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Fast and Robust Human Missions to Mars with Advanced Nuclear Electric Power and VASIMR® Propulsion

Franklin R. Chang Díaz[1], Mark D. Carter[1], Timothy W. Glover[1], Andrew V. Ilin[1], Christopher S. Olsen[1], Jared P. Squire[1], Ron J. Litchford[2], Nobuhiro Harada[3], Steven L. Koontz[4]

[1]Ad Astra Rocket Company, 141 W. Bay Area Blvd., Webster, TX 77598,
[2]NASA Marshall Space Flight Center, Huntsville, AL 35812
[3]Nagaoka University of Technology, Nagaoka 940-2188, Japan
[4]NASA Johnson Space Center, Houston, TX 77058
Contact: 281-526-0500, aarcinfo@adastrarocket.com

Abstract. Fast, operationally robust Human Missions to Mars, are enabled by high power nuclear electric propulsion. An attractive integrated system can be formed, for example, by combining the features of an advanced high temperature gas cooled nuclear magneto hydrodynamic (MHD) power plant (Litchford and Harada, 2011) with high power VASIMR® plasma propulsion. Light weight (< 10 kg/kWe) reactor and power conversion system concepts have been studied for many years and show great potential when coupled with recent advances in the VASIMR® engine development (> 200 kW, 5000 sec I_{sp}, 72% thruster efficiency, experimentally demonstrated (Longmier, 2011)). This framework for an integrated power/propulsion system has immense relevance to a fast human Mars mission architecture, and an evaluation of this concept has been initiated by a team from the Ad Astra Rocket Company, NASA and Nagaoka University in Japan. Particular attention has been devoted to operational issues, such as major systems failure modes and mission abort scenarios, driven by power and propellant system failures en route. This paper presents the initial results of this investigation, including the salient features of the integrated power/propulsion system and the major mission assumptions, and includes a comparison of the parameter space with current chemical and nuclear thermal propulsion mission options also under consideration.

Keywords: Nuclear Electric Power, Variable Specific Impulse Magnetoplasma Rocket, Human Mission to Mars, MHD Power Conversion.

INTRODUCTION

Human missions to Mars have been the subject of many engineering and scientific proposals through the 20th and the 21st centuries (von Braun, 1962). The most recent NASA study, called the Design Reference Architecture 5.0 (DRA 5.0, Drake, 2009), using Nuclear Thermal Rocket (NTR) propulsion, proposes a roundtrip mission lasting 914 days, including a 539 day stay on Mars' surface and 375 days of in-flight time. The long in-flight time associated with such a mission however results in a high radiation dose to the crew, even when extensive shielding is implemented. Based on "absolute" cancer probabilities, the historical NASA crew annual and career dose limits for middle aged men are ~50 rem/year and 100 rem/career respectively. When the 95% confidence requirement is applied, the career dose drops to 15 rem. Recent published estimates (Cucinotta, 2011) of "safe" days in deep space, defined as maximum number of days with 95% confidence to be below 3% risk of the radiation exposure-induced death (REID) limit during solar minimum with 20-g/cm^2 of aluminum shielding, are 150 days for an average 45 year old US male. This time increases to 198 days for a non-smoker. The exposure from Galactic Cosmic Radiation (GCR) for such long in-flight times far exceeds these dose limits. Therefore, advanced propulsion system technologies that can drastically shorten the in-flight trip times have tremendous value for crew safety.

The general architecture of a nuclear electric power and propulsion system is shown in Figure 1, along with photographs of the 200kW VX-200 VASIMR experimental prototype operating at full power with argon propellant at Ad Astra's research facility in the City of Webster, Texas. This paper shows how such systems, developed to multi-megawatt power levels and low specific mass or α (kg/kW), can reduce the in-flight time dramatically. Advanced magneto hydrodynamic (MHD) power conversion (Litchford, Harada, 2011), combined with high power (> 1 MW) VASIMR propulsion technology (Chang Díaz, 2000) are key elements of the system. The short in-flight times directly reduce or mitigate nearly all the key human health and safety challenges identified in the DRA 5.0. As described below, in addition to reducing the radiation exposure, NEP-VASIMR technology offers robust adaption to problem scenarios en-route, such as partial power or propellant failures, which can be addressed, albeit with an increased flight time, with an in-flight reconfiguration of the VASIMR engines' specific impulse schedule.

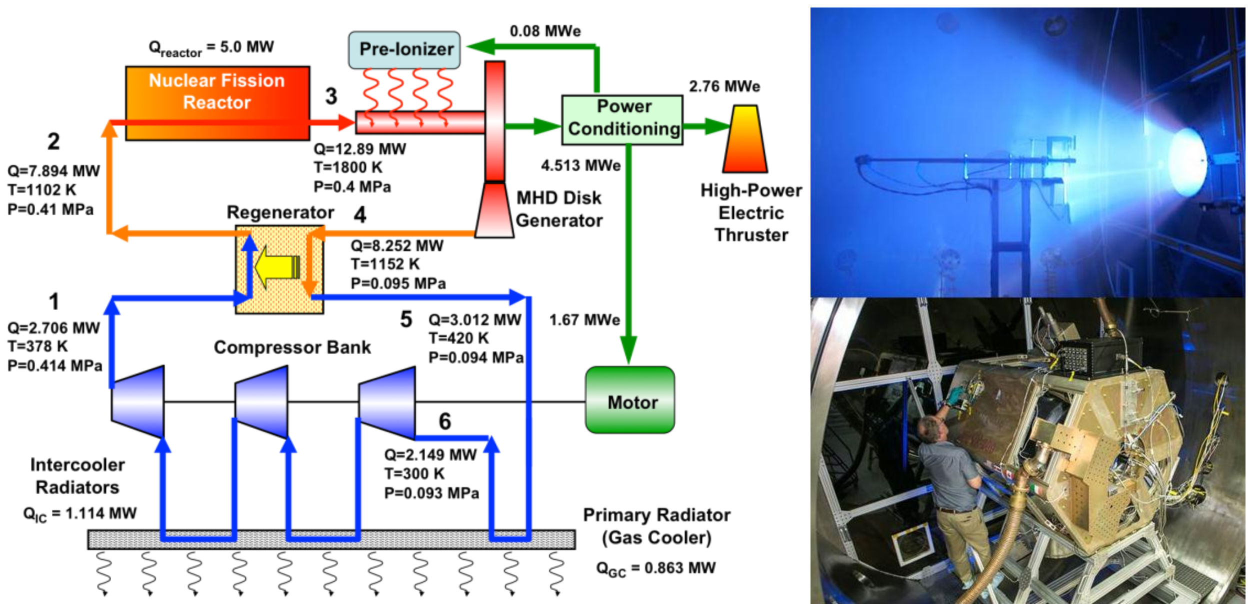

Figure 1. General architecture of a nuclear, multi megawatt MHD-VASIMR system (left) and the 200 kW VX-200 VASIMR prototype engine operating at full power with argon propellant at Ad Astra's Research Facility in Webster, Texas.

Against the backdrop of the DRA 5.0, this paper briefly describes advances in nuclear MHD power conversion and VASIMR technologies that could enable such robust mission scenarios. The majority of the paper presents and discusses mission trajectory results and approximate mass allocation scaling.

ADVANCES IN HIGH POWER NEP SYSTEM

Radiators

Light-weight advanced thermal radiators are required for NEP systems because all waste heat from the energy conversion and propulsion processes must be rejected by thermal radiation to the space environment. Weight reduction for these radiators can be achieved at the most fundamental level by taking advantage of the temperature scaling to the fourth power of the Stefan-Boltzmann law, but the upper limit for the heat rejection temperature is restricted by materials limitations and thermodynamic efficiency for the power conversion. The relevant design parameter for radiators is the mass per unit area of radiating surface. Articulating single-sided space radiators in use today typically operate at about 300 K and range from 6 to 10 kg/m^2. For radiator temperatures of 500 K, the heat rejection capabilities of both sides of the radiator become relatively insensitive to the space environment near or beyond Earth's orbit, so a reduction by a factor of as much as two can be obtained for high temperature radiator designs by using both sides of the radiator to reject heat. Additional weight reduction can be achieved using Carbon-Carbon materials with very high thermal conductivity currently being developed (Juhasz, 2008). All of these advances can be expected to lead to future radiator specific mass values approaching 1 kg/m^2.

Advanced Nuclear MHD Power

Thermodynamic system models can be used to project the mass requirements for power conversion. Several groups have performed such system studies (Anghaie, 2005; Litchford, 2011). For this work, we adapt the power plant concept and modeling approach of Litchford and Harada (2011) for a multi-megawatt closed cycle MHD nuclear plant using non-equilibrium He/Xe frozen inert plasma (FIP) working fluid. Power plant parameter assumptions are as follows:

Reactor	exit temp T_{reac}	exit pressure P_{reac}	Pressure loss ΔP_{reac}	Mass m_{reac}
	1800 K	.4 MPa	.025 MPa	3000 kg

Generator	Enthalpy extraction ratio	Isentropic efficiency	Heat loss	Power density MW/m^3	Magnetic field B_{gen} T	Current density j_c A/m^2	Coil density ρ_c kg/m^3	Density/Stress ρ/s_t kg/kJ
	.35	.8	.01	500	8	10^9	10^4	309
	Xe Seed Fraction	Pre-Ionizer Efficiency	Ionization Pot (eV)					
	.0001	.5	12.13					

Regenerator	Temp difference K	Heat loss	Pressure loss	Efficiency	Surface density β_{reg} kg/m^2	Heat Xfer coeff U_{reg} $W/m^2/K$	Density/Stress ρ/s_t kg/kJ
	50	.01	.01	1	1	500	309

Compressor	Number of stages N_c	Isentropic efficiency $\eta_{s,c}$	Pressure loss	Radiator	Temp T_{rad} K	Pressure loss	Surface density β_{rad} kg/m^2	Emissivity ε_{rad}
	3	.85	.01		600	.01	1	.9

Note, that the fission reactor mass estimate is based on the NERVA design (Holman, 1988) for a 350 MWt nuclear reactor with a mass of 1785 kg. It was increased to 3000 kg here to account for containment and shielding margin.

Multi-Megawatt VASIMR System

Thruster efficiency is also very important for mission requirements. In 2010, Ad Astra Rocket Company demonstrated a thruster efficiency of 72% at specific impulse of 5000 sec using its superconducting VX-200 experimental rocket with argon propellant at power levels up to 200 kW (Longmier, 2012). Early experiments and modeling with krypton indicate that, in the near future, VASIMR will be capable of thruster efficiencies of about 70% for specific impulse ranging from 2000 s to 5000 s. The system parameter assumptions for VASIMR were as follows:

VASIMR	Net power efficiency η_N	Radiator Temp T_{rad} (electronics)	Radiator Temp T_{rad} (rocket core)	Radiator Surface density β_{rad}	RF Power SS mass
	70%	300K	550K	1 kg/m^2	.4 kg/kW

The mass for all other VASIMR subsystems, for power levels between 200 kW and 2 MW, estimated from VX-200 and VF-200 designs, is 1000 kg. For larger power values, the mass is assumed proportional to the input power P, due to clustering of the thrusters. Figure 2 shows the specific mass (α) of the nuclear MHD space power plant and the VASIMR system as functions of total reactor power level. The VASIMR system mass is based on plasma model estimates and experimental data from the laboratory VX-200 experiment, as well as projected masses for the 200 kW VF-200 flight system.

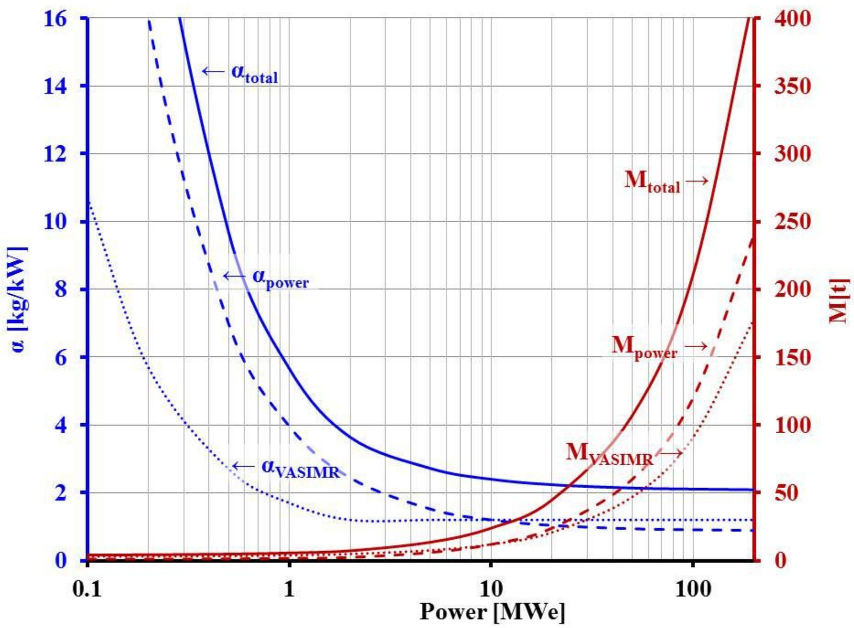

Figure 2. Specific and total mass for the nuclear MHD - VASIMR system

The NEP mass model shown in Figure 2, suggests that an advanced multi-megawatt nuclear MHD-VASIMR system could approach α values of ~2 kg/kW for powers above 10 MWe. As demonstrated in the next section, NEP missions to Mars based on this power and propulsion configuration can outperform NTR missions for total specific mass values as high as 15 kg/kW.

LONG STAY (DRA 5.0-like) HUMAN MISSION TO MARS

This section compares an NEP option as described above with NASA's nuclear NTR-DRA-5.0. In that mission scenario the full vehicle departs from low Earth orbit (LEO, 407 km) with an initial mass of 356.4 t, including a payload (PL) mass of 62 t. Upon arrival at Mars, the ship enters a 1-sol orbit (250 km x 33,793 km) that enables a landing to be attempted. To achieve an effective comparison, the NEP mission was designed preserving the payload mass, departure year and IMLEO as in the DRA 5.0. The NEP trajectory was optimized using the Copernicus interplanetary trajectory software (Ocampo, 2002). Figure 3 shows the resulting trajectory for a power level of 30 MWe and a total α of 2 kg/kW. The NEP mission results in a total in-flight time of 149 days, 226 days shorter than the DRA-5.0. The shorter in-flight time reduces the radiation dose by almost a factor of 3.

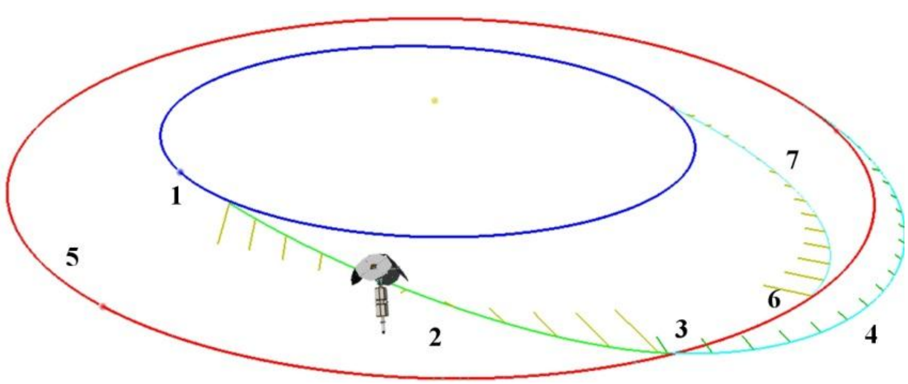

Figure 3. NEP-VASIMR Human Mission to Mars for P = 30 MW, α = 2 kg/kW.

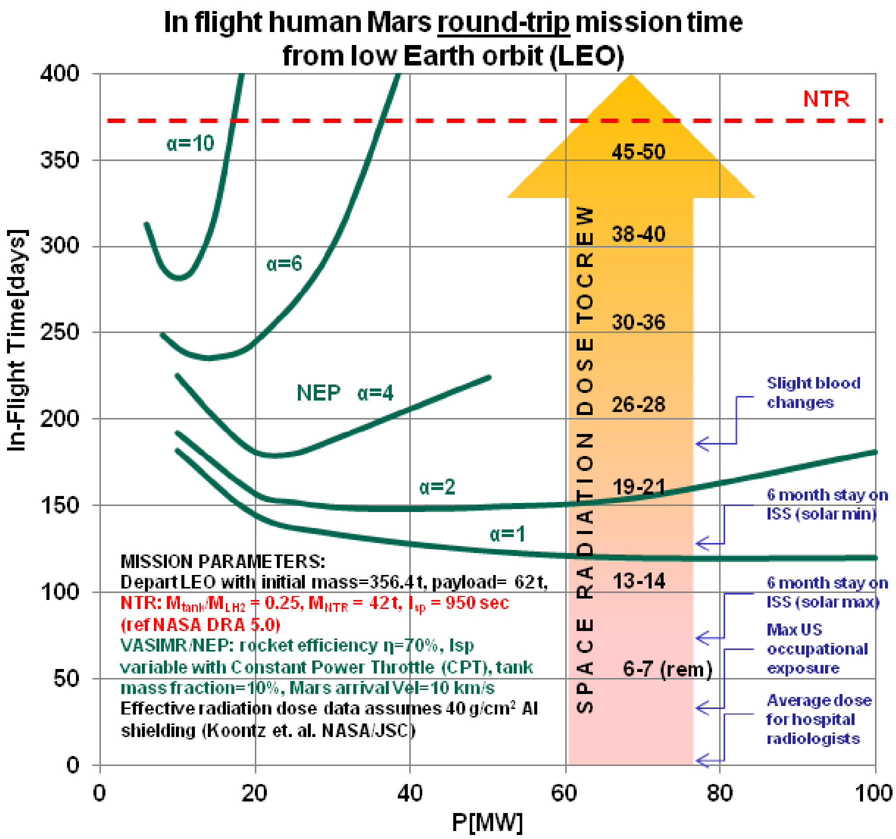

Figure 4. In-flight duration minima vs power for an NEP VASIMR human Mars mission. Increasing radiation doses are also shown for increasing interplanetary transit time. Radiation during surface time is not included.

The trajectory is composed of the following major segments:

1) LEO to Earth sphere of influence (ESOI): The orbital transfer vehicle (OTV) departs on 6/24/2035 from LEO with initial mass IMLEO = 356 t, spiraling to ESOI with a fixed I_{sp} of 2200 sec. The outbound spiral segment takes 16 days and uses 120 t of propellant; after escaping from ESOI, the OTV velocity relative to Earth is 3.7 km/s.

2) Heliocentric Earth SOI to Mars SOI (MSOI): The transfer lasts 60 days and uses 41 t of propellant. The thrust direction and variable I_{sp} are maintained in the range of [2000; 10,000] sec to minimize in-flight time.

3) Lander separation and arrival at Mars atmosphere: An arrival velocity of V_{arr} = 10 km/s is assumed with aero-braking for the Mars Lander (ML), which lands on the surface using conventional chemical propulsion. The OTV continues past Mars for rendezvous later in its orbit.

4) OTV rendezvous: After releasing the lander during the first Mars encounter, the OTV begins a thrust schedule that consumes 8 t of propellant over 200 days at a maximum I_{sp} = 10,000 sec, which brings the OTV within Mars' Sphere of Influence (MSOI) during its second encounter.

5) OTV parking: The OTV spirals down to Mars Minimum Orbit (MMO) over the course of 15 days, using 1 t of propellant at a maximum I_{sp} = 10,000 sec.

6) Mars departure: After staying on Mars for 718 days, the Crew Return Vehicle (CRV) launches from the surface and docks with the OTV. The OTV then spirals out from the one-sol orbit to MSOI in 4 days at an I_{sp} of 2200 sec and using 17 t of propellant.

7) Earth return: A heliocentric transfer from MSOI to ESOI takes 69 days and uses 27 t of propellant. The thrust direction and the variable I_{sp} is maintained in the range of [2000; 10,000] sec to minimize the in-flight time. The OTV arrives at ESOI on 12/8/2037 with a final mass of 124 t.

Note, that the nuclear MHD-VASIMR mission described here can also be implemented with a dual I_{sp} mode, instead of the full variable. For example, using two discrete values of the specific impulse, $I_{sp,1}$ = 2200 sec and $I_{sp,2}$ = 7200 sec increases the in-flight time for the trajectory shown in Figure 3 by 10%.

Figure 4 illustrates how the in-flight duration for the human mission to Mars using nuclear MHD-VASIMR technology depends on the specific mass of the nuclear power plant and VASIMR engines. For each value of α there is an optimum power level that yields the shortest transit time. The effective radiation dose, proportional to the in-flight duration, is shown by the yellow arrow, assuming 40 g/cm2 aluminum shielding for the crew while in space.

CONSIDERATIONS FOR FURTHER STUDY

There is significant flexibility in the NEP option to warrant a more in depth study. For example, the in-flight time can be traded for payload and vice versa, keeping the power and propulsion system fixed. Figure 5 shows the functional dependence for a fixed power of 20 MWe and a total specific mass 4 kg/kWe. For a long flight (as would be the case with a robotic resupply mission not involving humans) the same type of NEP-VASIMR vehicle can be configured in a robotic cargo mode to deliver a much larger payload.

A brief study of failure scenarios for the human mission was also considered, including partial loss of reactor power and propellant loss due to leakage or plumbing failures. While these need to be studied in greater detail, some salient features are evident. The NEP system considered here is robust in the case of failure of one, two or three of the four reactors. The failure was arbitrarily assumed to occur when the vehicle had freed itself of Earth's gravity. While the failures result in an increase in the transit time, the mission can still be carried out by ejecting the failed reactor(s) and continuing at lower power with the propulsion system transitioning to low I_{sp}.

A similar analysis was done for the loss of propellant case. For a 20 MW system operating at a specific mass of 4 kg/kW, the effect of losing up to 75% of the propellant remaining at the ESOI boundary was examined. In this scenario the round-trip mission can still be completed at the expense of longer total flight time. The system adapts to the propellant loss by increasing the specific impulse, which consequently reduces the propellant requirement. Figure 6 shows the functional dependence of the transit time to the two postulated failure conditions.

The inherent operational robustness of the NEP system is the result of the fundamental difference between NEP and the NTR or chemical options. While the latter two operate in short duration, fuel-intensive burns the former consumes fuel more sparingly, providing thrust over virtually the entire flight.

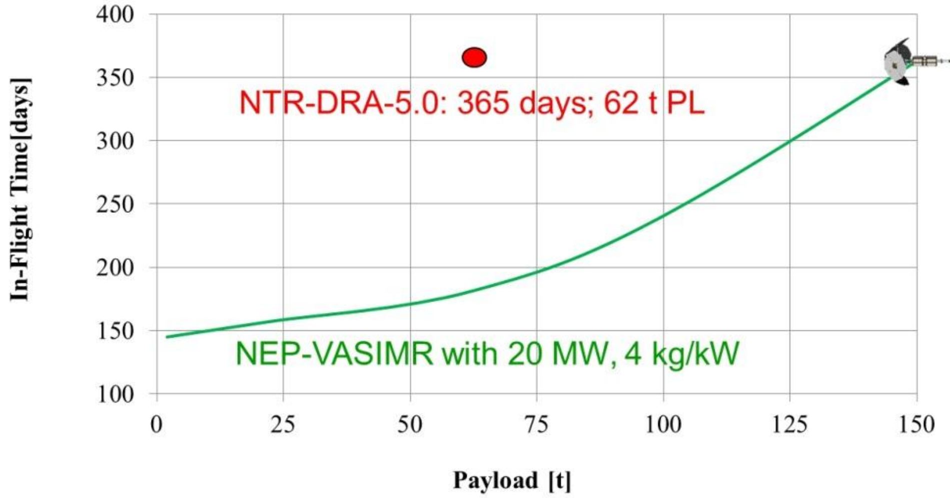

Figure 5. In-flight time as a function of the payload requirement for the NEP-VASIMR human mission to Mars.

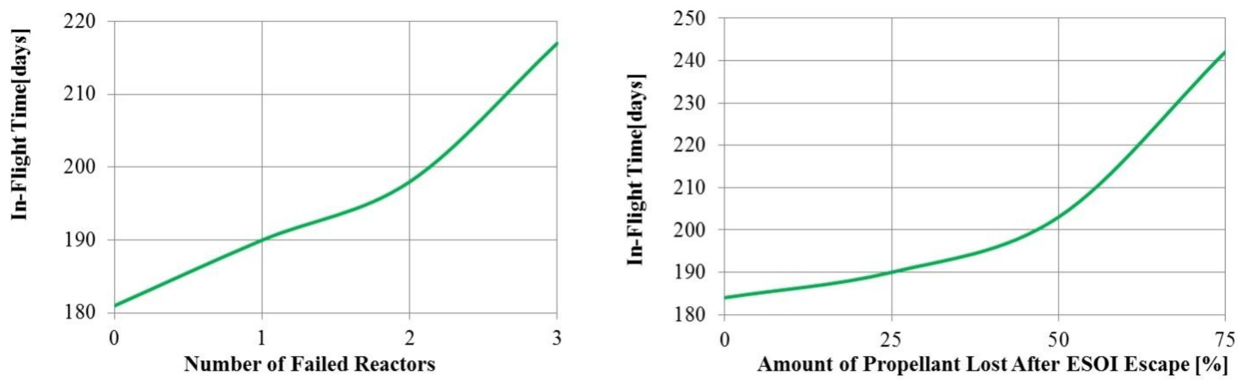

Figure 6. Power (left) and propellant (right) failure scenarios for 20 MW, 4 kg/kW NEP-VASIMR mission

CONCLUSION

The present paper demonstrates the importance of advanced, high power nuclear electric propulsion to reduce the in-flight mission time and hence the physiologically debilitating effects of prolonged interplanetary transits to Mars, including radiation exposure. Low alpha space nuclear power systems, using MHD conversion, combined with high power VASIMR propulsion technology offer significant advantages over the conventional nuclear thermal rocket (NTR) approach published in NASA's most recent Mars Design Reference Architecture (DRA 5.0). Much work remains to be done to enable these mission capabilities but the mass scaling and general potential of such systems are compelling, as they can lead to a significant reduction in radiation exposure to the crew, as well as inherent operational robustness in the event of unforeseen power and/or propellant system failures en route. A brief scan of potential failure scenarios shows that the system can successfully endure up to a 75% power or propellant loss conditions at ESOI escape and still complete the mission albeit over a longer time. Finally, in robotic non-human supply missions, nuclear MHD-VASIMR systems can deliver significantly larger payloads than their NTR or chemical counterparts.

NOMENCLATURE

B_{gen} = MHD generator magnetic field (T)
I_{sp} = Specific Impulse (sec)
j_c = MHD generator coil current density (A/m^2)
m_{reac} = reactor mass (kg)

M = mass (mT)
N_c = number of compressor stages
P = input power (W)
P_{reac} = reactor exit pressure (Pa)
T = trip time (days)
T_{rad} = radiator temperature (K)
T_{reac} = reactor exit temperature (K)
U_{reg} = regenerator heat transfer coefficient ($W/m^2/K$)
V_{arr} = arrival velocity (km/s)
α = specific mass (kg/kW)
β_{rad} = radiator surface density (kg/m^2)
ε_{rad} = radiator emissivity
η_N = VASIMR net efficiency (%)
$\eta_{s,c}$ = isentropic efficiency
ρ_c = MHD generator coil mass density (kg/m^3)

ACRONYMS

CRV - Crew Return Vehicle
DRA - Design Reference Architecture
ESOI - Earth SOI
GCR - Galactic Cosmic Radiation
IMLEO - Initial Mass at LEO
LEO - Low Earth Orbit
MHD - Magneto-Hydro-Dynamic
ML - Mars Lander
MMO - Middle Mars Orbit
MSOI - Mars SOI
NEP - Nuclear Electric Power
NTR - Nuclear Thermal Rocket
OTV - Orbital Transfer Vehicle
PL - Payload
REID - Risk of Exposure-Induced Death
SOI - Sphere of Influence
VASIMR® - Variable Specific Impulse Magneto-plasma Rocket
VF-200 - VASIMR® flight engine at 200 kW input power
VX-200 - VASIMR® experiment at 200 kW input power

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