Design of an Evolvable Nuclear Thermal Rocket Ferry for Geosynchronous Transfer. R. T. Beeson[1,2], A. C. Faler[1,3], and R. J. Garner[1,4], [1]Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83402, [2]Department of Aerospace Engineering, University of Illinois Urbana-Champaign, Urbana, IL, 61820, [3]Department of Astronautical Engineering, University of Southern California, Los Angeles, CA, 90089, [4]Department of Physics and Astronomy, University of Leicester, Leicestershire, UK, LE1 7RH.

Introduction: The United States first designed and tested Nuclear Thermal Rockets (NTR) from 1955-72 during Project Rover and NERVA. 58 years since the start of Rover, NASA is proposing the possible use of NTRs for manned Mars missions during the 2030-40 period, Design Reference Architecture 5 (DRA5) [1]. The long time lapse between the first NTR development program and the start of the next generation is partially a result of only government being able to justify the high cost and risk associated with NTR development.

The commercial sector has had little incentive to develop an NTR independent of government. The authors have investigated a new business model for the use of NTRs that may entice more commercial development. The proposed model uses an evolvable NTR ferry that will have three configurations. The first configuration will target high frequency geostationary transfer orbit (GTO) missions. The second configuration will be an upgraded vehicle capable of robotic interplanetary missions and the final configuration will be designed to meet the requirements of DRA5. Designing the system as an evolving vehicle allows for a lower initial investment from the commercial sector and starting with high frequency missions results in a quick, consistent and reliable source of income to offset additional research. It is conceivable that the first company that could execute the first step of this model would be in a prime position to reap the benefits of a large revenue stream from DRA5.

This paper focuses solely on the design of the reusable GTO NTR. The use of a global optimization genetic algorithm was used to aid in the solution of a design that could best be competitive with existing launch solutions for GTO missions. For details on the business justification of an evolvable NTR see *Beeson & Faler* [2].

Nuclear Rocket Engine: Because the development cost of new rocket engines is prohibitive, it is advantageous for an evolvable NTR to use only one engine size for all versions of the vehicle. NASA has stated that engines with 25klbf thrust would be desirable for DRA5. DRA5 missions would be the highest revenue generating streams for NTR application and therefore a 25klbf engine was chosen as the appropriate size for all configurations of the evolvable NTR.

A crucial decision was whether an LEU core could be designed with similar performance capabilities as an HEU core. Although no guidelines exist for the legal ramifications of using an LEU core in space [3], it is assumed that an LEU core should allow for relaxed regulatory processes of the NTR and therefore create an easier path for the commercial sector to develop these engines. A proof of concept for an LEU core with 25klbf thrust has recently been investigated [4] and the parameters of this engine were used for this study.

Optimization of Ferry: A typical GTO mission starts with the launch vehicle (LV) placing the payload into GTO and then the payload using it's own propellant to raise its perigee to insert into a geosynchronous orbit (GEO). The payload typically expends 40-47% of its initial wet mass to make this maneuver. Dual launch configurations are increasingly popular and GEO satellites are growing in size, which is driving the need for larger, more expensive LVs. A payload customer can enjoy the benefits of using an NTR ferry in two forms. Either they save money by launching on a less expensive LV to a nuclear safe orbit (NSO) where a GTO NTR can dock with it and then ferry it to its final orbit; or they can use the same LV, but now design their payload to make use of the extra mass margin available in the LV because the GTO NTR is acting as a ferry.

Operational Concept and Transfer Trajectories At the start of a mission, the GTO NTR will be located in a NSO with altitude greater than 400km. The payload with a mission specific propellant tank and occasionally a refueling tank for reaction control system (RCS) propellant is then launched into a comparable orbit. The GTO NTR has a small permanent propellant tank and an RCS of 24 110N MMH/NTO thrusters that allow it to maneuver and dock using a probe and drogue system. Propellant feed lines are connected via the docking ring and valves are opened to allow for LH_2 propellant to feed into the permanent tank.

In microgravity an impulse settling maneuver must be initiated by the RCS system to cause a small acceleration to the vehicle and shift LH_2 propellant to the pump inlets. Electric pumps are then used to initiate an engine conditioning phase. The NTR then enters the startup phase as the turbo pump is spooled by hot hydrogen from the regenerative cooling lines and increases mass flow to 14kg/s with a pressure increase from 200kPa to 7MPa at the core plenum. A shutdown and cooldown phase must follow the actual burn phase. Longer burn times are favorable for efficient use of

LH_2. The conditioning and cooldown phases contribute a small portion towards the total impulse albeit at a lower Isp.

At a chamber temperature of 2850K, pressure at 4.5MPa and coupled with a nozzle having an 80% bell contour and 200:1 expansion ratio result in an ideal Isp of 963s. Kinetic and turning losses as well as margin result in an ideal operational Isp of 919s for the NTR. Conditioning and cooldown lowers the average Isp of the burns further. Typically losses for each burn would be 2.9% for GTO transfer, 5.3% for GEO insertion, 10.2% for GEO deorbit, and 10.1% for NSO insertion.

The mission specific tank is used for the first three burns. Once reaching GEO, the payload is separated from the NTR and gapped using the RCS. After the GEO deorbit is completed, the remaining propellant in the mission specific tank is transferred to the permanent tank and then separated. The lower mass of the GTO NTR prior to NSO insertion allows it to have a slightly better burn Isp (10.1%) over the previous burn. The NTR can be strategically placed into an NSO that is optimal for the next mission scenario. The optimal orbit is dependent on a few key parameters that include the LV, launch location being used, mass to be ferried, and final destination.

Core Lifetime and Safety Considerations Critical to the reusability of the NTR is lifetime of the core, which uses 19.75% enriched ^{235}U in a Tungsten Cermet. Assuming criticality is lost when 3% of ^{235}U is consumed, the NTR has enough fissionable material at the start of operation for 90 GTO missions. One key concern for safety is the release of radioactive material from exposure to the H_2 propellant from Tungsten sublimation. Empirical data on Tungsten sublimation rates are available and at a fuel wall temperature of 3100K an insignificant thickness of 79μm will be lost over the predicted lifetime [5]. The fission products inventory has been estimated, with 14TBq of ^{137}Cs and 15.7TBq of ^{90}Sr over the GTO NTR lifetime. This is a small buildup and should be considered safe in comparison to the 245TBq that can be seen in ^{60}Co radiotherapy [6].

Propellant System Liquid Hydrogen (LH_2) was chosen as the propellant for the NTR because its low molecular mass allows for higher Isp than other propellant choices. The largest difficulty of using LH_2 is that with a propellant tank pressure of 1.5atm the vaporization temperature is 20K. Boiloff of LH_2 results in pressure build up within the tank, which requires venting and most importantly loss of significant amounts of propellant over short periods [d]. Boiloff can be controlled passively with the use of multi-layer insulation (MLI) and actively with a zero-boil off (ZBO) system that implements a cryocooler, heat-exchanger and radiator to remove heat from the propellant tank. Optimization of the NTR considered the mass, volume, and power requirements of each system to arrive at the best engineering design which as an active ZBO system on the permanent tank with 120 layers of MLI, but only 10 layers of MLI for the mission specific tank.

Power and Communications Technologically the power and communication systems are readily scalable from GTO to DRA5 needs, but the given choices can affect overall vehicle design. To simplify the first vehicle design it is assumed that the payload will be responsible for its own power and communications.

The communication system was designed to use NASA's Near-Earth-Network, using the S and Ka-bands via 0.46 and 0.4m parabolic antennas both at 5W with a max data rate of 1Mbps and $E_b/N_0 = 15$. The DRA5 configuration would use X and Ka-bands of the Deep Space Network (DSN) with 3.5 and 3m parabolic antennas at 100 and 150W with $E_b/N_0 = 3$ and max data rate of 50kbps.

The main power supply was chosen to be two ATK UltraFlex triple-junction ($\eta = 28.3\%$) solar arrays. Optimization showed the required GT configuration needed a power output of 1.5kW from 2.9 m^2 and DRA5 missions with 24.5kW from 178 m^2.

Shielding The reactor shadow shield was sized for a combined gamma and neutron exposure of 0.5MRad to the payload. It provided a 10 degree cone-of-safety and was composed of a 13.75 and 12.68cm layer of Tungsten and Lithium Hydride respectively.

Future Work: An improved design could be achieved by investigating the use of a more appropriately sized engine, which could be scaled-up with minimal additional development cost to reach DRA5 levels. The next most significant improvement could come from the design of a semi-closed cycle for engine startup and cooldown to conserve propellant.

Acknowledgements: The authors would like to thank the University Space Research Association and the Center for Space Nuclear Research for funding the aforementioned research through the Summer Fellows Program. Additionally the authors would like to thank Dr. Steven D Howe for guidance during this work.

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