Nuclear Cryogenic Propulsion Stage Conceptual Design & Mission Analysis

Extended Abstract

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INTRODUCTION

The Nuclear Cryogenic Propulsion Stage (NCPS) is an in-space transportation vehicle, comprised of three main elements, designed to support a long-stay human Mars mission architecture beginning in 2035. The stage conceptual design and the mission analysis discussed here support the current nuclear thermal propulsion going on within partnership activity of NASA and the Department of Energy (DOE). The transportation system consists of three elements: 1) the Core Stage, 2) the In-line Tank, and 3) the Drop Tank. The driving mission case is the piloted flight to Mars in 2037 and will be the main point design shown and discussed. The corresponding Space Launch System (SLS) launch vehicle (LV) is also presented due to it being a very critical aspect of the NCPS Human Mars Mission architecture due to the strong relationship between LV lift capability and LV volume capacity.

NUCLEAR CRYOGENIC PROPULSION STAGE DESIGN

Trajectory ground rules and assumptions (GR&A) for this particular human Mars mission (HMM) include: 1) trip times to/from Mars are to be as short as possible, within four (~4) SLS launches, 2) stay times are optimized for mission, 3) LEO parking orbit of 400 kilometer (km) altitude circular, inclination $\leq36°$, 4) Earth departure declinations less than 36°, 5) Mars elliptical parking orbit of 250 km by 33,800 km altitude (1 Sol), and 5) Earth return entry speed limited to 13 km/s (at 125 km atmospheric interface) when necessary. The GR&A for the sizing analyses include: 1) SLS performance to 130 x 130 nautical miles (nmi) of 109 metric tons (mt, 108.2 mt to 130 x 220 nmi) after all project margins have been deducted, 2) SLS shroud payload cylindrical dynamic envelope of 9.1 meters (m) x 25.2 m, 3) total piloted stack payload mass (Deep Space Hab, Orion, consumables, etc.) on launch pad of 78.5 mt, 4) NCPS engine characteristics of Isp, thrust, engine T/W, and shield mass are -- 900 seconds (sec), 75,000 pounds force (lbf) total thrust for 3 engines, engine T/W=3.5, and with 2.4 mt of external shielding per engine.

Core Stage Element

The core stage includes all 3 engines of 25,000 lbf each for the piloted stack for a total of 75,000 lbf. The usable propellant in the core stage is 47.3 mt for the 2037 mission, this amount being close to that required for the sum of both the Mars orbit insertion (MOI) and trans-Earth injection (TEI) burns, a desirable result (when possible). The core stage also has the larger reaction control system (RCS) thrusters for performing the large trajectory correction maneuvers (TCMs) en route to Mars and for return to Earth. All the propellant for both TMI burns (TMI-1 and TMI-2) goes through the core stage, and amounts to 157 mt, most of which is stored in the in-line and drop tanks. This configurations utilizes a "down-hill" flow for propellant during the non-zero stack g's during the burns, so the first ~157 mt is used to depart LEO used, and the last ~50 mt is for MOI and TEI. Note that the core stage requires nearly 16 mt of RCS propellant due to the extensive outbound and return TCM ΔVs (65 m/s each way).

In-line Tank Element

The in-line tank is the next transportation element in the stack. The usable propellant in it is 76.3 mt for the 2037 mission. Note that during ascent to LEO, and while phasing with previous on-orbit elements and participating in stack assembly, each transportation element is actually a fully functional spacecraft with all necessary subsystems to support that capability present on board; the required RCS propellant in LEO for orbit raising to the assembly orbit is approx. 2 mt, but also depending on element mass and initial orbit when dropped of by the SLS LV.

Drop Tank Element

The drop tank and saddle truss is the last transportation element in the stack. The usable propellant in it is also limited to about 76 mt. For the 2037 mission, however, 84 mt of propellant is needed to complete the mission. This implies a small additional drop tank is necessary. The RCS propellant needed in LEO for this element is approx. 3.6 mt, which is also required to rendezvous with previously deployed elements, again depending on element mass and initial orbit by the SLS LV.

TRAJECTORY DESIGN

The mission delta velocities (ΔVs) across the 15-year cycle have been tabulated. The total ideal in-space ΔV for the 2037 piloted mission is 6520 m/s. This is comprised of TMI-1, TMI-2, MOI and TEI of 1929, 2089, 934, 1475 m/s respectively. Note that a gravity loss of 377 m/s is added to the TMI-2 burn, and 1% g-losses are added for MOI and TEI in the sizing analyses.

Various curves have been plotted for the total TMI (TMI-1 + TMI-2) ΔV, and the MOI, and TEI ΔVs for the 15-year cycle. The varied results from each opportunity show the effect of Mars' elliptical orbit on the mission. Minimum ΔVs occur at different trip times for different opportunities, the sensitivity (steepness of the curves) also varies with opportunity, and both easy (e.g. 2035, w/ TMI ΔVs = ~3700 m/s) and difficult opportunities (e.g. 2037, 2041, & 2039 w/ TMI ΔVs = to 4100 m/s or greater for reasonable trip times) are apparent.

SLS LAUNCH VEHICLE UTILIZATION

All HMM elements are placed in various 130 nmi x apogee (130 to 220 nmi depending on LEO phasing requirements) by an SLS LV from the 183.77 series. This series is specifically designed for optimizing use of both lift capability (mass) and shroud capacity (volume). If the volume can be fully utilized at 100% lift capability, then the LV runs out of performance at the same time it runs out of space, thus fully optimizing use of the LV. The shroud for this series is ~8 m longer to accommodate the lower density of hydrogen (LH_2) propellant. While the lift capability is ~20 mt less than the stock 130 mt SLS (w/ a 17-m shroud length), the volume allows ~20 mt or more LH_2 to be lifted than with the shorter, standard shroud. The short SLS second stage (with the small engines) also allows the shroud to be much longer than with the standard longer second stage (with the large engines) and still fit within height constraints.

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CONCLUSIONS

The NCPS version of the HMM optimizes/minimizes the number of launches to put the stack in place in LEO, from an in-space transportation element point of view as well as from a point of view synergistic with the SLS LV. Both the ETO portion and the in-space portion of the mission are designed and optimized in consideration with the other portion of the mission in mind.

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