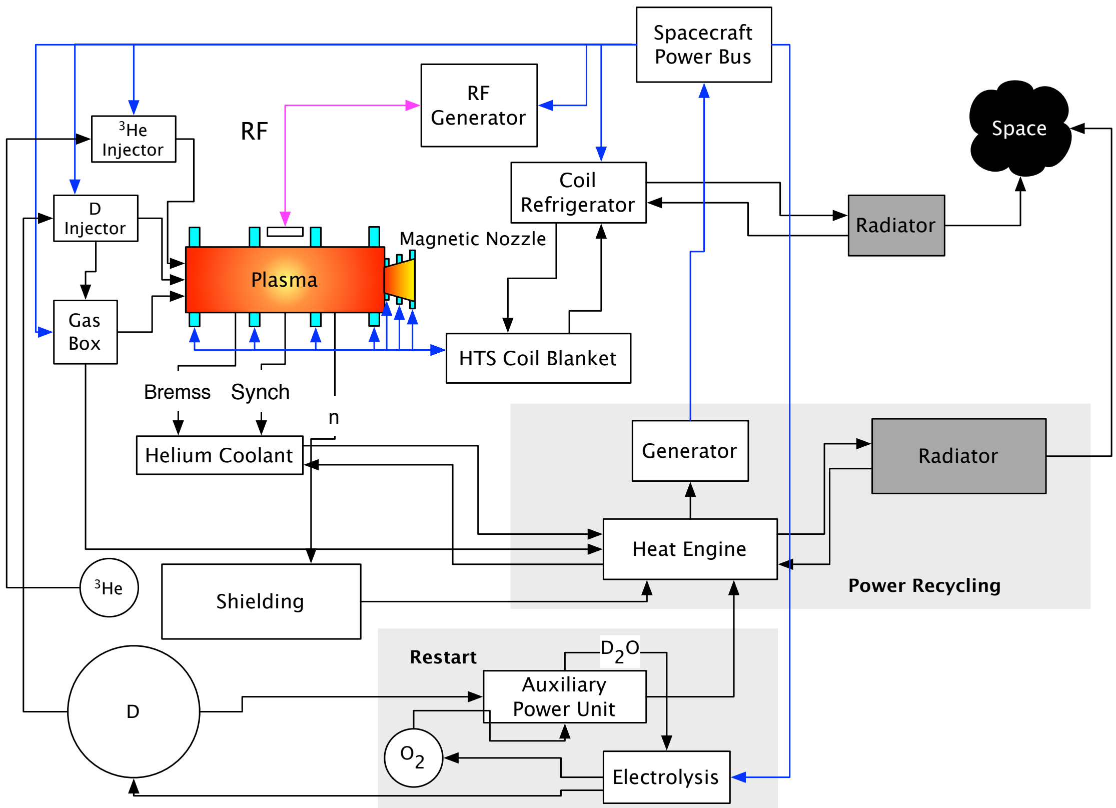

Figure 5: Direct Fusion Drive subsystems.

Should an engine shut down, a combustion engine produces short term heat to drive the heat engine for startup power. Waste heat flows to the radiator system. The RMF_o system is driven by the RF generators in the upper right. Left-over power is used to power the spacecraft systems.

Magnetic field lines from the gas box pass close to the core plasma. This, the scrape-off layer, (SOL), is approximately 5 cm thick. Between the SOL and the neutron shielding is a 5-cm-thick vacuum space. The neutron and X-ray shielding protect the magnet coils and RMF_o antenna from radiation damage. Note, no high-integrity vacuum vessel is needed around the core plasma because the vacuum of space.

Thermal power from synchrotron and Bremsstrahlung radiation can also be converted to electrical power using a Stirling cycle power generation system, [20]. Studies show that it has the best specific power of all thermal energy conversion systems. Other options are using a Brayton cycle ([21]) and direct conversion methods ([22]). Power can also be extracted using the RF system.

The magnetic nozzle and thrust augmentation systems allow directional control of the plasma and control of the thrust level and exhaust velocity. A magnetic nozzle, as described by [23], [24], and [25], redirects the flow from the FRC to free space. The nozzle consists of a throat coil and two or more additional nozzle coils to allow expansion and plume control of the flow. All the coils are superconducting but the radii of the magnetic nozzle coils are smaller than those in the reactor core. Magnetic nozzles have been found to be highly efficient, especially with weakly magnetized propellants, with a plume efficiency greater than 85% cited in [26].

Table 1 on the next page gives operating parameters, masses and power numbers for the engine for the DFD transfer vehicle. The specific power is greater than 1 kW/kg which is in line with other studies.

Table 1: DFD transfer vehicle engine design

Parameter	Value	Units
Area radiator	180.32	m^2
Beta	0.88	
Gain	23.23	
Magnetic field	5.4	T
Mass total	4437	kg
Number density D	1.40e+20	
Specific power generation system	0.001	kg/W
Structural fraction	0.20	
Temperature D	100.0	kEV
Specific mass heating system	0.000	kg/W
Mass		
Mass heating	550.00	kg
Mass magnet	516	kg
Mass power generation	468.00	kg
Mass radiator	378.67	kg
Mass refrigerator	52	kg
Mass shield	1733	kg
Mass structure	739	kg
Power		
Number density e-	7.00e+20	
Power Fusion Losses	7.80	MW
Power RMF Into Plasma	0.50	MW
Power RMF_0	1.10	MW
Power bremsstrahlung	2.05	MW
Power electric	4.68	MW
Power fusion	11.50	MW
Power into the gas box	1.00	MW
Power net electric	3.58	MW
Power per unit radiator area	0.02	MW/m^2
Power synchrotron	4.57	MW

The DFD power balance is illustrated in Figure 6. About 36% of the power is available for propulsion and 17% is available for spacecraft electric power. Note that the specific power is based on the fusion power generated. If we used the thruster power it would be 0.425 kW/kg. The trajectory numbers used the total power as the basis for the mass calculations.

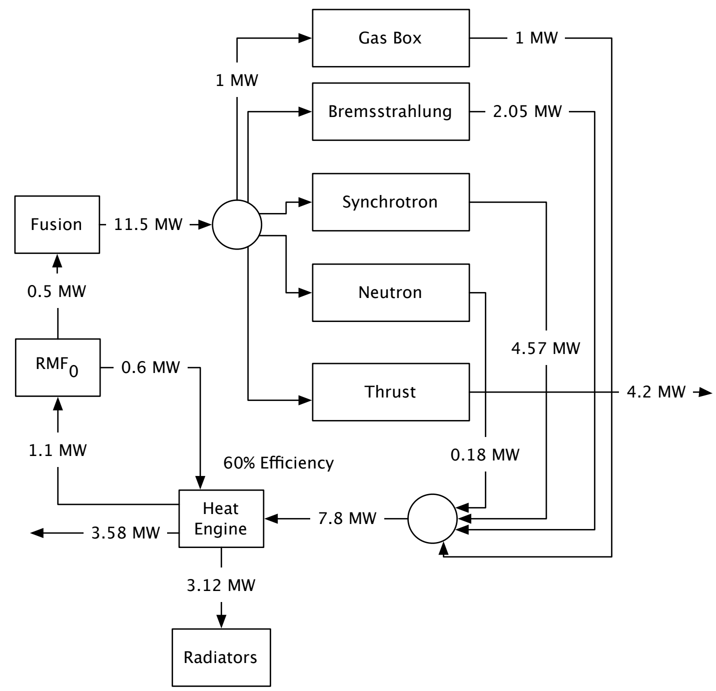

Figure 6: DFD Power balance

Shielding

The shielding system uses a 0.64 cm thick layer of tungsten to absorb the bremsstrahlung x-rays and a 20 cm layer of $^{10}B_4C$ for neutron shielding. The heat from the bremsstrahlung is absorbed by helium gas flowing past the tungsten. The tungsten would reach a temperature of 2000 K and ultimately be rejected to space by the radiators at 625 K. Figure 7 shows the shielding geometry.

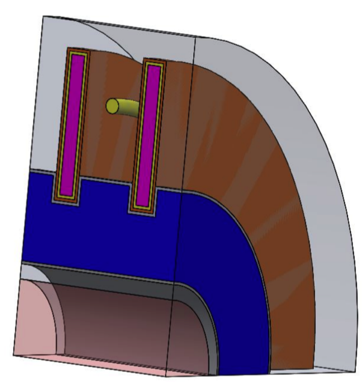

Figure 7: Shielding.

The shielding system was analyzed using Attila, a particle simulation code that solves problems in space, angle and energy. Research to date has only included neutrons from D-D reactions. D-T reactions will be avoided by rapid loss of the T product from one branch of the D-D reaction.

Startup Power

Chemical combustion will be used to produce the power necessary power for starting the reactor. A few 10's of kilograms of H_2, which produces 142 MJ each when combined with O_2, is enough for start up. The power released from this reaction first energizes the superconducting coils, and then heats the plasma through the RMF_o system. This startup system needs to run for approximately 100 seconds, hence is sized at 2 MW. The heat engine and incorporated generator would be used with this additional heat source. The O_2 would be recovered through electrolysis if necessary. During the mission if one engine shuts down, one of the other engines would be used to startup the shutdown reactor.

III. SPACECRAFT DESIGN

Overview

The Mars Transfer Vehicle with a docked Orion capsule is shown in Figure 8. The module to which the Orion is docked is the NASA Deep Space Habitat shown in Figure 9. To house the astronauts for over 300 days, our mission uses the 500 day configuration of NASA's Deep Space Habitat (DSH). The habitat is module-based, similar to the International Space Station. The DSH will consist of a Habitation module incorporated with a Multi-Purpose Logistics Module (MPLM). The module will provide for living quarters, storage areas, science stations, an Environmental Control and Life Support System (ECLSS), a galley for food preparation, a Waste Hygiene Compartment, microwave, refrigerator, exercise equipment, and anything else necessary for the astronaut's survival [2]. The habitat will also provide all the necessary food and water, and the crew quarters will provide protection against a Solar Particle Event [2]. In addition, the habitat will have a docking station for the Orion spacecraft. Figure 9 shows the 500 day configuration schematic.

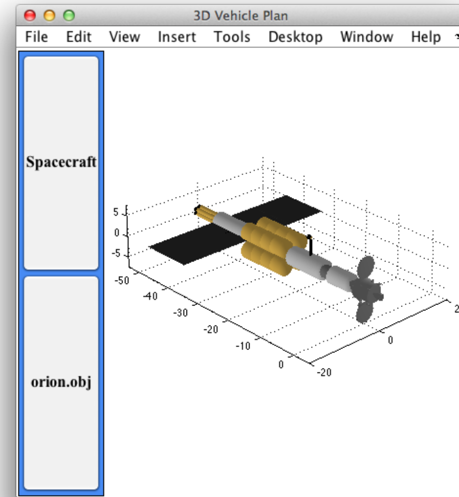

Figure 8: Mars transfer vehicle.

Configuration

The six engines are at the far end of the transfer vehicle. The gray cylinder houses the attitude control actuators, heat engines, reaction control system, plumbing for the radiators and supporting systems. The radiators are attached to this structure. The attitude control actuators would be control moment gyros (CMGs). Momentum will build up in the CMGs due to external disturbances and thrust vector misalignments with the center-of-mass. Momentum unloading, that is removal of the excess momentum in the CMGs, would be accomplished by tilting the DFD exhaust plasmas and using the reaction control system. The four tanks shown contain deuterium. The helium-3 tank is nestled between the tanks. A truss structure supports the tanks. The NASA Deep Space Habitat is connected to the truss. An Orion spacecraft is shown docked to the end of the Deep Space Habitat. The Orion would not accompany the transfer vehicle to Mars. A high gain antenna is mounted on the spacecraft.

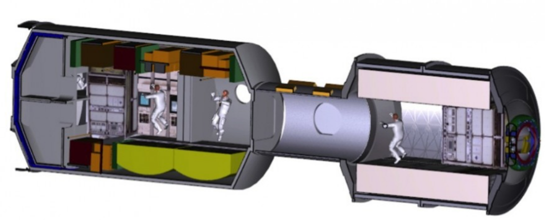

Figure 9: NASA Deep Space Habitat

Mass Budget

Table 2 gives the mass budget for the DFD transfer vehicle. The masses are for the components of the engine. Fuel mass is not included. The magnet mass is computed using the virial mass theorem [27] that estimates magnetic mass from the material density, induced stress, magnetic field, and the radius of the magnet. Other component masses are estimates based on similar hardware.

Table 2: DFD transfer vehicle mass budget. The Orion spacecraft would not be carried on the SLS launch.

Component	Mass	Units
Orion.obj Subsystem Total	1.535e+04	kg
ECLS Subsystem Total	3.988e+04	kg
Propulsion Subsystem Total	8.981e+04	kg
Telemetry and Command Subsystem Total	14.62	kg
Miscellaneous Subsystem Total	1700	kg
Total	1.468e+05	kg

IV. MISSION DESIGN

Launch

The Mars mission uses the NASA Space Launch System for launch into low Earth orbit. NASA's Space Launch System is an advanced, heavy-lift launch vehicle which will provide an entirely new capability for science and human exploration beyond Earth's orbit. The SLS has two variants, 70 MT (metric tons) and 130 MT. The Mars orbital mission will require one 130 MT SLS launch, as the spacecraft weighs 129 MT. A separate launch brings the crew to the spacecraft in an Orion spacecraft. On-orbit testing and checkout is done prior to the arrival of the crew.

Alternatively, the Mars mission could use SpaceX's Falcon Heavy launch system for launch into low Earth Orbit. The Falcon Heavy is capable of launching 53 MT. The DFD transfer vehicle could therefore be sent to low Earth orbit in three launches and assembled in space. Once launch would consist solely of 53 MT of fuel. Another launch would consist of the remaining 4 MT of fuel along with the approximately 40 MT Deep Space Habitat. The final launch would consist of the remaining structure including the DFD engines, radiator core, and truss which would weigh about 32 MT. The astronauts could be sent up in this final launch as well in the Orion spacecraft or in SpaceX's Dragon capsule. This is an interesting option to consider as it is predicted that three Falcon Heavy launches might be cheaper than one 130 MT SLS launch.

Earth/Mars Transfer

The round-trip mission to Mars, with a spacecraft powered by DFDs and carrying NASA's Deep Space Habitat, involves two orbit transfers which involve a long burn, a coasting period and another long burn. The spacecraft enters and departs Earth and Mars orbits using the DFD. No aerodynamic braking is required.

This double-rendezvous problem typically requires waiting for a full synodic period (i.e. the next time the two planets return to their current alignment), which is 780 days for Earth and Mars. The goal, however, is to make this roundtrip as quickly as possible. Therefore, the new roundtrip trajectory takes a "short-cut" of sorts, traveling inside Earth's orbit on the return flight. This enables the overall mission to be shortened to just 310 days, including a 30 day stay in Mars orbit. The trajectory is shown in Figure 12.

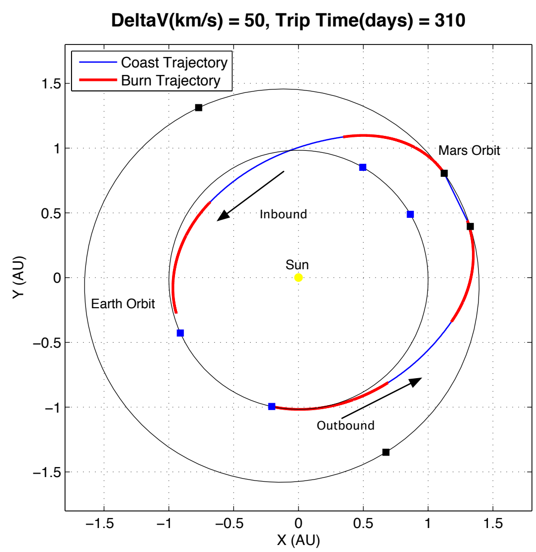

Figure 12: A round trip mission to Mars takes only 310 days including 30 days in Mars orbit.

V. CONCLUSION

Direct Fusion Drive permits a high scientific return human mission to Mars Orbit in the 2030 time frame which is compatible with the SLS schedule. The DFD transfer vehicle would form the basis of future space

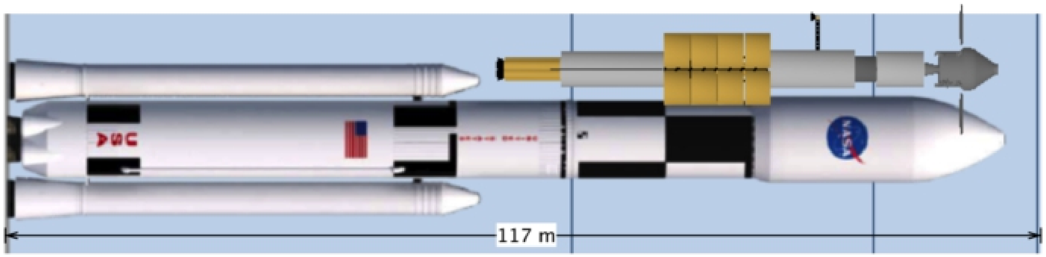

Figure 10: SLS 130 MT variant with the Mars spacecraft superimposed.

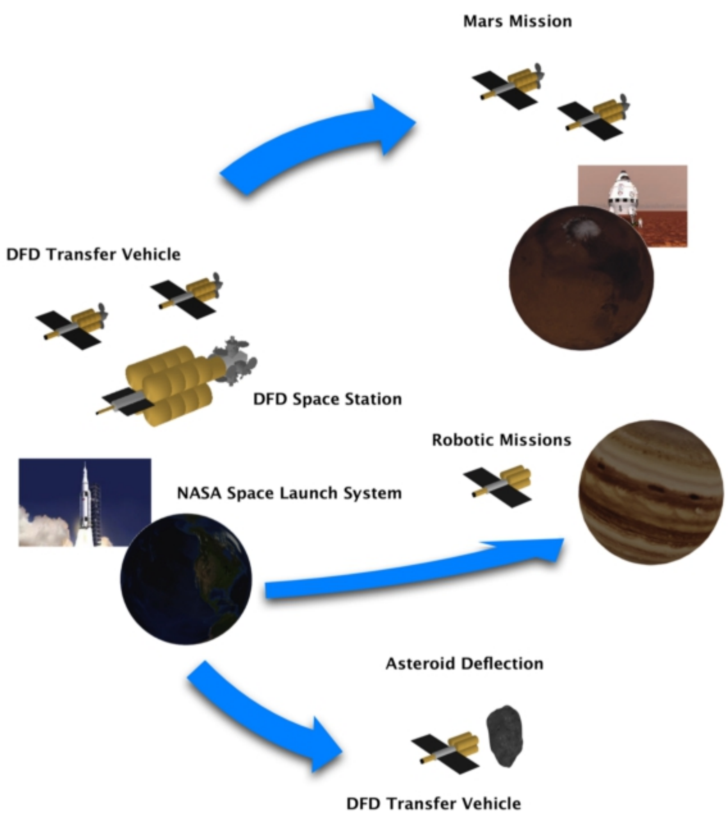

Figure 11: Direct Fusion Drive will open space to new avenues of exploration and rapid industrialization.

transportation as shown in Figure 11 on the preceding page. A terrestrial test engine could be in operation within 12 years at a cost of $78M USD, which is comparable to the cost of a single Radioisotope Thermoelectric Generator (RTG).

Near term work will include the completion of the PFRC-2 ion heating experiment, detailed trajectory analysis, and subsystem designs for the engine components. Design of PFRC-3 will begin once the ion heating experiments are complete. This will be larger than PFRC-2 and demonstrate higher temperatures and pressures. PFRC-4 will demonstrate fusion power generation. Additional work will be done on the integration issues of multiple engines, in particular the effect of one engine's field on another.

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