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Low-Enriched Uranium Nuclear Thermal Propulsion Systems

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The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. For example, using NTP for human Mars missions can provide faster transit and/or round trip times for crew; larger mission payloads; off nominal mission opportunities (including wider injection windows); and crew mission abort options not available from other architectures. The use of NTP can also reduce required earth-to-orbit launches, reducing cost and improving ground logistics. In addition to enabling robust human Mars mission architectures, NTP can be used on exploration missions throughout the solar system. A first generation NTP system could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Characteristics of fission and NTP indicate that useful first generation systems will provide a foundation for future systems with extremely high performance. Progress made under the NTP project could also help enable high performance fission power systems and Nuclear Electric Propulsion (NEP). Guidance, navigation, and control of NTP may have some unique but manageable characteristics.

Nomenclature

CFEET = Compact Fuel Element Environmental Test
DOE = Department of Energy
HAT = NASA Human Architecture Team
HIP = Hot Isostatic Press
NASA = National Aeronautics and Space Administration
NCPS = Nuclear Cryogenic Propulsion Stage
NTP = Nuclear Thermal Propulsion
NTR = Nuclear Thermal Rocket
NTREES = Nuclear Thermal Rocket Element Environmental Simulator
PEC = Pulsed Electric Current
SLS = Space Launch System

I. Introduction

Development efforts in the United States have demonstrated the viability and performance potential of NTP systems. For example, Project Rover (1955–1973) completed 22 high power reactor and fuel tests. Peak performances included operating at a fuel element hydrogen exhaust temperature of 2550 K and a peak fuel power density of 5200 MW/m3 (Pewee test), operating at a thrust of 930 kN (Phoebus-2A test), and operating for an accumulated time of 109 minutes (NF-1 test).[1] Results from Project Rover indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse greater than 900 s could be feasible. Excellent results have also been obtained by Russia. Ternary carbide fuels developed in Russia may have the potential for providing even higher specific impulses. Cermet fuels, developed primarily for use in high performance space fission power systems, also show potential for enabling high thrust, high Isp NTP systems.

Many factors would affect the development of a 21st century nuclear thermal rocket (NTR). Test facilities built in the US during Project Rover are no longer available. However, advances in analytical techniques, the ability to utilize or adapt existing facilities and infrastructure, and the ability to develop a limited number of new test facilities may enable a viable development, qualification, and acceptance testing strategy for NTP. The use of low-enriched

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uranium (LEU) will reduce cost both directly through savings related to safeguards and security, and indirectly by enabling use of an optimal development approach and team. Although fuels developed under Project Rover had good performance, advances in materials and manufacturing techniques may enable even higher performance fuels. Potential examples include cermet fuels and advanced carbide fuels. Precision manufacturing will also enable NTP performance enhancements, and advanced manufacturing techniques (including additive manufacturing) will reduce the cost of NTP systems.

NTP systems may also have certain unique guidance, navigation, and control characteristics. Understanding these characteristics will help ensure that maximum benefit is obtained from the use of NTP. Specific characteristics include the need to design to ensure subcriticality during all credible launch accidents, the need to rapidly increase engine power during startup while minimizing instabilities, the need for remote operation (e.g. trans-earth injection burn if returning from Mars), the desire to maximize propellant efficiency (startup, full thrust operation, and "cool down"), the desire (or need) to enable certain abort scenarios, and potential unique options for reducing trip time (e.g. Venus swingby).

NTP will only be utilized if it is affordable. The NTP development and qualification strategy must be optimized to obtain all required data while minimizing cost through a combination of analysis, non-nuclear testing, and nuclear testing. Strategies must be developed for affordably completing required nuclear testing. A schematic of an NTP engine is shown in Figure 1.

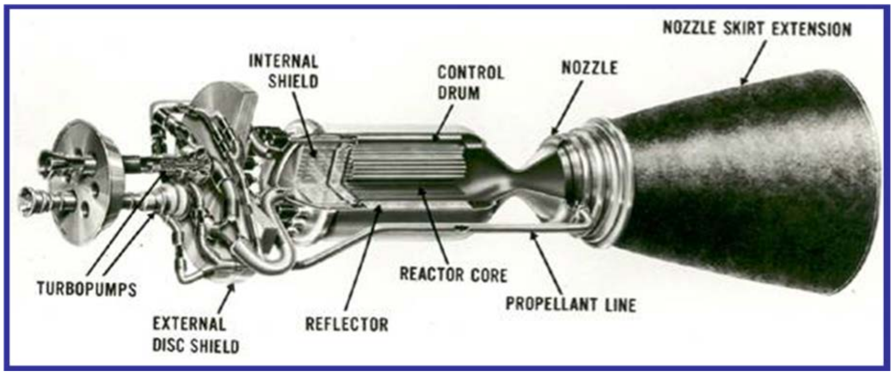

Figure 1. Schematic of an NTP Engine.[2]

II. Attributes of NTP

NTP has several unique attributes compared to other high thrust propulsion systems. In NTP, energy comes from fission, not chemical reactions. Because the energy density of fission is seven orders of magnitude great than that of the best chemical reactions, space fission systems can often be viewed as having unlimited energy density. The peak power density of NTP systems is limited primarily by the ability to transfer heat from the fuel to the propellant.

The fact that NTP uses energy from fission also allows a wide range of propellant choices. Hydrogen has been proposed for use in first generation systems because its low molecular weight allows specific impulse to be maximized for a given core operating temperature. However, future NTP systems could potentially use other propellants if desired, including volatiles obtained via in-situ resource utilization.

The startup of an NTP system is relatively slow, typically requiring over thirty seconds to go from zero thrust to full thrust. In addition, the shutdown of an NTP system is relatively slow, with core power typically still a few percent of operating power a few minutes after shutdown, decreasing to < 0.1% of operating power within several hours. It will be important to optimize the integrated mission efficiency when using NTP systems.

For some NTP engine designs, once the engine is shutdown it would not be able to be restarted for ~48 hours due to reactivity effects from Xe-135.

Feedback mechanisms within the NTP engine can be complex. The reactivity of the reactor can be affected by both the density of hydrogen in the core and the temperature of various engine compoents. For moderated systems (e.g. the Rover/NERVA engines and many LEU designs) the presence of hydrogen will tend to increase reactivity.

Cooling of certain reactor components (such as the reflector) will also increase reactivity. The Rover/NERVA program demonstrated many aspects of NTP operation, and that NTP reactors can be designed to operate in a safe, stable manner.

III. Basic NTP Operation

The operation of a first generation NTP engine is conceptually simple. Hydrogen from a propellant tank is pumped through a solid core reactor where it is heated to high temperature (~2700 K) and exhausted through a converging / diverging nozzle to obtain a specific impulse on the order of 900 s. However, as with all rockets, the actual NTP engine will be a complex system.

A typical cross section of an NTP reactor is shown in Figure 2. The core contains a high temperature uranium-bearing fuel (proposed fuels include W/UO_2 cermet or a “graded” core consisting of both Mo and W cermets), coolant channels (for hydrogen flow), and other components/materials as needed. The core is surrounded by a neutron reflector (typically Be or BeO) that also contains the control system. As with all nuclear reactors, the system effectively runs on a neutron balance. At steady state power, the neutrons produced by fission equal the neutrons lost to absorption or escape. If more neutrons are being produced by fission than are being lost to absorption or escape, the reactor power will be increasing. If less neutrons are being produced by fission than are being lost to absorption or escape, the reactor power will be decreasing. Numerous factors affect the neutron balance (reactivity), including the amount of hydrogen in the core, the temperature of various reactor components, fission products, and the amount of uranium that has been lost through fission or release. Reactors can be designed (in general) to passively maintain steady-state operation. However, when additional adjustments are needed a variety of approaches can be used. The approach shown in Figure 2 uses control drums, on which an ~120 degree segment is covered with a neutron absorbing material (often B_4C). If there is a need to increase reactivity, the B_4C is rotated away from the core, reducing neutron absorption in the B_4C and allowing more neutrons to be reflected back into the core where they can potentially be absorbed in uranium and cause a fission. If there is a need to decrease reactivity, the B_4C can be rotated towards the core resulting in more neutrons being absorbed in the B_4C and fewer being available to cause fission in the uranium bearing fuel. Most control drum movement will occur during engine startup and shutdown. A relatively small amount of control drum movement will be needed during steady state operation to compensate for uranium that is fissioned, neutron absorption by the resulting fission fragments, uranium that is lost from the core due to fuel element degradation, and other factors.

IV. NTP Guidance, Navigation, and Control

Some aspects of guidance, navigation, and control (GNC) will be unique for NTP systems. However, there do not appear to be any insurmountable issues or concerns.

For example, although slow by chemical propulsion system standards, the start up of a nuclear thermal rocket is quite rapid compared to the start up of most terrestrial fission reactors. Reactivity effects from the introduction of hydrogen into the engine and temperature changes within the engine will need to be compensated for by rotation of external control drums or by varying effective reflector thickness to vary the fraction of neutron escape from the reactor. Depending on NTP engine design, the nested control loops utilized for NTP operation could be very complex.

The relatively slow startup and shutdown of NTP will also require that slow changes in thrust at the start and end of a burn be taken into account in a way the allows propellant to be used as efficiently as possible. There may also be deviations between the predicted thrust as a function of time and the actual thrust as a function of time.

NTP missions have the potential to be significantly different from missions previously flown, and this could also drive GNC requirements. These include trans-earth injection burns (returning from Mars), options for Venus swingbys to reduce transit time, and potential abort scenarios.

Second generation (or beyond) NTP systems may incorporate electric propulsion at some level, using energy from the reactor to power electric thrusters. This “bimodal” operation may also have unique guidance, navigation, and control characteristics.

As NTP designs mature, guidance, navigation, and control issues should be addressed to ensure maximum mission benefit from the NTP system.

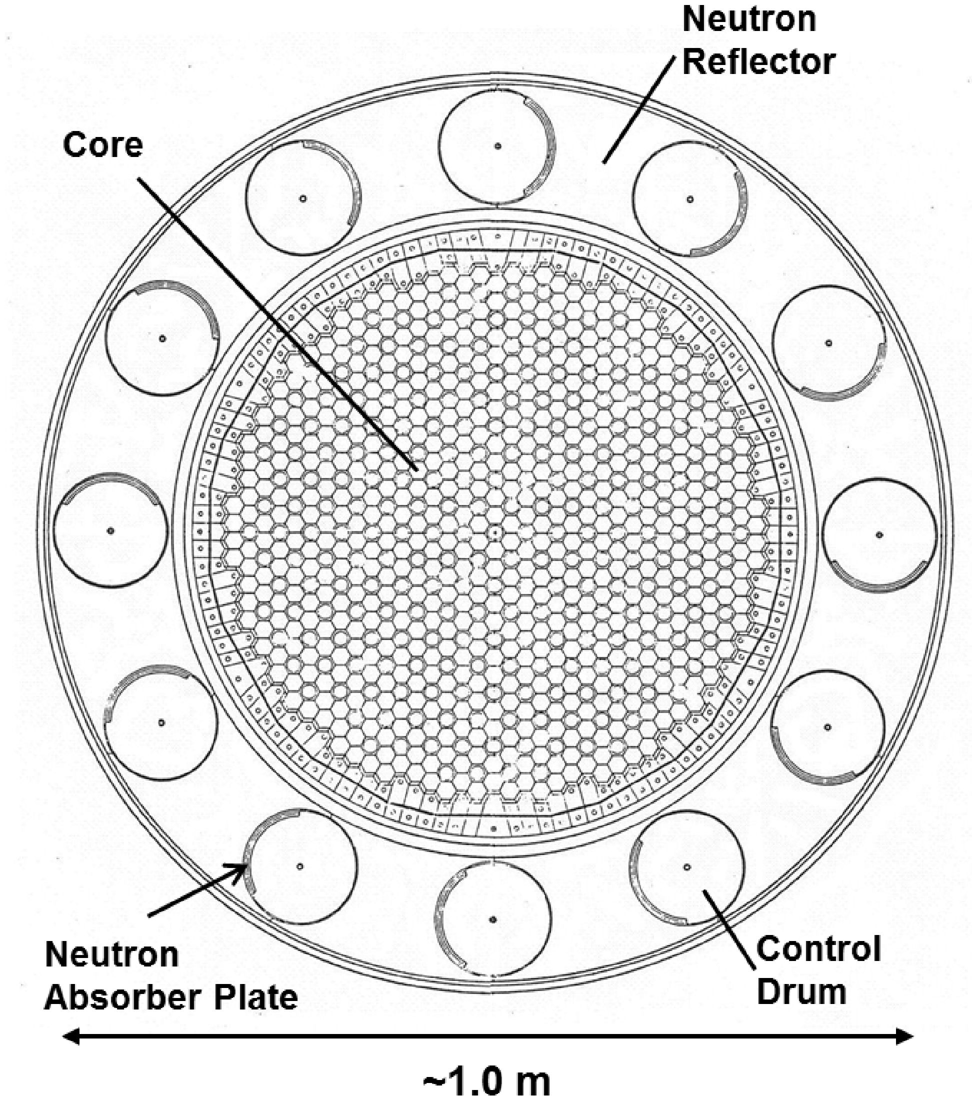

Figure 2. Representative Cross Section of an NTP Reactor[3]

V. Ongoing Work Related to NTP Technology Development

A. Mission Analysis

Ongoing mission analysis continues to demonstrate the potential mission benefits from NTP and advanced nuclear propulsion. For example, first generation NTP (Isp~900 s) not only enables traditional conjunction class missions with reduced transit time and a reduced number of launches, but can also enable opposition class missions that could reduce the total crew time away from earth from 30+ months to ~15 months, while still allowing for at least a 60 day stay at Mars. As shown in Figure 3, advanced fission propulsion systems could enable even more ambitious missions, helping enable sustained exploration and eventual colonization of Mars.

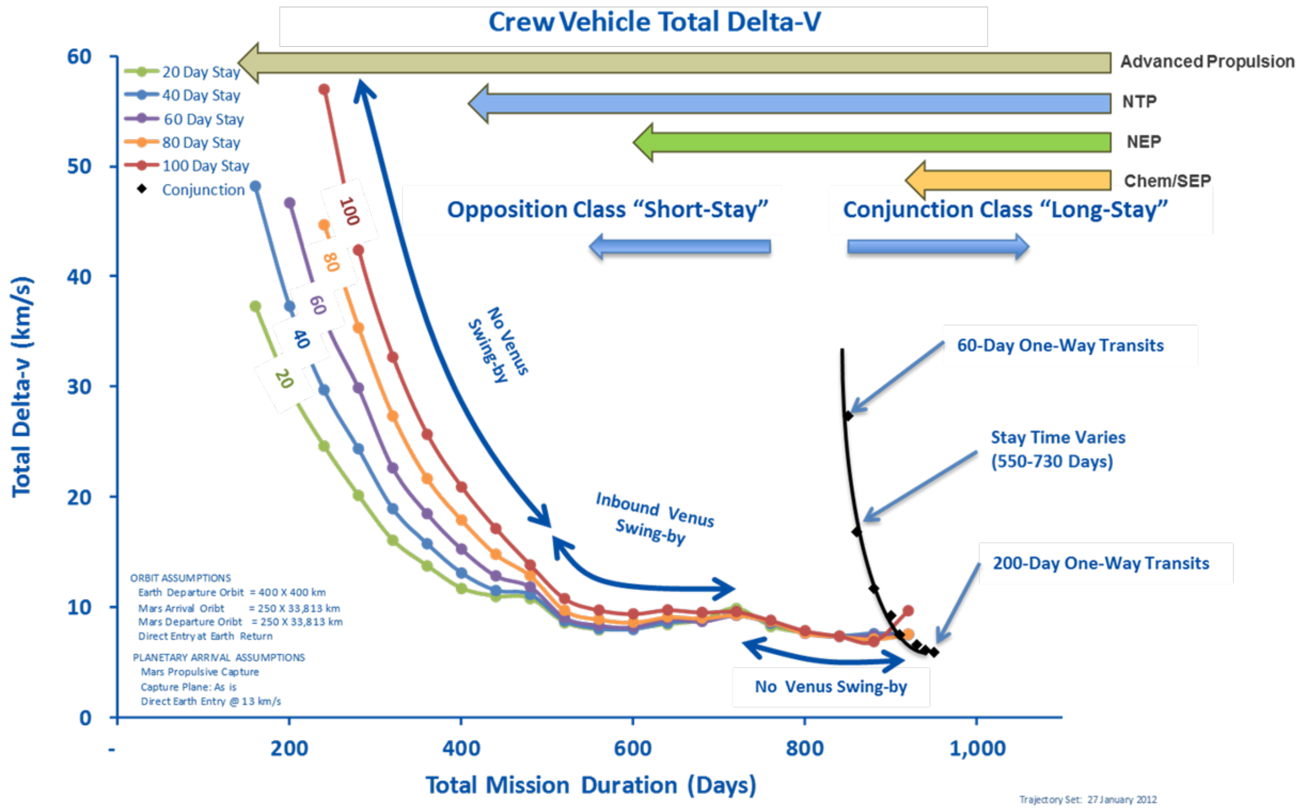

Figure 3. Crew Vehicle Total Delta-V (km/s) for Various Mars Mission Scenarios

B. NTP Fuel Design / Fabrication

Early NTP fuel materials development is necessary to validate requirements and minimize technical, cost, and schedule risks for future exploration programs. The development of a stable NTP fuel material is a critical path, long lead activity that will require a considerable fraction of program resources.

The NTP project is working with industry, universities, and the Department of Energy (DOE) to evaluate and initiate development of fuels suitable for use in a first generation NTP system. Fuel options under consideration include W/UO$_2$ cermet, Mo/UN cermet, and Mo/UO$_2$ cermet. LEU systems using only W/UO$_2$ cermet fuel would require that the tungsten be purified in W-184 to reduce parasitic neutron absorption to acceptable levels. Concepts based on a "graded" fuel system could potentially reduce required tungsten purification by using molybdenum based cermets in the cooler regions of the core and only using tungsten as needed in the very high temperature regions. Modern fabrication techniques may enable either approach.

Current research at MSFC is focused on developing fabrication processes for prototypical W/UO$_2$ cermet fuel elements. Cermets are typically formed by densification of powders using Powder Metallurgy (PM) processes. Tungsten based cermets with surrogate ceramic particles have been fabricated to near theoretical density using Hot Isostatic Press (HIP) and Pulsed Electric Current (PEC) techniques. During HIP, the cermet powders are consolidated in sacrificial containers at 2000°C and pressures up to 30 ksi. The PEC process consists of high speed consolidation of powders using DC current and graphite dies. For both HIP and PEC processing, the powder size and shape, powder loading, and processing parameters significantly affect the quality and repeatability of the final part. Figure 4 shows a typical microstructure and image of a net shape consolidated cermet part. The part is a 19 hole configuration that had uniform shrinkage during consolidation and good tolerance on the flow channel geometry.

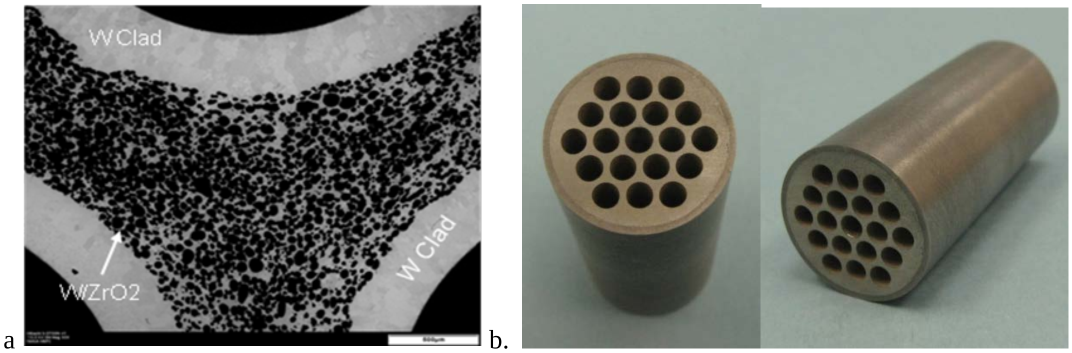

Figure 4. a) Micrograph of a W/60 vol% ZrO_2 CERMET with integral W claddings b) Consolidated W/40 vol% HfN CERMET sample.

C. Affordable NTP Development and Qualification Strategy

As previously noted, both the US and Russia have conducted highly successful NTR ground test and technology development programs. Although all of those programs were cancelled prior to flight, the cancellation typically occurred because the mission requiring NTP was cancelled, not because of insurmountable issues associated with NTP. However, if NTP is to be used, its development, qualification, and utilization must be affordable and done in a way that is technically, programmatically, and politically acceptable.

Progress is being made on a ground test concept designed to capture all potentially contaminated exhaust from an NTP ground test. An exhaust capture subsystem could significantly improve the viability of NTP ground testing, and could enable the use of established rocket engine test facilities for such testing. A schematic of the concept is shown in Figure 5. The basic approach is to burn the hydrogen after it leaves the NTP engine and condense the resulting steam. Any fission products released from the fuel during testing would be contained in the water and the overall capture system. Standard techniques would then be used to perform any required decontamination.

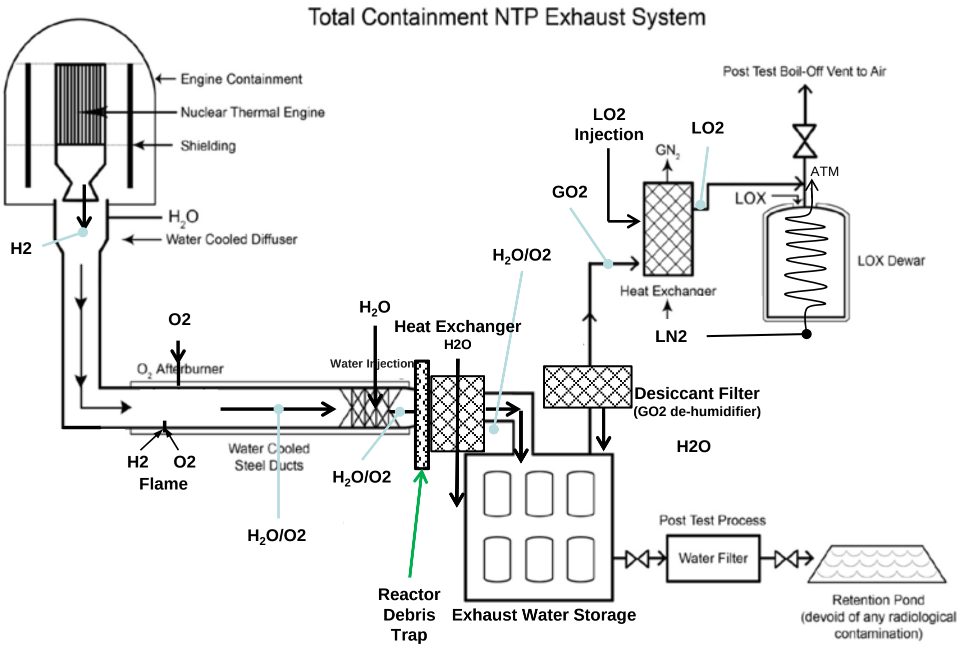

Figure 5. Option for NTR Exhaust Capture During Ground Testing.

In addition to ground testing a full scale NTP engine, a flight demonstration is being investigated to help qualify the NTP stage. The flight demonstration would use the same NTP engine being developed to support a human Mars mission, but would have the option of running de-rated either in terms of thrust or Isp. The flight demonstration would also allow demonstration of unique GNC features, prototypic shielding, passive tank repressurization (partial or full) and other aspects of the NTP stage that would be difficult to demonstrate during a ground test.

VI. Conclusion

The potential capability of NTP is game changing for space exploration. A first generation NTP system could provide high thrust at a specific impulse on the order of 900 s, roughly double that of state of the art chemical engines. Near-term NTP systems would provide a foundation for the development of significantly more advanced, higher performance systems. Although the guidance, navigation, and control of NTP systems may have some unique aspects, there do not appear to be any showstoppers. For NTP to be utilized, an affordable development and qualification strategy must be devised.

References

[1] Koenig D. R., "Experience Gained from the Space Nuclear Rocket Program (Rover)," LA-10062-H, Los Alamos National Laboratory, Los Alamos, NM, 1986.
[2] NASA Image: NERVA Illustrations and Technical Drawings