NUCLEAR THERMAL PROPULSION FOR OUTER PLANETS ROBOTIC EXPLORATION. Saroj Kumar[1], L. Dale Thomas[2], and Jason T. Cassibry[3] [1]Department of Mechanical & Aerospace Engineering, University of Alabama in Huntsville, saroj.kumar@uah.edu, [2]Department of Industrial & Systems Engineering and Engineering Management, University of Alabama in Huntsville, [3]Propulsion Research Center, University of Alabama in Huntsville.

Introduction: Chemical propulsion has been the primary propulsion system from the beginning of space age for interplanetary robotic missions[1]. However, the chemical propulsion system has shown its limitations towards the exploration of outer planets and beyond due to its low energy density and low specific impulse. An outer planet mission using only chemical propulsion system would not be possible without multiple gravity assists or by utilizing a super heavy lift launch vehicle. On the other hand, the advancements in the Nuclear Thermal Propulsion (NTP) system using Low Enriched Uranium (LEU) NTP engine system design have demonstrated the improved performance towards payload mass and short transit time[2]. High thrust and high specific impulse (over twice the best chemical propulsion engine) NTP system can enable missions which have been limited due to the large ΔV requirements. An NTP propelled spacecraft with high ΔV would reduce the trip time by up to a factor of two or more when compared with a chemical propulsion system spacecraft requiring multiple gravity assists.

This work examines the capability of an NTP powered spacecraft for Jupiter rendezvous mission and discusses the advantages in terms of payload delivery and trip time in comparison to the conventional chemical propulsion powered spacecrafts.

Nuclear Thermal Propulsion: In NTP system, the heat energy from the fission reactor is transferred to the propellant which is then ejected through the nozzle. The fuel injected into the reactor core where it is heated to temperatures of about 2,500K or above and then ejected via nozzle. Figure 1 below shows major elements of an NTP system consisting of fuel tank, turbopumps, nuclear reactor and nozzle. The NTP engine do not require propellant combustion to generate heat but use heat source from the nuclear reactor to generate much higher exhaust temperatures of the propellant. The NTP system is generally designed with hydrogen as fuel and does not require any oxidizer which in turn lowers the molecular weight of the exhaust gas.

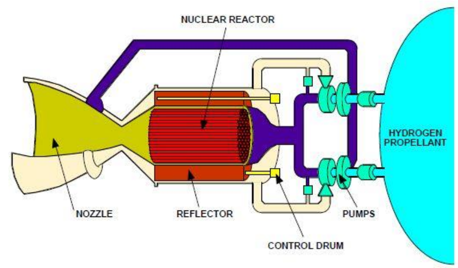

Figure 1: Major elements of an NTP system[3]

Spacecraft Design: The total wet mass of the spacecraft is 4350kg where 2300kg is allocated for spacecraft flight system bus and science payload and 2050kg of storable chemical propellant for planetary orbit insertion and trajectory correction maneuvers. The dry mass estimates of the spacecraft mass estimates are derived from the JPL mission concept studies to gas giant systems[4]. The mission design is based on expendable mission mode which consists of an NTP injection stage attached to the spacecraft to provide high ΔV during the Earth departure. The injection stage after the Earth escape maneuver will separate from the spacecraft. The injection stage consists of NTP engine system and LH_2 propellant tank. The NTP engine baselined for this study has capability to produce 15klbf of thrust and a steady state vacuum specific impulse of ~900 seconds. The dry mass estimates for the NTP injection stage and spacecraft have been derived based on the literature studies and the propellant requirement is approximated based on the total ΔV needed for the mission[5]. The propellant tank sizing is cylindrical which has a length of 9.4 m and diameter of 5.0 m. Table 1 shows the NTP injection stage and spacecraft mass breakdown.

Table 1: NTP injection stage and spacecraft mass breakdown

Vehicle	Mass (kg)
NTP Engine	2,560
Tank dry mass	2,200
Spacecraft flight system bus and payload	2,300
Chemical propellant	2,050
LH_2 propellant (with 3% ullage volume)	12,650
Total ‘wet’ mass at launch	21,760

The spacecraft and NTP injection stage have been designed by keeping in mind that both the elements can fit within the payload fairing of future commercial launch vehicles such as ULA's Vulcan Heavy and Blue Origin's New Glenn. Figure 2 shows NTP injection stage and spacecraft configuration.

Figure 2: NTP injection stage and spacecraft configuration

Mission Design: The launch vehicle will deliver the spacecraft and NTP injection stage to a circular parking orbit of 1000 km. The selected parking orbit complies with the minimum required altitude for final end-of-life storage[6]. The trajectory design of the spacecraft was divided in three phases. The first phase consists of Earth escape phase. During the Earth escape phase, the spacecraft departs from low Earth orbit using NTP powered system. The second phase of the spacecraft is the coasting phase. During this phase, heliocentric propagator is used without any active propulsion system to determine the spacecraft's expected trajectory. The NTP injection stage is separated from the spacecraft after the Earth escape maneuver. The third and last phase of the trajectory consists of planetary capture and orbital insertion phase. During this phase the spacecraft's onboard chemical propulsion system is utilized to reduce the spacecraft's heliocentric velocity and perform Jupiter Orbit Insertion (JOI) to achieve targeted orbit around Jupiter. Figure 3 shows the heliocentric trajectory of the spacecraft.

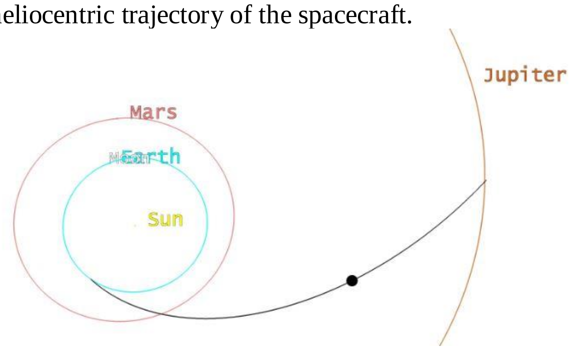

Figure 3: Spacecraft E-J heliocentric trajectory

The mission design demonstrates that the spacecraft with total wet mass of 4350kg using a highly efficient NTP injection stage in expendable mission mode can be delivered to Jupiter in 2.1 years using a single high-class commercial launcher. Further mission analysis can be demonstrated with tradeoffs between trip time and payload mass. Thus, a mission requirement with payload mass of 5mT or more can be delivered with increased trip time or mission concepts for New Frontiers class spacecraft can be delivered to Jupiter in under 1year of trip time. This capability using NTP system opens up the possibility of new class of missions for outer planets exploration which will not be possible using only chemical propulsion system.

Acknowledgements: This research was carried out at the University of Alabama in Huntsville and has been supported by the National Aeronautics and Space Administration (NASA), under Contract Number MTS_UAH_021217.

References: [1] List of interplanetary voyages, Wikipedia [2] C.R Joyner. et al. (2020) *Nuclear Technology*, *1-15*. [3] M.G Houts. et al. (2017) *AAS 17-144*. [4] Spencer J. et al. (2010) *NASA mission concept study report*. [5] S.K Borowski (1995) *AIP Conference Proceedings Vol. 324 American Institute of Physics*. [6] R. Frisbee et al. (1991) *Conference on Advanced SEI Technologies*.