IMS Trident
Propulsion and Power Systems group

Agne Paskeviciute (agnep@kth.se)
Atsushi Shirahama (atsshi@kth.se)
Connor Starkman (starkman@kth.se)
Federico Rorro (rorro@kth.se)
KTH Royal Institute of Technology, Stockholm, SE-100 44.

***Abstract*—The red planet has interested humanity as an interplanetary habitat for a long time, therefore is considered for colonization purposes in 2030s. In order to make such journey possible, one of the most important sub-systems needed for the spacecraft are propulsion and power systems. In this paper, different existing and currently under-development technologies are taken into account, considering their development status and operational capabilities.**

In the first phase of the study, suitable electric, chemical and nuclear thermal propulsion systems are explained and compared in terms of mass. Nuclear Thermal Propulsion system powered by liquid hydrogen is chosen as the best candidate. Two clusters of five engines in each, are used as the main propulsion source for the Trident spacecraft. Regarding the attitude control, nine small thrusters powered by methane are used. It is assumed that propellant can be manufactured on Mars, therefore propellant needed one-way only is taken for the trip.

Regarding the power generation systems, different generator cycles are considered. Brayton cycle due to its simplicity and reliability when operating at high power levels is chosen. For redundancy, solar arrays are also used, which provide the necessary 150 kW of power for spacecraft cooling system. Power management and distribution system will ensure the power reaches necessary sub-systems such as life support, communications and spacecraft cooling.

The total weight of power and propulsion systems is approximately 1,032.5 tonnes, from which 710 tonnes are needed for propulsion systems, and 322.5 tonnes for power generation and management systems. The spacecraft weight excluding such systems is 1,200 tonnes. The final cost of the propulsion system is estimated to be roughly 392 million USD, excluding research and testing costs.

***Index Terms*—Human Spaceflight, Mars Exploration, Space Propulsion, Power Systems.**

CONTENTS

I. INTRODUCTION

NASA has identified Mars as an important interplanetary destination due to its proximity and small technology complexity required to establish human life on Mars (compared to other planets in Solar system). National Space Policy of The United States [1] states that by mid-2030s, the humans shall be sent to Mars and safely returned to Earth. Both long and short term stay at Mars options are being considered for such mission, as stated in NASA's DRA 5.0 study [2], however due to risks discussed by IMS Trident Operations and Logistics team [3], short term stay at Mars options will be considered in this report. The short term stay trajectory to Mars is called "Opposition Class Trajectory", which is showed in Figure 1.

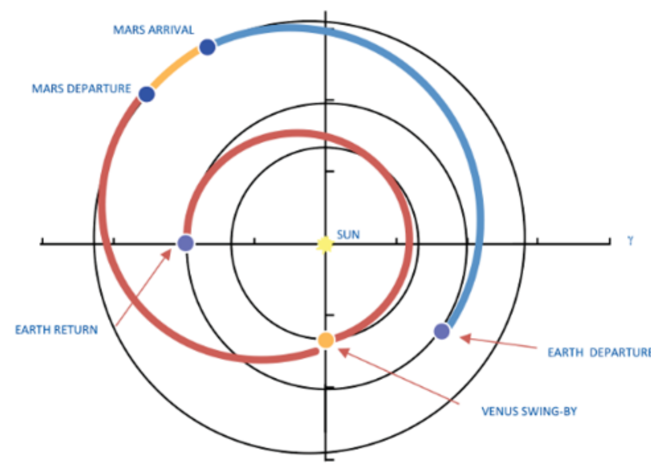

Figure 1. Opposition Class Trajectory [3]

Total trip time break-down (Table I, [3]) is presented in the following table. The total travel to Mars and back is shown to be 540 days, where 220 days are needed to reach Mars, and 290 days to come back. A 30-day long stay in Mars is included in the total time of the trip.

Table I
MISSION TO MARS TIME DISTRIBUTION [3]

Trajectory	Time
Earth-Mars travel	220 days
Staying on Mars	30 days
Mars-Earth travel	290 days
Total travel time	540 days
Launch window	2 years and 2 months

A critical part of any space mission is the total payload that can be taken. Therefore, one of the most important tasks of such mission design is to maximize the payload versus the spacecraft mass ratio. Since typically around 80% of total spacecraft mass is propulsion (including propellant) and power systems [4], this report will analyze different propulsion and power systems options which will not only contribute to mission success, but will also concern minimizing the mass and thus the cost of such spacecraft.

The task of designing propulsion and power systems for such spacecraft considered the following initial requirements:

- Power and propulsion systems must be safe and reliable.
- Propulsion system must be able to reach ΔV of 2.36 km/s one way and 5.69 km/s return trip [3].
- Propulsion system must prove the spacecraft to be able to reach Mars within 220 days and return within 540 days from the start of the trip [3].
- Propulsion system must be able to transport payload of 1,200 kg mass [9].
- Power and propulsion systems must be built for more than few return trips.
- Power systems must be able to provide enough power for crew and passengers communication within the spaceship and with Earth.
- Power and propulsion systems must be ready by the year of 2032.

It is assumed that several missions to Mars have already been performed. It is also assumed that on Mars there is basic infrastructure to host the whole crew and provide the necessary food and energy. In all scenarios discussed in this report, a key idea is to use local resources from Mars to produce propellant for the trip back. Since it is not the first trip to Mars, the infrastructure for propellant production is assumed to be already existing there. For instance, it is possible to use carbon dioxide extracted from Mars to produce methane and oxygen, which both are good propellants. Hydrogen, which is also a good propellant, can be extracted from Martian surface too [5].

This spacecraft will only act as a Mars Transportation Vehicle (MTV), going between Earth's orbit and Mars' orbit. Therefore, a descent capsule must be available on Mars to bring the crew and passengers to and from the Mars' surface. Also, a launch vehicle to launch the crew and passengers from Earth surface to and from MTV.

II. Main Propulsion System Choice

In order to choose the most suitable propulsion system, many existing and under development systems were compared. The criteria was to reach Technology Readiness Level (TRL) 9 by 2032 was applied to all systems. Also, all systems have to have a lifetime of at least 1,5 years - which is the time of the mission to Mars and back with the margin added. Moreover, while chemical propulsion systems have to be able to fire for hours, electrical propulsion systems have to be able to fire continuously for 220 days one way, and slightly less when traveling back.

A. Comparison of Propulsion Systems

Below will be presented a comparison of the different propulsion systems considered in this paper. They must all met the different requirements mentioned previously in this report.

1) Chemical Propulsion: This kind of propulsion system provides thrust by a chemical reaction in which propellant is burned. The following types of chemical propulsion systems were considered: solid, liquid and hybrid. Solid and hybrid propulsion systems were ruled out first. Solid propulsion motors cannot be shut down once started, and typically would be used for lift-off missions only. Hybrid engines are usually more complex than liquid one, and require more space than the latter. However, liquid propulsion systems showed high potential to be used for our spacecraft for 2032 mission to Mars. Liquid propulsion systems are well developed and tested, thus the risk factor is low. However, great mass of propellant is needed which is the biggest contribution to initial spacecraft's weight. Moreover, propellant mass also greatly influences the size of propellant tanks, which should be strong enough adding even more weight.

2) Electrical Propulsion: This type of propulsion system provides thrust by accelerating propellant creating an electric and/or magnetic field in which charged particles are accelerated. The following systems were compared: resistojet, arcjet, solid pulsed inductive thruster (PIT), variable I_{SP} magneto-plasma rocket (VASIMR), hall thruster, ion engine, magneto-plasma dynamic thruster (MPDT). Since journey time is one of the main criteria, only propulsion systems with I_{SP} above 2000 s were considered, because they require less fuel for the whole mission. Thus, some of them were ruled out: resistojet (< 350 s), arcjet (< 1000 s). PIT also did not match the criteria due to low operational time [5][6]. Another important parameter for electrical propulsion system was ability to process hundreds of megawatts of power at reasonably high efficiencies [6]. Hall thrusters have been operating at power levels of up to 150 kW, which yields thrust level to low for a human mission. Due to electrostatic nature of ion propulsion, increased power and thrust require corresponding increases in thruster size. For example, requiring only 177 kW of power thruster with size of 1,5 m, which is considerably too large and too heavy compared to other options. The two electric propulsion devices that are capable at operating at megawatts power level with a single or very few thrusters are VASIMR and MPDT. The main drawback of electrical propulsion systems are the very high mass of power generation system required to make the engine running. Also they would generate level of thrust which are usually too low for this human mission to Mars.

3) Nuclear Thermal Propulsion: This system works by heating the propellant to very high temperatures and simply expelling it trough a properly shaped nozzle. Although the technology is still under development and only few satellites were tested before [7], the concept is known since 1960s. The main advantage of this type of propulsion is very high thrust levels with comparatively low mass of propellant required. And also the heat generated can be used to produce electrical power to use on the station, as later explained.

B. Methodology and Assumptions Used for Estimating Mass of Each Propulsion System

Two liquid propulsion options running on LOX/Hydrogen and LOX/Methane were compared. The propellant for nuclear thermal propulsion was also taken to be hydrogen. The main reason behind this is that both hydrogen and methane can be produced on Mars. As mentioned in the introduction, it is assumed that the infrastructure there already exists, since it is not the first mission [8]. This means that at the beginning of the mission, only propellant needed one-way has to be taken, which results in lower propellant mass followed by substantial mass savings of propellant tanks.

For electrical propulsion options, nuclear reactor and nuclear power generator were assumed. Since the systems have to be operating at megawatts power level, without a nuclear reactor on board it would require large solar panels and massive batteries. This would create other challenges, such as complicated structural supports and deployment mechanisms, not to mention the increased weight of the spacecraft. Also problem may arise if there is no enough light hitting the panels for a long period of time.

The calculations and methods used for estimating the final mass of the propulsion system are presented below. As mentioned in the introduction, all calculations are based assuming spacecraft mass without the propulsion and power systems to be 1,200 tonnes [9]. The velocity change required is 2.36 km/s one way, and 5.69 km/s both ways [3].

For clearance of how the mass of different systems is calculated, the following Table II presents what contributes to the final mass of each system.

Table II
MASS CONTRIBUTIONS FOR EACH PROPULSION SYSTEM

System type	Propellant	Tanks	Nuclear Reactor	Power Generator	Engine
Liquid Propulsion	Yes	Yes	No	No	Yes
Electrical Propulsion	Yes	Yes	Yes	Yes	Yes
Nuclear Thermal Propulsion	Yes	Yes	Yes	No	Yes

Then below there are figures for mass required by the different systems, and how they have been calculated.

1) Propellant Mass: knowing I_{SP} value for each system, the initial spacecraft mass M_i, the Δu increment, the final mass can be found from the equation below. The difference between the initial mass and the final mass is the propellant used for the trip.

$$\Delta u = I_{SP} g_e ln \frac{M_i}{M_f} \tag{1}$$

2) Nuclear Reactor Mass: reactor providing thermal power is necessary for both nuclear thermal and electrical propulsion systems. Nuclear thermal engine's design already consists of a nuclear reactor that produces thermal power. Thus, the mass of nuclear reactor is already included in the engine's mass. More details regarding nuclear thermal engine mass please can be found in the sub-section II-B4.

The mass of the reactor for electrical propulsion systems was scaled up from N. Berend, et al. study [11] which assessed nuclear electric propulsion options for a round-trip mission to Mars.

3) Power Generator Mass: electrical power generator (conversion cycle) is needed for converting thermal power from the nuclear reactor to electrical power. It is the heaviest part of the electric propulsion (NEP) system. N. Berend et al. [11] estimates total mass of power generator and propulsion system by knowing value α:

$$\alpha = \frac{M_T}{P_e} \tag{2}$$

Where M_T is the mass of power generator and propulsion system, and P_e is the electrical power provided. Different conversion cycles are compared including Brayton, MHD and Rankine [11]. Brayton cycle is the only one able to convert power at hundreds of Megawatts power level, therefore is chosen for further calculations. Specific mass of $\alpha = 1$ kg/kW is predicted to be achieved within 10 years [11].

4) Engine & Propellant Tanks Mass: for liquid propulsion engine and fuel tanks mass is given as a fraction of propellant mass: $W = 0.12 m_{prop}$ [8]. For nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) engine and fuel tanks mass is given as thrust to weight ratio: $\frac{T}{W}_{NTP} = 3.5$, $\frac{T}{W}_{NEP} = 25$ [12] [13].

C. Results and Discussion

Table III shows final mass estimations for the different propulsion systems. Masses for sub-systems such as power distribution, cooling, solar panels, etc. are not included here and will be discussed in the subsequent sections.

The final values were calculated running numerous iterations to match the initial LEO mass, which includes habitable module, all LSS on board and propulsion systems. Initial LEO mass is unknown from the beginning (since the propulsion system mass is not known), and a guess is taken until the error reduces. Since power systems masses are not included, the final system mass would slightly increase. However, the purpose of this table was to compare different systems and select the best suited one.

Nuclear reactor for electrical propulsion system was scaled up from the data given in Berend's study [11]. It was estimated, that roughly 2,000 MW of power will be needed for both MPDT and VASIMR engines to generate enough thrust to reach Mars in 220 days.

It is clear from the table that the best candidate is Nuclear Thermal Propulsion System (NTP). The main weight savings for such system are due to its smaller nuclear reactors and the absence of power generator to produce electricity to run the engines. Also, with such high I_{SP}, significant propellant savings were achieved, which allow for smaller propellant tanks.

Table III
APPROXIMATE MASS BUDGETS FOR DIFFERENT PROPULSION SYSTEMS

	Chemical		Electric		Nuclear
	LOX/H_2	LOX/CH_4	MPDT	VASIMR	Thermal
I_{sp} (s)	446	361	5,000	3,000 - 30,000	900
Propellant (tonnes)	920	1,220	540	380	500
Nuclear reactor (tonnes)	N/A	N/A	600	600	-
Power generator (tonnes)	N/A	N/A	2,000	2,000	N/A
Engine and fuel tanks mass (tonnes)	110	150	2,000	2,200	58
Total approx. propulsion system mass (tonnes)	1,030	1,370	5,140	5,180	**560**

D. Final Propulsion System Choice

The principle and schematics of chosen NTP engine is presented in the Figure 2. This engine was developed during the NERVA program run by NASA in the 70s.

It can provide up to 336 kN of thrust per engine with a weight of 7.7 metric ton,and it is 10 m long. The thrust were throttled down to 250 kN to increase reliability and operational time. To make sure the spacecraft can escape the Earth's gravity field in LEO, and do so in a reasonable time 2000 kN of thrust is required. To provide this amount of thrust at least 8 engines will be needed. The final design includes 10 engines, since 2 are added for redundancy. The engines are divided in two cluster of 5 engines each, that will be placed at the two side of the spacecraft.

III. ATTITUDE CONTROL

Attitude control system is needed for Trident in order to have control in mid-flight, to provide functions like station keeping or emergency maneuvers. It would not be either efficient nor practical to use the main engine with their high thrust capability for small attitude adjustment. Therefore it was decided that there would be gyroscopes as well as small chemical thrusters to provide attitude control during the mission. Due to the large size of the spacecraft, sets of both of these systems will be needed to supply enough torque or thrust.

When evaluating different types of attitude control systems the efficiency, reliability, and capabilities were considered. The initial analysis were based on the existing systems, and the ISS system were considered. It uses a set gyroscopes and thrusters to complete any station keeping that is needed. While this is proven to work, the thrusters are overly expensive to use for large maneuvers. For example a 180 degree turn would cost roughly one million dollars [15]. Due to the large cost of thrusters other methods, such as gyroscopes or a magnetic field, that apply torque to the ship were considered. Systems that would need the use magnetic fields were immediately ruled out after the team had discussed the idea with the concept team. This because the addition of the magnetic field generator, mainly electric coil, would be too heavy and would require a large amount of power that should be provides to keep it working. But the main concern was the unpredictable properties of the magnetic field outside of a planets' sphere of influence, and the lack of magnetosphere in Mars would make the system highly inefficient. A method such as the ZPM maneuver that was recently developed and tested on the ISS was very promising, as it did not require any chemical propulsion and was able to rotate the ISS a full 180 degrees [15]. The ZPM maneuver was done using only gyroscopes, but it still needs the use of a gravitational force to assist during the rotation, and during the transfer it's value varies significantly. So in addition to using gyroscopes for station keeping, thrusters will need to be used as well for maneuvers when there is no substantial gravity present.

On the ISS the thrusters use a mono-propellant Hydrazine, which is expensive and difficult to manufacture and store. Therefore alternate types of propellant were considered for the journey to Mars. One of the best solutions found was methane, as it can be produced on Mars. This will allow to cut the amount of propellant needed for the journey in half. The team is assuming that by 2030 a small thrust capability engine will be have been developed. This assumption is based off of the current developments of Methane fueled rocket engines that have been made for a Martian descent vehicle by NASA [16]. In order to effectively be able to move the Trident, 9 thrusters will be installed to cover all axes of motion.

The mass of the entire attitude control system was rounded up to be 10% of the spacecraft's mass, totaling to about 150 tonnes. This value can seem very high, but this percentage includes the gyroscopes, thrusters, propellant, as well as all the sensors and devices needed to keep track of the position of the spacecraft[17]. The approximation is on the higher end to not under estimate the amount of mass that would need to be launched.

IV. POWER GENERATION & COOLING SYSTEMS

All on-board systems and spacecraft communication will require a certain amount of power. The request for minimum power required is around 150 kW [26], which includes the power to run all the Life Support Systems (LSS) and the communications between the spacecraft and the Earth. Another 150 kW of power is required for cooling systems. The means of extracting such amounts of electrical power, together with relevant details and specifications, are presented in the next paragraph below.

A. Power Generation

The nuclear reactor selected for the production of the required thrust, produces in the mean time a lot of heat. Some of this is used to heat up the propellant that will then be expelled through the nozzle, so generating thrust. The rest can be used to generate electricity to power the spacecraft's systems. To do so a Brayton cycle is used. As discussed in the main propulsion system choice section II above, this cycle is different from the Rankine cycle used today on Earth to generate electric power in every nuclear power plant. However,

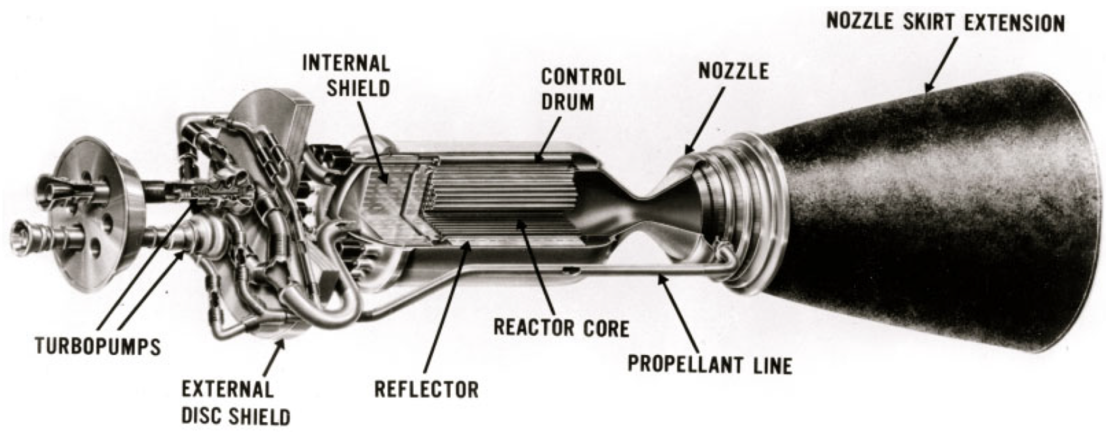

Figure 2. Schematic of NERVA-derived "Expander Cycle" NTR Engine [12]

due to it's simplicity and ability to process high amounts of power, is selected. This power generator can generate up to 10 MW of power with a mass of 160 metric ton required for the whole conversion system. This is the result of two separated generators, for redundancy and safety reasons, that can provide up to 5 MW of power each. The value is interpolated from data found in the paper by Melissa et al. [18].

This amount of energy in never fully required and so during normal operations the engines are throttled down. In this case the reactor will then generate less heat and so the power generated will also be lower. But the system will be designed so that even in this condition the on-board systems will have enough electricity to work properly.

Also having two separate and independent systems will guarantee higher safety for the crew, in case one of them present some problem. But this design can provide enough energy even after many years of operations, when the performances and efficiencies of the power plant have decreased due to aging and wearing of the components.

B. Cooling Systems

The major problem with nuclear power generation is the massive amount of heat that is generated during operational regime. This heat must be dissipated in order to avoid uncontrolled nuclear reaction. For power plant on Earth the cooling is left to the water, a big amount of it extracted and then put back in nearby lake or sea. In space there is not much water available. In the Trident spacecraft designed for Mars mission, even the 63 metric tonnes of drinking water necessary for the crew are not enough to manage the heat generated. Because due to the high working temperature, this small amount of water is useless to guarantee the necessary cooling capability required by a nuclear reactor.

Many researchers pointed out the importance of employing liquid metal[27]. Only this can guarantee that the high temperature of the reactor, in the order of 1500 K, do not turn the cooling substance into vapor. If this happens the fluid capability to transport great amount of heat will be greatly reduced. A big penalty of such system is the increment in mass that it requires. For Trident spacecraft 140 metric tonnes of metal are required. This value is obtained supposing that the area required to dispose the heat is around 1000 m^2 [9], which was obtained from the radiation heat transfer formula. The system must be running continuously, to avoid uncontrolled nuclear reaction. For this reason it is not powered by the power generator that transforms heat from the nuclear reactor into electricity. Instead the cooling system is powered by solar panels, which are used only to guarantee high safety in case the reactors have any problems. More details on the solar panels system are provided in the following section.

C. Solar Panels

Solar panels are currently used on spacecrafts that orbit within a certain distance from the Sun. Together with batteries they can provide the required power to the on board systems. This is what is used today on the ISS. The best option for future interplanetary space missions consist in using triple junction solar panels, as confirmed by NASA study performed in 2002 [19]. This technology allows to have very high efficiencies in the order of 30% [19] [20] [21]. And by 2032 higher efficiencies, in the order of 45% [24] can be expected. But to dimension the solar panels, the Sun's irradiance has to be known. This is the value of energy from the Sun that reaches a certain point in space. In the top of Martian atmosphere it has a mean value of 250 Wh/m^2 [22]. The triple junction cells have power density of 480 W/m^2 [25]. Thus, in order to generate the required 150 kW to be sure that the cooling system is working at all times, the required area for the solar panel has to be around 350 m^2. In addition to that batteries will be needed to provide a sufficient buffer in case the irradiance is reduced. To dimension the solar array in addition to the efficiencies it has been considered the inevitably damage on the solar cells that arises due to radiation over many years of operation in space.

Finally, all the generated power has to be distributed to the appropriate systems in the spacecraft. Such power management and distribution system is assumed to weigh 21 tonnes [11].

V. Risk Assessment

One of the biggest concerns related Nuclear Thermal Propulsion is its safety. As it is well known, nuclear energy poses certain risks to health and safety of people, and to the environment. This section is mainly focused on addressing such risks and proposing means to avoid them.

A. Political Considerations

The conference on the Statute of the International Atomic Energy Agency (IAEA) was held on 23rd October 1956 [14]. During the conference, the safe and peaceful use of nuclear energy were discussed. By February 2016 the number of IAEA member countries had risen to 168. The agency defines the regulations that are necessary to allow a safe use of nuclear power. It also defines the restrictions of its use in civil and military applications. The use of nuclear power in space require more attention, due to the harsh environment and difficulties to have a directly controlled operations from Earth. In order to make sure that nuclear power is safely employed in space it should be well researched and extensively tested on ground to prove it can run efficiently and without much maintenance. Another series of test will be required to prove that it is safe enough to be used in vacuum and for space mission, especially with humans on board. Otherwise, any other political and public support is impossible to predict, although it is very low today regarding the nuclear power plants.

B. Reliability of Technology

The NTP engines were extensively tested in the 70s by NASA, but the program was then closed. This was due to cut in funding by the different administrations, who didn't see investing in this technology as an important point. But the research then performed brought to the creation of the NERVA program [12]. During those years the engines were tested for many hours of continuous firing and through many re-ignitions without major problems. This has proven the feasibility of the concept and the reliability of the technology.

However, elevated doses of radiation may affect the hardware of the vehicle. The neutrons from radiation physically change atoms of the material from which the hardware is built, which affects the mechanical properties of the vehicle such as resistance. Appropriate shielding of the vehicle can reduce such effects [23].

C. Crew Safety

The crew safety is of primary concern in space exploration. More attention is required considering this is a commercial flight, in order to increase the chances of selling the tickets to passengers. Chances are low civilians would buy tickets knowing that the journey would possess serious threat to their safety and health, which can be mainly affected by radiation coming from space and nuclear engines. Therefore, the reactors in the engines are shielded from radiation to reduce the possible harmful consequences. To increase the protection even more the reactor and the crew compartment are designed to be the on opposite sides of the spacecraft [9]. To have even greater protection, between the reactors and the human compartment there will be tanks of LH_2 placed that will provide additional shielding.

In the further future, there will be a possibility to shorten trip times using electrical propulsion options [10]. In this case, humans will spend less time traveling, which will reduce the risks caused by radiation and weightless environment.

VI. Cost Analysis

The overall cost of the propulsion system is roughly 392 million dollars, neglecting the cost of the research and testing that would be needed to develop new technologies. As it is difficult to approximate costs of technologies that do not exist yet, many prices were assumed based on similar data or scaled based off known figures. The major contributions to the cost are the 10 nuclear thermal engines, which were assumed to be 10 million each [28], and the beryllium for the heat rejection system, which was 172 million for 511 kg. Additional costs such as the propellant (3 million), fuel elements (1 million), the thrusters (10 million each), and the attitude control system (16 million) were also considered. These values were scaled up from values of the ISS or current market values for the chemicals [29].

VII. Conclusions

The design of Nuclear Thermal Propulsion system together with solar arrays is shown in the Figure 3 below [9].

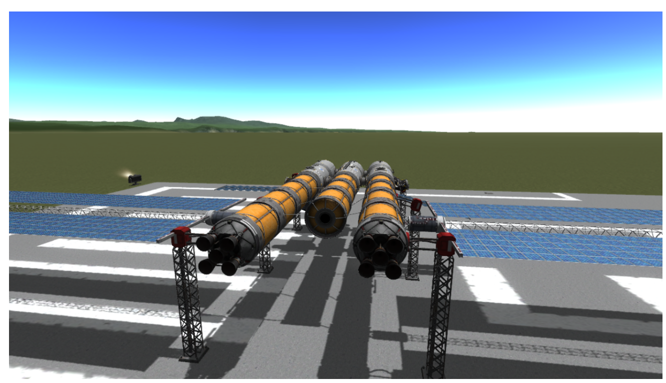

Figure 3. ITM Trident Spacecraft [9]

The spacecraft has 2 clusters of 5 NERVA-derived engines each of which 2 are redundant, which increases the safety and reliability of propulsion system. 9 additional attitude control thrusters will be installed on the spacecraft to ensure all axes of motion are covered.

The power for the spacecraft will be provided by converting thermal power from nuclear reactors using Brayton cycle technology. Additionally, the system will also have redundant power source of solar arrays which can provide enough electrical power to run the cooling system for the spacecraft. In case of nuclear reactor failure, the crew will have enough power to keep the spacecraft cool.

Regarding the risks of cosmic radiation, and nuclear power radiation, not only the cooling system using liquid metal will shield the spacecraft, but also liquid hydrogen tanks will keep the nuclear engines far enough from the crew compartment.

The final mass for the propulsion and power system design include:

- Nuclear Thermal Propulsion mass of 560 tonnes.
- Attitude control propulsion system mass of 150 tonnes.
- Brayton power generation cycle mass of 160 tonnes.
- Cooling system mass of 140 tonnes.
- Power management and distribution mass of 21 tonnes.
- Solar panels mass of 1.5 tonnes.

The final mass for power and propulsion systems needed for Trident spacecraft with payload of 1,200 tonnes, is approximately 1,032.5 tonnes. The final cost of the propulsion system is estimated to be roughly 392 million USD, excluding research and testing costs.

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