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Abstract – *During the summer of 2006, students at the Center for Space Nuclear Research sought to augment the current NASA lunar exploration architecture with a nuclear thermal rocket (NTR). An additional study investigated the possible use of an NTR with existing launch vehicles to provide 21 metric tons of supplies to the lunar surface in support of a lunar outpost. Current cost estimates show that the complete mission cost for an NTR-enhanced assembly of Delta-IV and Atlas V vehicles may cost 60-80% more than the estimated Ares V launch cost of \$1.5B; however, development costs for the current NASA architecture have not been assessed. The additional cost of coordinating the rendezvous of four to six launch vehicles with an in-orbit assembly facility also needs more thorough analysis and review. Future trends in launch vehicle use will also significantly impact the results from this comparison. The utility of multiple launch vehicles allows for the development of more robust and lower risk exploration architecture.*

I. INTRODUCTION

During the summer of 2006, students at the Center for Space Nuclear Research investigated the feasibility of using a nuclear thermal rocket (NTR) to augment current NASA exploration architecture in support of a Lunar Outpost.[1] The mission objective was to provide support to a Lunar outpost with six resident astronauts for six months. Costs for the alternative strategy were to be estimated and then compared against the currently planned Lunar exploration architecture.

An additional comparative study was implemented to examine the possibility of using the current arsenal of Earth-to-orbit launch vehicles, coupled with an NTR, as an alternative means to achieve a payload delivery to the lunar surface of 21 metric tons. Assessment of technology capabilities for in-orbit construction was also performed, as some assembly would be required to form a single lunar transfer vehicle from multiple launch vehicles. Additional costs and logistics needed for completion of the comparison of the NTR-enhanced launch fleet strategy against the ESAS mission strategy were identified. Potential benefits were also acknowledged during this analysis, as well as their import for future exploration.

II. LUNAR MISSION CHARACTERIZATION

The National Aeronautics and Space Administration (NASA) has defined their current plan for manned lunar exploration in the Exploration Systems Architecture Study (ESAS).[2] The ESAS mission architecture, derived from existing space shuttle technology, uses chemical propulsion for all periods of travel.

The unmanned portion of the ESAS mission places 125 metric tons into Low Earth Orbit (LEO) to deliver a 21 metric tons payload to the lunar surface. Details of the original and NTR-enhanced ESAS mission requirements have been previously reported.[1,2] In summary, a cargo launch vehicle (CaLV), which is the Ares V, will be the primary launch system with an Earth departure stage (EDS) providing the final burn to enter LEO and the initial injection burn into a trans-lunar orbit (TLO). Upon arrival to the moon, a lunar surface access module (LSAM) will provide lunar orbit capture (LOC) and land the payload on the moon's surface. The launch of the CaLV is to occur at a Cape Canaveral launch site.[2]

Previous studies determined that the augmentation of the current ESAS mission by replacing the chemical EDS stage with a nuclear propulsion stage could either increase the lunar surface payload by 36.2% or reduce the initial mass in LEO by 24.1%.[1] All other aspects of the mission remained as previously described in the ESAS mission requirements.

II.A. Launch Fleet Implementation

Characteristics of various foreign and domestic launch vehicles were investigated, with the Delta IV Heavy and Atlas V Heavy Launch Vehicles recognized as providing the most volume for liquid hydrogen propellant and having two launch sites available per launch vehicle at both the Vandenberg Air Force Base in California and the Cape Canaveral Air Force Station in Florida.[3-5] The utilization of launch vehicles and facilities within the United States is of added benefit for addressing concerns of necessary security for the handling of nuclear materials.

The concept is that multiple launches from the Earth's surface could rendezvous in orbit and be assembled into a single vehicle for transit to the moon. It was determined that six launch vehicles would be necessary to provide a delivery of 21 metric tons to the lunar surface. The nuclear reactor, shielding, structural support, and auxiliary components could be launched in a single Delta IV Heavy rocket. The payload could be launched in either a Delta IV or Atlas V launch vehicle depending on size of payload compared to faring size of the launch vehicle, and the quantity of additional materials necessary for in-orbit assembly. The primary limitation is faring dimensions, not mass, on either launch vehicle for fuel storage. Although lightweight, liquid hydrogen propellant for the NTR requires significant amounts of volume. Four launch vehicles, two of each launch vehicle type, are necessary to provide sufficient propellant for the assembled transit vehicle using a tungsten-cermet reactor operating with a specific impulse, I_{sp}, of 850 s. Additional tanks could be included to increase the mass of the delivered payload.

Figure 1 shows a rendered depiction of how the assembled transfer vehicle might appear. At the right of the vehicle is the nuclear reactor core and exhaust nozzle, with radiation shielding between the reactor and turbomachinery. The four propellant tanks form the bulk volume of the transfer vehicle. Structural support is necessary between hydrogen tanks, the rocket engine, and the payload delivery structure (including LSAM), shown attached on the left of the figure. The assembled vehicle would provide entry into TLO and braking into a low lunar orbit (LLO) with the final payload delivery to the lunar surface provided by the LSAM.

Maximizing the I_{sp} of the NTR at 950 s would require the launch of only two Delta IV Heavy rockets with liquid hydrogen propellant. Thus an assemblage of four launch vehicles would be necessary to provide a comparable supply of 21 metric tons to a lunar outpost.

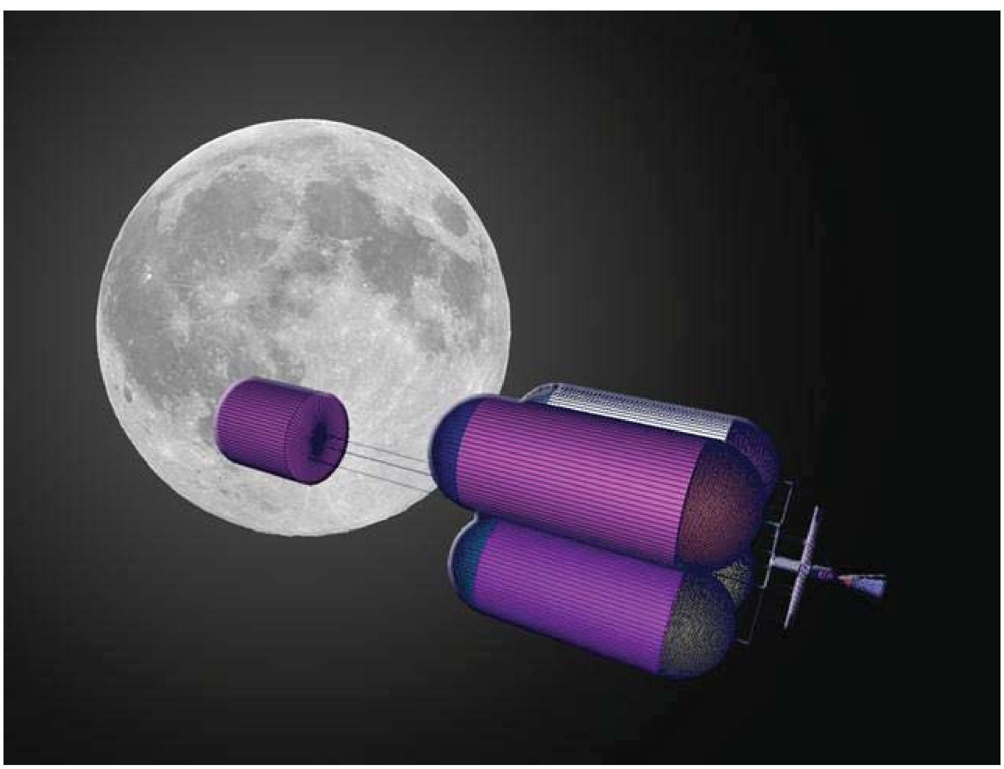

Figure 1. Assembled Lunar Transfer Vehicle.

II.B. Nuclear Thermal Rocket Engine

Because of the demonstrated failings of beaded and composite fuel during the ROVER/NERVA tests,[6] more durable nuclear fuels would be needed for the high-temperature reactors needed for space nuclear propulsion. Tungsten-cermet fuel has potential to serve as a high-endurance fuel with excellent compatibility with high-temperature hydrogen gas. Most importantly, fission product retention has been effectively demonstrated using tungsten-cermet material.[7]

The conservative design for a tungsten-cermet core has specifications of an I_{sp} of 850 s, thermal power level of 650 MW, and a hydrogen propellant flow rate of 18.0 kg/s (Fig. 2). An estimated maximum I_{sp} of 950 s is achievable within material endurance limits and a flow rate of 16.1 kg/s. The reactor is optimized for a fast neutron spectrum with a ^{235}U enrichment of 93% to achieve a higher power density. Beryllium reflectors with rotating boron-carbide control drums are necessary to control reactor reactivity. Further information regarding the tungsten-cermet core has been previously reported.[1]

A summary of past and current efforts to define a tungsten-cermet reactor for space power and propulsion has been compiled. Investigation into the alloying of rhenium with the tungsten shows an optimum hardness for a rhenium content of six weight-percent.[8] Furthermore, the mass and size of the reactor system can be significantly reduced through the use of ^{233}UN fuel instead of $^{235}UO_2$ fuel at an enrichment to 93%.[9] The reactor design for the analysis in this study is based upon the uranium dioxide fuel form.[1]

A 45-cm thick zirconium-hydride shadow shield placed between the reactor and turbomachinery is sufficient to reduce the neutron and gamma radiation levels delivered to the rocket electronics, turbomachinery, and payload. As the reactor core design is optimized, the overall mass of the reactor, system, and shield may significantly decrease.

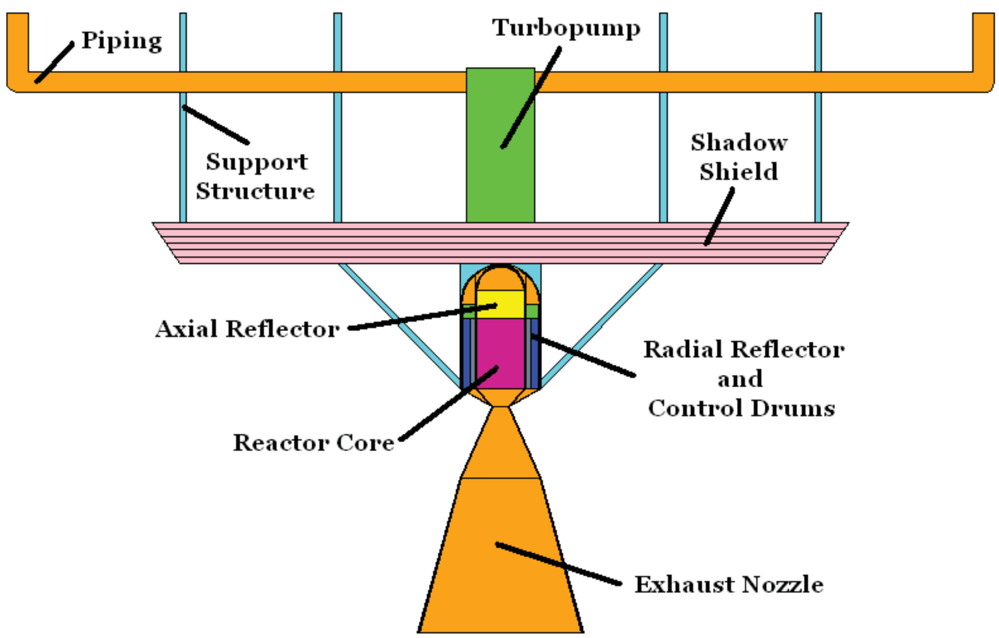

Figure 2. Nuclear Thermal Rocket Engine.

II.C. Logistics of Assembly

Launch coordination is the foremost concern for the assembly of multiple rockets in orbit. The question arises whether to develop in-orbit infrastructure such as a space garage or to use existing facilities such as the International Space Station (ISS) as a platform from which in-orbit assembly can be performed nearby. The cheapest option would be to promote the use of our current space investments, especially with coordinated efforts between current international partners.

The launch of multiple Earth-to-orbit vehicles is also of importance. With the necessity for the construction time of launch vehicles and the pre-launch preparation time for both vehicles and launch facilities, significant synchronization is necessary; the development of the United Launch Alliance can facilitate the coordination of such efforts. The tracking of multiple launch vehicles to their rendezvous location in orbit will be another important task. However, some time in orbit will be necessary for assembling the transfer vehicle and awaiting the launch of additional components. The boil-off of liquid hydrogen in the tanks is of concern. Additional reserve fuel of 10% has been accounted for in the sizing of the launch fleet. However, significant delays in the mission may result in insufficient fuel for lunar transit, and the requisite launch of an additional fueled tank from the Earth's surface or the use of a propellant supply depot.[10] The construction of solar shades at the construction site may reduce boil-off concerns,[11] albeit at a larger scale than defined in the reference. Optimized means of cryocooling may also be an option,[12] but would require additional technological development. The use of a passive vortex phase separation system can eliminate concerns of hydrogen gas being pumped through the rocket turbomachinery.[13]

The assembly of the launch vehicles will require the development of several space construction technologies. Currently, NASA uses only mechanical fastening and adhesive bonding for in-space construction.[14] Both of these methods, particularly the mechanical fastening, require extensive pre-launch ground preparation. The development of in-space machining and welding would significantly facilitate in-space assembly and construction. Research has already been conducted in both of these areas and can provide a foundation for future development.

An experimental system designed by a group from the University of Washington and flown on NASA's microgravity research aircraft initially showed no variation in the cut with gravity (a more detailed analysis having been unavailable) and demonstrated the potential use of air flow to remove chips from the working area.[15] Most research into in-space welding has been conducted by the former Soviet Union. The research and testing of their space program showed that electron-beam welding is the most effective for in-space welding.[16] In 1984, Svetlana Savitskaya tested the universal portable instrument (URI), which used an electron beam for heating, brazing, cutting, welding, and the deposition of coatings onto a surface.[17] It was determined that, with the modulation of beam current to force gas and oxide inclusions to the surface of the weld rather than forming bubbles in the weld, in-space welds of high quality could be produced.[16] Further development of the manufacturing and welding technologies already demonstrated would be necessary for the ultimate utility of such a space garage and would greatly expand options in-orbit spacecraft assembly.

III. EVALUATION OF LAUNCH COSTS

The current launch cost estimate for the Ares rockets utilized in the ESAS lunar mission is ~$3K/lb (~$7K/kg) to LEO.[18] This same source shows a comparable, albeit slightly greater, cost for Delta IV and Atlas V launch vehicles. The total cost to place 125 metric tons in LEO would be approximately $875M. Using 2004 data for the current launch vehicles and accounting for inflation, the estimated average cost to place mass into LEO is ~$12K/kg and the launch of four Delta IV vehicles and two Atlas V vehicles would be approximately $1.4B.[19] The basis for the lower launch costs of the Ares V rocket is economy of scale although there is no launch data to support this. A brief look at the Delta II and Atlas 2AS launch costs, scaled from 2000 data,[20] also demonstrates an average launch cost of ~$12K/kg. Therefore, it is believed that the cost of an Ares V launch vehicle into orbit carrying 125 metric tons would similarly be $1.5B. Complete launch costs are assumed to be defined as shown in Table I, not including optional insurance costs.[21] The exact cost to develop the new launch vehicles and upgrade launch facilities for larger vehicles is unknown. Development of the NTR engine is expected to cost an additional ~$3B using a contained test facility or as low as $1B using SAFE testing of the NTR.[22] The cost to develop a future engines, including testing, would be expected to decrease with increased demand.

TABLE I

Complete Cost Launch for Expendable Vehicles.[21]

Level I: Launch Cost	
Vehicle Cost	Vehicle Recurring Cost
Direct Operations Costs	Ground Operations and Launch Cost Mission Operations and Flight Cost Propellant and Gases Cost Transportation Cost Launch Site User Fee per Launch Launch Failure Implications (Direct and Indirect Cost Reserve)
Level II: Total Cost per Launch (Price)	
Indirect Operations Costs	Program Administration and System Management Marketing, Customer Relations and Contracts Office Technical Support, Vehicle Improvements Development Amortization, Royalty or Cost Recovery Profit, Taxes, Fees, etc.
Level III: User's Total Cost per Launch	
Insurance	Insurance against Launch Failure Insurance against Payload Loss

The assembly of large space structures is an additional cost inherent to a launch fleet rendezvous. Studies have been performed to assess productivity rates of human assembly in orbit.[23] It was determined that current launch costs to orbit are dominated by the transportation costs. Human assembly with its associated infrastructure would cost ~10% of the total cost. However, launch costs are very heavily influenced by demand; as the demand increases, launch and assembly costs will be reduced, but the fraction of total cost related to assembly will increase.

The integration of free-flying robots for in-orbit assembly of large space structures has a high degree of complexity for optimum integration and still needs further investigative planning prior to implementation.[24] It is assumed that human assembly would be the primary means of constructing the lunar supply vehicle. Therefore, the assembly cost for assembling six launch vehicles is estimated at $140M per delivery of 21 metric tons to the lunar surface. An additional cost of $140M is included to account for potential materials costs for building the constructive support structure needed between the six launch vehicles or supplying a space construction platform.

The final estimated cost for the delivery of 21 metric tons of payload to the lunar service to supply a lunar outpost is shown in Table II. The use of six launch vehicles is estimated to cost approximately 80% more than that of the estimated cost for a single Ares V lunar supply mission. The launch of four Delta IV vehicles with an NTR operated at an I_{sp} of 950 s would still cost an estimated 60% more, assuming that a reduction in launch costs to only four Delta-IV Heavy rockets. However, development costs for the ESAS vehicles and logistics costs for coordinating the launch and construction of multiple launch vehicles have not been completely assessed.

TABLE II

Cost Estimate for Lunar Base Supply ($B).

Cost	**ESAS Mission**	**Fleet of 6 rockets**	**Fleet of 4 rockets**
Mission	1.50	1.40	1.14
Assembly	0.00	0.14	0.11
Structural	0.00	0.14	0.11
NTR Engine	0.00	1.00	1.00
Total Cost	**1.50**	**2.68**	**2.37**

III.A. Additional Needed Costs and Logistics

Although a basic cost assessment has been performed, additional information would be especially pertinent for long-term application of this analysis. Development costs for the ESAS vehicles and upgrade costs for existing launch facilities could significantly encumber any long-term advantage over multiple launch vehicles. The increased use of the smaller launch vehicles would also decrease the effective launch costs, promoting more competitive prices for payload delivery to the lunar surface. There may be additional costs associated with the coordination of multiple launches at a single rendezvous location and development costs for in-orbit space construction, especially if performed near an existing space structure such as the ISS. Concerns of interest include the feasibility and cost of developing in-orbit assembly facilities. Finally, current launch systems are not man-rated, and can only be used for transport of materials and supplies to the lunar surface. Development of man-rated vehicles is mandatory for the establishment and supply of a manned lunar outpost.

III.B. Developing Future Space Exploration Capabilities

One of the penalties for using an NTR for lunar transfer is the additional mass for shielding of the nuclear reactor. While small reductions in launch mass can equate to larger cost savings, significant increases in propulsive techniques solely to reduce fuel mass may not be the best option. Propellant mass represents the lowest cost and most reliable element of a launch vehicle.[20] However, the development of NTR propulsion for missions further from the moon such as Mars, reusable lunar transport systems, or fast transit capabilities would benefit, especially in the case of rapidly intercepting near-Earth asteroids and comets. As launch costs decrease with increased demand, the ratio of fuel cost to total launch cost will also increase and a reassessment of propulsion strategies will be necessary.

The utility of multiple launch vehicles with in-orbit construction allows for the establishment of more robust and lower risk space exploration architecture. Loss of a single launch vehicle would result in a smaller loss of mission components necessary for delivery of Lunar supplies. Furthermore, the launch mass is not constrained by the mass of a single Earth-to-orbit launch vehicle. Launch vehicles and payloads of varying sizes and masses can be assembled to form a single space vehicle of desired transfer capabilities.

Development of in-orbit assembly techniques would also be of benefit for future space activities such as exploration missions, growth of extraterrestrial infrastructure, in-space repair of orbiting satellites and in-space reusability of space transfer vehicles. The capabilities necessary for space construction techniques will be vital in performing repairs and building replacement parts while performing exploration missions to Mars and beyond.[25]

Finally, the development of longer fairings for either of the current launch vehicle may allow for a further reduction in the number of launch vehicles into orbit. The increase in rocket structure mass may be offset by the reduced mass of hydrogen propellant. Costs association with development, testing, and subsequent launching of the modified launch fleet are unknown.

IV. CONCLUSIONS

Costs have been estimated for the utility of a tungsten-cermet NTR vehicle comprised of multiple launch vehicles to deliver a supply payload of 21 metric tons to a lunar base. The spacecraft is comprised of Delta IV and Atlas V launch vehicles coupled with a nuclear thermal rocket propulsion system and constructed in-orbit using human assembly. The total cost is approximately 60-80% greater than the estimated cost of $1.5B for an Ares V rocket. The associated costs for developing the ESAS launch vehicles, coordination of multiple launch vehicles for in-orbit assembly, and establishment of an in-orbit assembly facility have not been assessed. Knowledge of these additional factors, as well as future trends in launch vehicle use, will significantly impact the results of this comparison for provisioning lunar base supplies. The potential benefits of developing in-space construction techniques and NTR propulsion capabilities have also been discussed. The utility of multiple launch vehicles allows for the development of more robust and lower risk exploration architecture.

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