Opening the Solar System: An Advanced Nuclear Spacecraft for Human Exploration.

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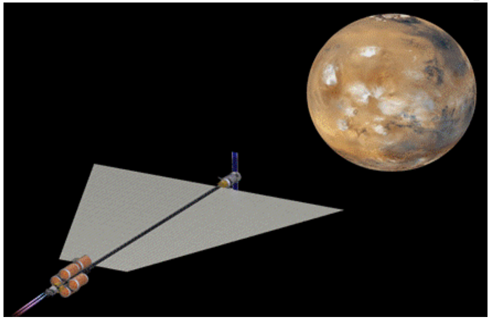
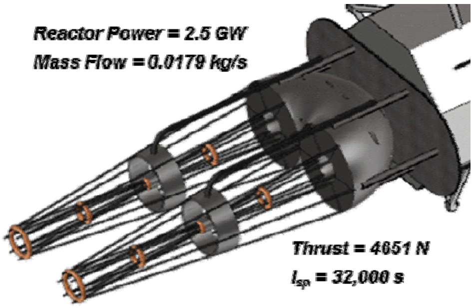
Introduction: Human exploration of the solar system is limited by our technology, not our imagination. We dream of a time when we can freely travel among the planets and truly become a spacefaring people. However, the current state of our technology limits our options for architecting missions to other planets. Instead of sailing the seas of space in the way that we cruise the seas of Earth, our limited propulsion technology requires us to depart Earth on a giant cluster of gas tanks and return in a lifeboat. This inefficient approach to exploration is evident in many of today's leading mission plans for human flights to Mars, asteroids, and other destinations. The cost and complexity of this approach to mission architecting makes it extremely difficult to realize our dreams of exploration beyond Low Earth Orbit (LEO).

This does not need to be the case. Researchers at NASA's Marshall Space Flight Center (MSFC) have been investigating the feasibility of a new take on nuclear propulsion with the performance to enable a paradigm shift in human space exploration. During the fall of 2013, engineers at MSFC's Advanced Concepts Office developed a spacecraft concept (pictured below) around this new propulsion technology and redefined the human Mars mission to show its full potential. This spacecraft, which can be launched with a fleet of soon-to-be available SLS launch vehicles, is fueled primarily with hydrogen, and is fully reusable with no staging required. The reusable nature of this design enables a host of alternative mission architectures that more closely resemble an ocean voyage than our current piecemeal approach to exploration.



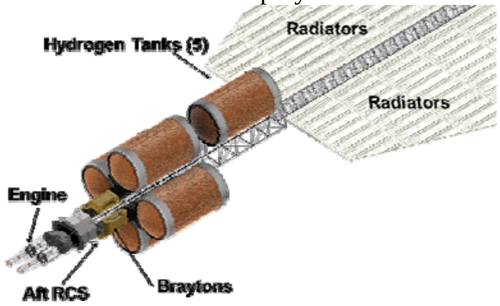
The Engine: The heart of this new spacecraft concept is the Afterburning Fission Fragment Rocket Engine (AFFRE) which uses an electrostatically-held dusty plasma of fissioning nanoparticles to produce high energy fission products[1]. These fission products are directed out of the dusty plasma through a toroidal reactor using magnetic fields. Once out of the reactor, the particles flow through a magnetic converging-diverging nozzle created by a series of four beryllium magnet rings. Hydrogen is injected into the flow of fission fragments at the nozzle's throat, interacting with the particle flow and heating to plasma before being expanded through the magnetic nozzle creating thrust. This engine, depicted below, has two C-D nozzles to take advantage of the toroidal shape of the reactor.



Investigations of the basic physics of the engine support the performance values quoted. This particular design consists primarily of carbon-carbon structures with a hydrocarbon oil moderator. The torus reactor has a major and minor radius of 3m and the overall length of the engine is 13m. While the total engine weighs approximately 200mt, using oil as the moderator allows us to launch the dry engine structure in one SLS launch and add the ~90mt of moderator oil during on-orbit construction. A relatively thin tungsten gamma ray shield protects the crew and other critical systems from radiation exposure.

The Spacecraft: The challenge tackled by the ACO design team was how to integrate an engine of this magnitude into a feasible spacecraft for human exploration. The chief concern was balancing the reactor power required to support a viable thrust level with the heat rejection challenge associated with high reactor power. The two largest spacecraft subsystems are the propulsion system and the thermal control system.

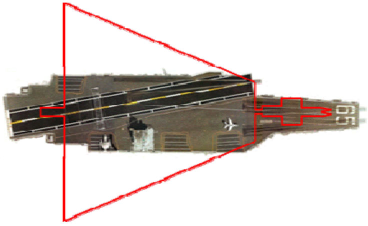
With a reactor power of 2.5 GW, the rejection of heat is a major challenge. Roughly 1/3 of that energy is imparted in the hydrogen by the fission fragments. While some of the heat is reflected out of the reactor as IR energy, there is still a need to reject ~450MW of thermal energy from various systems. Four cooling loops were designed to handle this requirement. The first operates at 140K to remove heat from the superconducting magnet assembly. The second operates at 590K and removes heat from the moderator. The third operates at 1200K and rejects heat from the reactor's internal heat shield. The fourth loop rejects waste heat from the Brayton power conversion units used to convert reactor heat to electrical. All four loops feed into 22,791m^2 of double-sided deployable radiators.



The spacecraft uses Brayton power conversion units to convert reactor waste heat into power. Three Brayton engines, based on a design developed by Glenn Research Center for the HOPE (Human Exploration of the Outer Planets) study[2], provide the 300 kW of electrical power required to run the engine, support the crew, and store the liquid hydrogen. This last function is prime example of the paradigm shift enabled by the AFFRE technology. Long-term storage of liquid hydrogen is typically a concern for human exploration because propulsion-driven spacecraft mass limitations cannot support the systems required. With AFFRE, the performance supports larger spacecraft and the ample waste heat provides a power source that enables the use of 20K cryo-coolers currently available, making long-term cryo storage possible.

A segmented truss structure forms the spine of the vehicle and supports the deployable radiator arrays. The initial FEA analysis shows that an extremely lightweight structure can be used given the low thrust levels. The avionics architecture includes standard communications and guidance systems. Due to the size of the spacecraft, assembly in LEO prior to operation will be required. The avionics design accounts for this, giving each segment of the spacecraft its own health monitoring systems along with imaging systems to assist in coordinating assembly.

The spacecraft, with a 25% dry mass contingency, weighs 566mt. The propulsion system, including hydrogen tanks, weighs 269mt. The thermal control system is estimated at 281mt. Structures, avionics, and power make up the remaining 16mt. The overall vehicle length is 282m with a span of 205m at its widest point. For perspective, the picture to the right shows the AFFRE spacecraft overlaid on the USS Enterprise aircraft carrier. The size of the spacecraft necessitates orbital assembly and it is estimated that six SLS launches will be required to support initial assembly. After that, hydrogen will be delivered to support a specific mission. Each hydrogen tank is designed to maximize SLS lift capability and can hold 68.8mt of liquid hydrogen. The spacecraft accommodates up to 8 of these tanks.



New Architectures Enabled: As an example of the game-changing potential of this design, mission analysts at MSFC ACO re-architected a human Mars mission around this new spacecraft design. The mission is based on the Mars DRA 5.0[3] with some very significant improvements. In a standard Mars architecture two cargo stacks are flown to Mars followed by a crew flight. The crew must rendezvous with a pre-deployed lander in Mars orbit and descend to the surface where they rendezvous with a pre-deployed surface infrastructure. The typical mission duration is 1000 days, including a 500 day stay at Mars and two transfer legs that total ~500 days in deep space.

In an AFFRE version of this mission, all elements are delivered on one AFFRE spacecraft flight, including a single Mars lander, reducing overall mission complexity and risk. Transfer from Earth to Mars can be achieved in 104 days with a return leg of 128 days for an overall transfer time of 232 days, less than half of the current standard Mars mission in-space transfer duration. These faster trip times result in lower consumable masses and significantly reduced crew health risks from radiation exposure.

The true paradigm shift comes when planning a campaign of missions. Staging is not required to enable mission closure and propulsive capture is performed on Earth return, leaving a fully functional spacecraft in LEO at the end of a mission. Therefore, this AFFRE spacecraft can be refueled and refurbished in LEO and can fly multiple missions. For a traditional 4-mission Mars exploration sequence, all spacecraft elements must be replaced for each mission resulting in approximately 36 SLS launches required. By reusing the AFFRE spacecraft, only propellant launches are required for subsequent missions, making the 4-mission Mars sequence achievable in 26 SLS launches.

Conclusion: While much work remains to develop this new technology, our studies have shown that the AFFRE changes not only spacecraft design, but the very approach to exploration. Enhanced performance and reusability open the doors to sailing rather than staging, potentially enabling the next giant leap in human space exploration and transforming us into a truly spacefaring people.

References: [1] Clark R. A. and Sheldon R. B. (2005) AIAA JPC, *2005-4460*. [2] Adams R.B. et al.

(2003) *NASA/TP-2003-212691*. [3] Drake B.G. et al. (2009) *NASA/SP-2009-566*.