Revisiting Nuclear Thermal Propulsion for Human Mars Exploration

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Nuclear Thermal Propulsion (NTP) has long been considered as a viable in-space transportation alternative for delivering crew and cargo to the Martian system. While technology development work in nuclear propulsion has continued over the year, general interest in NTP propulsion applications has historically been tied directly to the ebb and flow of interest in sending humans to explore Mars. As far back as the 1960's, plans for NTP-based human Mars exploration have been proposed and periodically revisited having most recently been considered as part of NASA Design Reference Architecture (DRA) 5.0. NASA has been investigating human Mars exploration strategies tied to its current Journey to Mars for the past few years however, NTP has only recently been added into the set of alternatives under consideration for in-space propulsion under the Mars Study Capability (MSC) team, formerly the Evolvable Mars Campaign (EMC) team. The original charter of the EMC was to find viable human Mars exploration approaches that relied heavily on technology investment work already underway, specifically related to the development of large Solar Electric Propulsion (SEP) systems. The EMC team baselined several departures from traditional Mars exploration ground rules to enable these types of architectures. These ground rule changes included lower energy conjunction class trajectories with corresponding longer flight times, aggregation of mission elements in cis-Lunar space rather than Low Earth Orbit (LEO) and, in some cases, the pre-deployment of Earth return propulsion systems to Mars. As the MSC team continues to refine the in-space transportation trades, an NTP-based architecture that takes advantage of some of these ground rule departures is being introduced.

This paper outlines an investigation of NTP for human Mars exploration that takes into consideration these more recent concepts for Mars exploration campaigns and couples it with new ideas on the development strategy for Nuclear Thermal Rocket technology. It is believed that the use of Low Enriched Uranium will greatly reduce the regulatory overhead involved with development and test of an NTP system. This will translate into a reduction in cost and schedule making the use of NTP for a Mars mission more programmatically viable. While this paper does not delve into the development strategy, the analysts ensured that the NTP performance assumptions made were consisted with this new development strategy. This work also leverages several bottoms-up mass estimation studies that were completed as a follow on to DRA 5.0 by designers at NASA's Marshall Space Flight Center and Glenn Research Center. The result is a three element NTP vehicle consisting of a core stage, an in-line stage, and a drop tank. The core stage has three nuclear thermal rocket engines that provide approximately 25,000 pounds of thrust each while delivering a specific impulse of 900 seconds. The NTP vehicle configuration can be customized to contain different elements depending on the overall energy requirement of the tasks specified. In this way, cargo and

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crew delivery stacks can be tailored to minimize the number of NTP elements used for a given mission architecture or campaign. An overview of the design of these various NTP vehicle elements is provided.

The analysis of NTP for human Mars exploration begins with a complete evaluation of NTP usage for each of the flight opportunities to Mars from 2033 to 2050. This time span covers a complete cycle of Mars opportunities and provides insight into the benefits and penalties of sizing a single set of NTP elements capable of flying to Mars in any of these opportunities. The variability of the energy requirements for these different opportunities is somewhat tempered by the decision to aggregate elements higher in the Earth gravity well than LEO thus reducing the ΔV requirement for Earth departure however, the investigation across opportunities provides valuable insight regarding the driving requirements for propellant loading in each of the three NTP vehicle elements. Aggregation in higher orbits also provides an opportunity to better balance the volume and mass constraints of the launch vehicle. The study investigated both elliptical aggregation orbits and aggregation in cis-Lunar space and found that cis-Lunar aggregation resulted in elements that packaged well in the SLS launch vehicle fairing while maximizing the throw mass to trans-Lunar injection. High elliptical orbits do offer an opportunity to further optimize this balance but also present unique challenges in environments and station keeping. Both options are presented along with a discussion of the advantages and disadvantages of each. Cargo delivery, specifically the pre-deployment of landers for accessing the Martian surface, is also considered. In these cases, work completed over the past few years on lander design suggests that Mars landers will be too large to fly to cis-Lunar space for aggregation with their trans-Mars injection propulsion systems. Therefore, elliptical orbit aggregation is the baseline for lander delivery with the altitude of the aggregation orbit driven by the size of the landers to be delivered. In these cases, a single core stage can provide the energy required to perform trans-Mars injection. After setting the baseline performance estimates for both crew and cargo delivery, a series of sensitivity analyses were performed. Mass and technology performance estimates are both subject to variability in the early phases of planning an exploration campaign which is not slated to get underway for another 15 years or more. Therefore, it is important to understand the sensitivity to habitat and lander mass as well as the sensitivity to assumptions made for propellant storage efficiency and overall engine performance. The results of these sensitivity analyses point to the robustness of an NTP-based Mars campaign. Overall, these analyses highlight the promise of NTP for Mars exploration. By aligning with some of the mission and campaign assumptions of the EMC, results show significant savings in mass when compared to DRA 5.0. In direct comparison with alternative in-space transportation options from the EMC, NTP is shown to be competitive in metrics such as number of launches and overall architecture mass while showing potential shifts in overall mission risk. Sensitivity analyses show that the combination of high thrust and high specific impulse make NTP-based architectures more robust than other options, a desirable quality to have in a still-evolving mission design space. These analyses provide the community with an alternative point-of-departure for NTP-based human Mars exploration campaigns.