Overview of High-Performance Centrifugal Nuclear Thermal Rocket Propulsion System

Jimmy Allen[1], Michael Johns[2], Mark Patterson[2], Michael Houts[3], Florent Heidet[4], Nicholas V. Smith[5], John E. Foster[6]

[1]*Dynetics, Inc., 1000 Explorer Blvd NW, Huntsville, AL 35806, jimmy.allen@dynetics.com*
[2]*Southern Research, 757 Tom Martin Dr. Birmingham, AL 35211, mjohns@southernresearch.org, mpatterson@southernresearch.org*
[3]*NASA Marshall Space Flight Center, Huntsville, AL 35812, michael.houts@nasa.gov*
[4]*Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439, fheidet@anl.gov, mjarrett@anl.gov*
[5]*Idaho National Laboratory, 1955 N Fremont Ave, Idaho Falls, ID 83415, nicholas.smith2@inl.gov*
[6]*The University of Michigan, 500 S. State Street, Ann Arbor, MI 48109, jefoster@umich.edu,*

INTRODUCTION

The Centrifugal Nuclear Thermal Rocket (CNTR) is designed to enable advanced space exploration missions while simultaneously minimizing engine development risk.

The CNTR is essentially a high performance nuclear thermal propulsion (NTP) system, with propellant heated directly by the reactor fuel. The primary difference between the CNTR and traditional NTP systems is that rather than using traditional solid fuel elements, the CNTR uses liquid fuel with the liquid contained in rotating cylinders by centrifugal force. The CNTR performance goal is to provide high thrust at a specific impulse of 1800 s using hydrogen propellant, and 900 s using passively storable propellants such as ammonia, methane, or hydrazine. If achieved, such performance would enable 420-day round trip human Mars missions and other advanced space missions. The ability to efficiently use any volatile as propellant could also greatly facilitate the development of in-space resources such as asteroids and Kuiper Belt objects.

A schematic of a 19 cylinder CNTR is shown in Fig. 1, a cross-section of a CNTR rotating cylinder fuel element is shown in Fig. 2, and a diagram showing the CNTR propellant flow path is shown in Fig. 3.

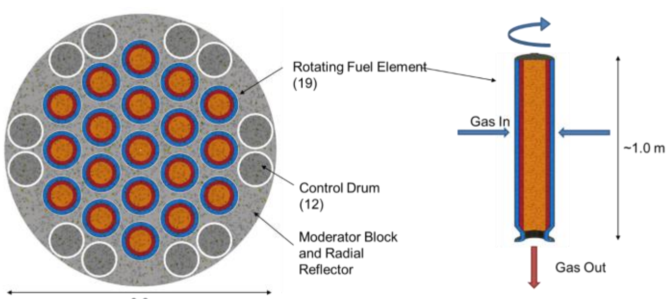

Fig. 1. Schematic of 19 cylinders CNTR

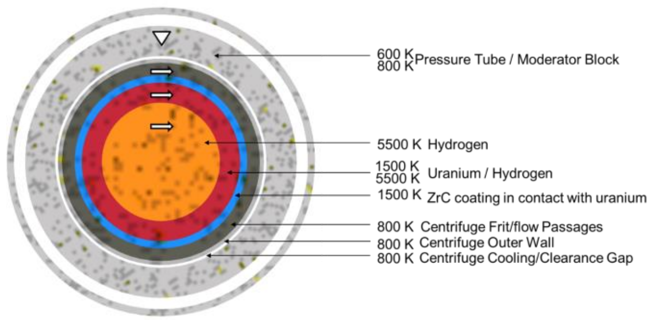

Fig. 2. Cross-section of CNTR Rotating Fuel Element

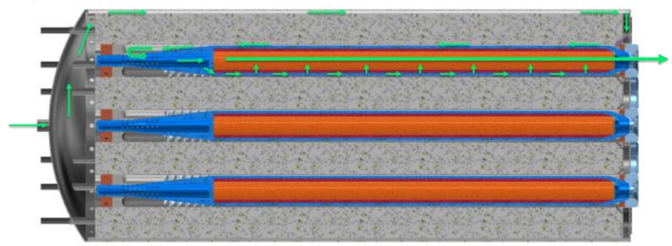

Fig. 3. Propellant Flow Path in the CNTR

Similar to traditional NTP systems, propellant from the propellant tank (not shown) passes through the neutron reflector, regeneratively cooled section of the nozzle, neutron moderator, and structure before entering the fueled region. This flow configuration allows all moderators and structural materials within the CNTR to remain at a relatively low temperature (< 800 K). The CNTR uses radial propellant inflow through the fuel (similar to certain traditional NTP systems), but instead of a solid fuel uses metallic liquid uranium fuel. As shown in Figure 3, the propellant enters through the porous rotating cylinder wall at ~800 K, passes radially through the molten uranium fuel, and exits axially through a central channel into a common plenum prior to being accelerated through a converging/diverging nozzle. Liquid uranium near the inner cylinder wall is maintained at ~1500 K by the inflowing propellant. Uranium temperature near the center of the rotating cylinder could potentially reach 5500 K, but only contacts the propellant and does not contact any structural material. The system operates at high pressure (>500 psi) to avoid bulk boiling of the uranium metal, and methods for further reducing uranium entrainment in the propellant are under consideration. Other fuel forms may also be considered, including UO_2, UN, and UC.

The reactor shown in Figure 1 assumes SiC structure (patterned after the Transformational Challenge Reactor), a $ZrH_{1.87}$ moderator block (patterned after the Russian "TOPAZ" reactor), and 19.75% enriched metallic uranium fuel. Initial neutronic calculations show a reactor mass of 1300 kg at a k_{eff} of 1.05, although the reactor design remains to be optimized and design detail needs to be added.

BACKGROUND

Extensive development and testing related to solid core, hydrogen cooled nuclear rocket engines was performed from 1955 to 1973 under the Rover/NERVA project [1]. Liquid core nuclear rocket engines have been envisioned since at least 1954 [2], and systems analogous to the CNTR were proposed throughout the 1960s [3]. Even higher performing nuclear propulsion systems (such as gas core nuclear thermal rockets) have been envisioned [4]. The insight gained from previous nuclear thermal propulsion projects and studies will be useful in devising a development and qualification approach for the CNTR.

Potential CNTR Advantages

Potential advantages of the CNTR approach include the following.

1. Except for the metallic uranium fuel and a coating on the inside of the rotating cylinder wall, all solid materials are maintained at <800 K.
2. There are no thermal stresses in the fuel and no significant compatibility issues between the fuel and propellant.
3. In addition to hydrogen (for highest specific impulse), the CNTR can essentially use any volatile for propellant.
4. The high uranium density of metallic liquid uranium facilitates the use of High Assay Low Enriched Uranium (HALEU) while still maintaining acceptable system mass. Other fuel forms could also be considered.
5. If Iodine-135 (a fission product) can be exhausted during the engine burn, there will be no restrictions on engine restart related to Xenon-135 poisoning,
6. If certain other fission products can be exhausted during the engine burn, operational constraints associated with shutdown decay heat removal will be mitigated.
7. If successfully developed, the CNTR would have a high specific impulse (~1800 s) at high thrust, which may enable viable near-term human Mars exploration by reducing round-trip times to ~420 days. The CNTR could also use a storable propellant at an Isp of ~900 s, enabling long-term in-space storage of a dormant system.

Initial Risk Reduction Efforts

Initial CNTR risk reduction efforts will focus on demonstrating technologies and engineering approaches needed for the CNTR to succeed. Some of those technologies and engineering approaches are as follows.

1. Adequate heat transfer between the metallic liquid uranium and the propellant must be demonstrated.
2. A porous rotating cylinder wall must be developed that allows propellant to flow into the cylinder while not allowing molten uranium to be forced out (by the centrifugal force) through the propellant flow passages. The porous wall should also be designed to help ensure adequate mixing between the propellant and uranium by finely distributing the inflowing propellant and by distributing the propellant flow to match the axial power profile within the rotating cylinder.
3. A coating must be developed for the inside of the rotating cylinder wall that is compatible with liquid uranium and all potential propellants at ~1500 K.
4. The rotating cylinder itself must be designed and fabricated, with transpiration and film cooling as needed to avoid potential hot spots.
5. Reliable methods for rotating the cylinders at several thousand RPM must be developed, and methods for accommodating the failure of individual cylinders must be devised.
6. Methods for startup and shutdown that minimize the loss of uranium fuel and avoid vibrational instabilities must be devised.
7. The reactor and cylinder exit must be designed to ensure that the uranium loss rate from the system is acceptable, with a HALEU loss goal of <0.01% of the propellant mass.
8. Methods for replenishing HALEU (as needed due to burnup or entrainment in the propellant) must be devised.
9. The neutronic design of the core must be optimized. Experience from previous (lower temperature) liquid reactor development programs should be used to ensure stable operation during startup, operation, and shutdown.
10. Methods for incorporating the CNTR reactor into an NTP engine must be devised. The CNTR uses a moderator block approach. Methods used for incorporating traditional NTP reactors into an NTP engine with a moderator block may be directly applicable.
11. A rapid, affordable CNTR development program must be devised. In addition to state-of-the-art computational work, early proof of concept experiments will be important.

CONCLUSIONS

A high thrust propulsion system capable of providing 1800 s Isp could enable 420-day round trip human Mars missions and other advanced space missions. The ability to efficiently use any volatile as propellant could also greatly facilitate the development of in-space resources such as asteroids and Kuiper Belt objects. The CNTR is one potential approach for providing such capability. Modern reactor design, materials, engineering, computational techniques, and experimental techniques will be used to address key potential issues with the CNTR.

ACKNOWLEDGMENTS

The authors would like to acknowledge Michael Eades for initial neutronic calculations related to the CNTR and Thomas Godfroy for initial drawings and design of experiments. Numerous students and recent graduates have also made significant contributions to refining the CNTR conceptual design and design approach. These include Ethan Fisher (Mississippi State University), Tyler Gates (Texas A&M University), Darrin Leer (University of North Carolina Charlotte), Miller McSwain (University of Tennessee Knoxville), and Rittu S. Raju (University of Michigan). Part of this work is supported by the NASA Space Technology Research Fellowship (Grant Number: 80NSSC18K1161) and the NASA Internship Program. Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Nuclear Energy under contract DE-AC02-06CH11357.

REFERENCES

1. D. R. Koenig, *Experience Gained from the Space Nuclear Rocket Program (Rover)*, LA-10062, Los Alamos, New Mexico (1985).
2. J. MCCARTHY, "Nuclear Reactors for Rockets," *Jet Propulsion 24*, p. 36 (1954).
3. S. T. NELSON, and J. GREY, "Conceptual Design Study of a Liquid-Core Nuclear Rocket," *Journal of Spacecraft and Rockets*, Vol. 2, No. 3, p. 384-391 (1964).
4. R. G. Ragsdale, "Mars in 30 Days by Gas-Core Nuclear Rocket," *Astronautics and Aeronautics*, Vol. 10, p. 65-71 (1972).