2004

NASA FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
ALABAMA A&M UNIVERSITY

MODELING AND TESTING OF NON-NUCLEAR, HIGH-POWER SIMULATED NUCLEAR THERMAL ROCKET REACTOR ELEMENTS

Prepared By:	Daniel R. Kirk
Academic Rank:	Assistant Professor
Institution and Department:	Florida Institute of Technology Mechanical and Aerospace Engineering Department
NASA/MSFC Directorate:	Transportation
MSFC Colleague:	Dr. Charles Schafer

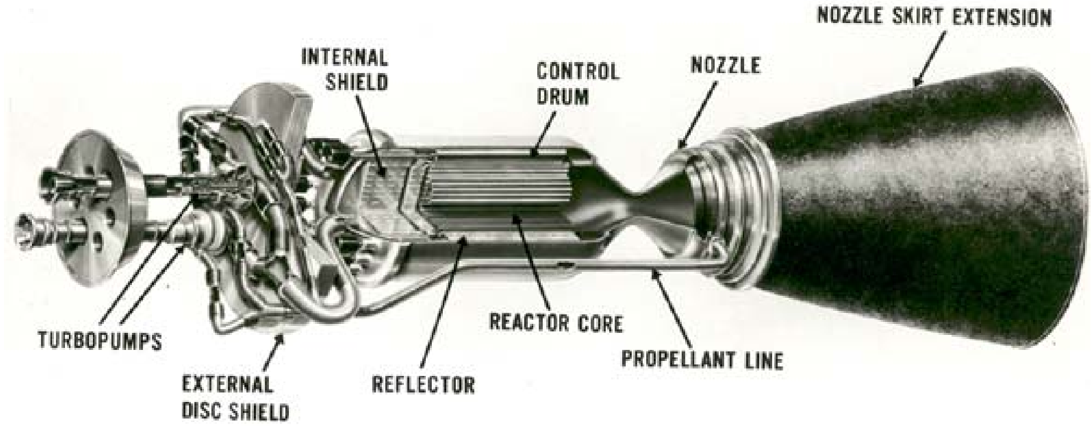
Introduction

When the President offered his new vision for space exploration in January of 2004, he said, “Our third goal is to return to the moon by 2020, as the launching point for missions beyond,” and, “With the experience and knowledge gained on the moon, we will then be ready to take the next steps of space exploration: human missions to Mars and to worlds beyond.” A human mission to Mars implies the need to move large payloads as rapidly as possible, in an efficient and cost-effective manner. Furthermore, with the scientific advancements possible with Project Prometheus and its Jupiter Icy Moons Orbiter (JIMO), (these use electric propulsion), there is a renewed interest in deep space exploration propulsion systems. According to many mission analyses, nuclear thermal propulsion (NTP), with its relatively high thrust and high specific impulse, is a serious candidate for such missions.

Nuclear rockets utilize fission energy to heat a reactor core to very high temperatures. Hydrogen gas flowing through the core then becomes superheated and exits the engine at very high exhaust velocities. The combination of temperature and low molecular weight results in an engine with specific impulses above 900 seconds. This is almost twice the performance of the LOX/LH_2 space shuttle engines, and the impact of this performance would be to reduce the trip time of a manned Mars mission from the 2.5 years, possible with chemical engines, to about 12-14 months, [1, 3, 4, 6, 8, 11, 17, 23].

Nuclear rocket engines are not a new concept, and were designed, built and tested under the Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) program from 1956-1972, but were never implemented into the space program. An excellent summary of the Rover/NERVA program is given in Reference [8], with many more details about the program contained in References [1, 4, 7, 23, 26]. An example of a nuclear thermal rocket and cross-section of the reactor core developed during the NERVA project are depicted in Figure 1. Many of the reactor and system concepts that are the subject of contemporary interest are similar to those depicted in Figure 1, although new advancements in materials fabrication and geometries have arisen since the NERVA Project, [3, 21, 23, 25]. Unfortunately, despite the nearly $10 billion (1992 constant dollars) invested, the promises of aerospace nuclear propulsion remained unrealized. The past four decades have witnessed repeated episodes in which nuclear propulsion projects are initiated and development and testing take place, only to be followed by growing doubts about the merit or utility of the proposed applications, and ultimately the project's cancellation. However, with a new, energetic, clearly thought out vision for space exploration, NTP may finally prove itself a “superior capability in the space domain” and “the day is not far off when nuclear rockets will prove feasible for space flight,” [6].

The work presented herein qualitatively and quantitatively defines a non-nuclear test program to characterize the heat transfer processes attendant to a single fuel-element, and a single cooling channel in a nuclear thermal rocket. A model employing the current understanding of heat transfer processes taking place within the reactor core has been developed to facilitate the design of an experimental test bed. The goal of the experiment is to provide NASA MSFC with a capability for assessing and evaluating candidate NTP materials over a range of conditions relevant to nuclear rocket missions.



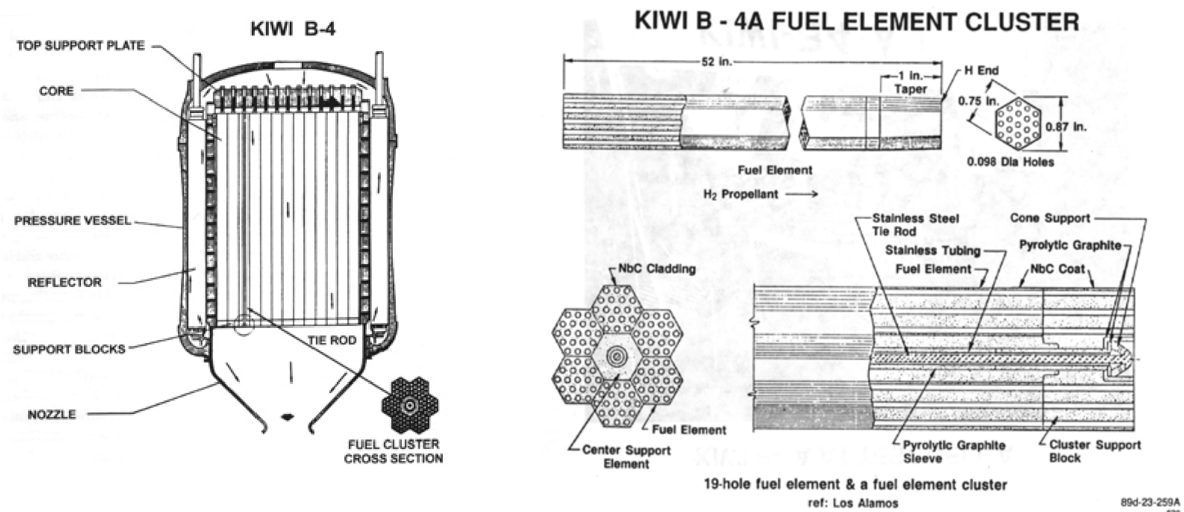


Figure 1: Typical Rover/NERVA Nuclear Reactor Configuration and Core Cross-Section.

As indicated in Reference [17], “One of the key questions that has arisen… is [how] to test a nuclear rocket engine in the current societal environment. Unlike the Rover/NERVA programs in the 1960’s, the rocket exhaust can no longer be vented to the open atmosphere.” Additionally, since the nuclear and heat transfer processes taking place within a NTP device are essentially decoupled, there exists compelling motivation to learn as much as possible through a non-nuclear test program. Such non-nuclear experiments would be a safe, cost-effective, and beneficial precursor to nuclear testing.

Heat Transfer and Fluid Dynamics Modeling Results

Among the research issues attendant to the development of a nuclear thermal rocket engine is the need to have a detailed understanding of the high temperature, high power heat transfer issues associated with extracting thermal energy from a nuclear power source with hydrogen as the working fluid. An important first step in gaining this understanding is developing analytical models of simulated nuclear thermal reactor cooling elements to help understand the heat transfer processes taking place. Furthermore, it is critical to accurately model the hydrogen thermal and transport properties at these elevated temperatures and pressures, [18, 19, 20, 22, 24]. An example of results from a model, which simulates the heat transfer mechanisms taking place in a typical cooling channel, is depicted in Figure 2. The upper figure illustrates reactor power distribution as a function of axial location along (solid line) and the integrated power level versus axial position along the reactor (dashed line). The integrated power level is computed from reference data, [1, 3, 8, 11] for a single element, single cooling channel by taking the total reactor power and dividing by the number of cooling holes. This value is then used as an input for actual reactor power distribution based on reactor physics. For the case examined here, a 5 GW reactor was selected, with an equivalent power per cooling channel of about 55 kW.

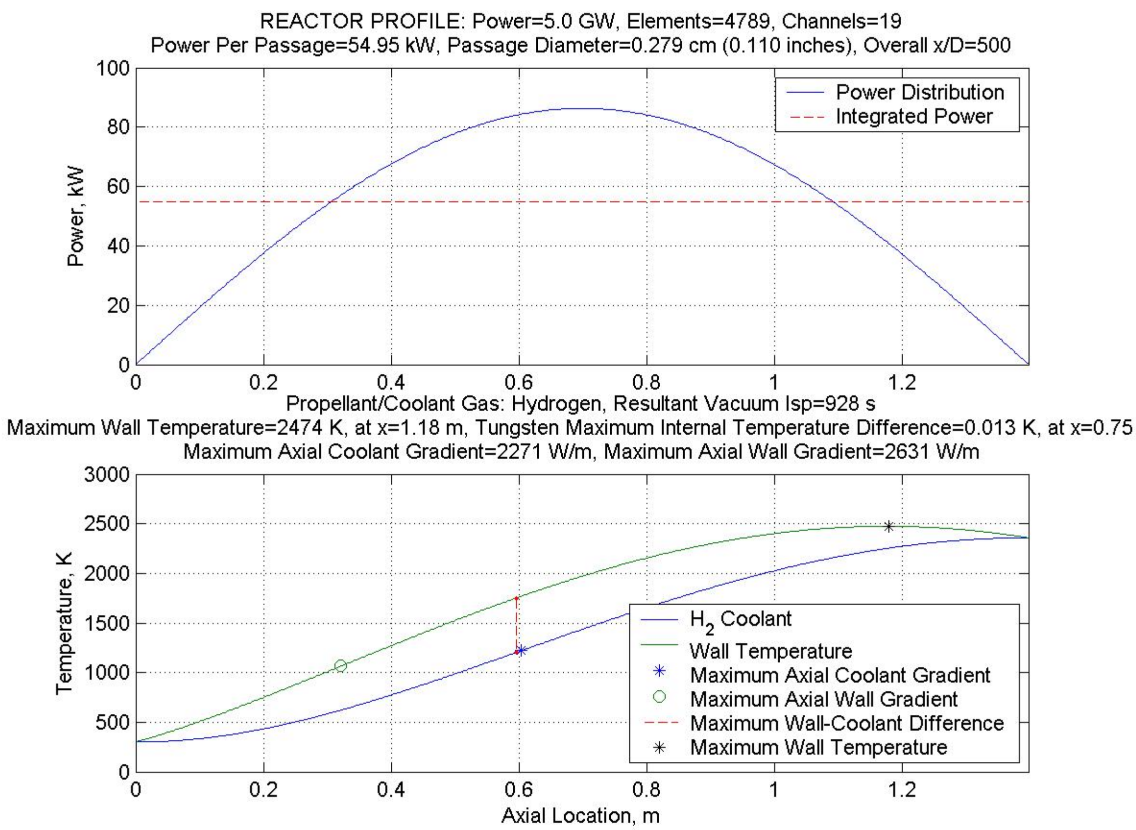


Figure 2: Example of Heat Transfer Model Results for a Single Cooling Channel of a NERVA-Type NTP Rocket

The lower plot depicts the H_2 coolant/propellant temperature and the inner wall temperature. The location of the maximum H_2 temperature is at the exit of the channel, whereas the maximum wall temperature is typically located about 80 percent downstream. Also shown are the location and value of the maximum axial gradients in coolant temperature and in wall temperature, and the location of the maximum axial difference between the wall and fluid temperatures. Both of these regions have experienced material failures in prior NERVA experiments, and are important to capture in an experimental simulation.

Experimental Design Considerations

Although the ultimate goal of the experiment is to investigate candidate nuclear materials in hot hydrogen flow, the use of hot hydrogen introduces handling, safety and cost issues that must be carefully addressed. Significant knowledge may be gained through the use of inert, surrogate test gases such as helium, nitrogen and argon. In such experiments, non-dimensional temperatures and heat transfer coefficients may be matched with actual hot hydrogen tests and the behavior of materials and the physical processes taking place at these evaluated conditions may be explored, [9, 18]. Validation of data acquisition, instrumentation and diagnostic capabilities of the facility can be completed prior to the additional complexities associated with hot hydrogen. Furthermore, less costly test articles, made of materials such as steel or tantalum, which do not have to be impervious to hydrogen, may be utilized. A model to provide the appropriate scaling parameters (mass flow, geometry, power settings, pressure, etc.) was developed to guide a test program using substitute fluids.

In order to meet the requirements of an experiment with flowing hot hydrogen, a series of preliminary safety, storage, handling and venting concerns were addressed. Fortunately, preliminary tests will utilize relatively low flow rates of hydrogen (1-2 g/s) and will not require additional complexities such as a dedicated storage facility, post-test hydrogen collection or burn stacks. Readily available, standard bottles will be utilized for preliminary investigations.

The experiment will be located in a 15 x 15 x 10 m dedicated test cell at the Propulsion Research Laboratory. The simulated elements will be housed in a 2 m long and 23 cm diameter cooled vacuum chamber, which contains multiple viewing and instrumentation ports. Due to elongation of the test article at high temperature, bellows fittings to relieve thermal expansion stresses will be located at each end. A 100 kW inductive heating system, which is available at the PRL, will be utilized to generate the intense thermal boundary conditions. Heating coils will be designed to provide a power input profile similar to that shown in the upper diagram of Figure 2 (recall that each cooling channel removes ~ 55 kW from the reactor), [27]. Because of the thermal molecular and transport properties of argon, an entire cooling element (19 cooling holes) may be simulated at these power levels at actual temperatures and heat fluxes. Diagnostics for temperature measurement will include non-intrusive optical pyrometers, which are capable of measuring external and internal surface temperatures along axial locations of the test article.

Future Applications for the PRC

The data obtained from these experiments will be utilized to gain valuable knowledge about the heat transfer processes taking places at elevated temperatures and pressures. The proposed experiment will be the first ever to operate at such extreme thermal conditions and large length-to-diameter ratios (L/D~500) with hot hydrogen flow. The data will be compared with known convective heat transfer correlations and appropriate coefficients will be determined. Furthermore, valuable data about materials integrity and suitability as a reactor fuel will be gained. The structural degradation and mass loss impact due to flowing hot hydrogen on candidate materials will also be assessed. These data will be critical in guiding the design of a next generation nuclear thermal rocket system.

Resources

This project utilized MATLAB for the heat transfer and fluid mechanic analyses, as well as for establishment of a hot hydrogen database. Numerous texts, reports, publications, workshop summaries, etc. were used to establish a technical and historical context of previous NTP technologies and to form the reference comparison cases. Expertise and exchange of ideas from several MSFC directorates (TD 06, TD 40, SD 46, and ED 33) was established to foster collaboration and expedite specification of appropriate diagnostic and instrumentation.

Conclusion

The Propulsion Research Laboratory at NASA Marshall Space Flight Center is uniquely suited to lead in the development of a next generation nuclear thermal rocket engine. To facilitate this process, a non-nuclear, safe, cost-effective experimental program has been developed with the ultimate goal of providing valuable information on heat transfer and material properties in a flowing hot hydrogen environment. When completed, the experiment will be capable of simulating conditions inherent to NTP systems, but never before investigated in a laboratory setting.

Acknowledgments

The author would like to thank Dr. Charles Schafer, Dr. William Emrich, Harold Gerrish, and Dr. Stephen Rodgers, as well as the entire team of engineers and scientists at the Propulsion Research Laboratory. Additionally, the advice and expertise in the areas of materials science and diagnostics from Dr. Binayak Panda and Dr. Jan Rogers is very much appreciated. I look forward to working with each of you in the future to bring this promising experiment to fruition. Finally, sincere gratitude to Dr. Michael Freeman, Dr. Razi Hassan, Dr. Gerald Karr, and Dr. Jeanelle Bland Day for their superior efforts in directing and coordinating the NASA Summer Faculty Fellowship Program.

Selected References

1. Angelo, J.A., and Buden, D., Space Nuclear Power. Orbit Book Company. © 1985.
2. Anghaie, S. Personnel Communication at NASA MSFC on July 20, 2004.
3. Blevins, J.A., Patton, B., Rhys, N.O., Schmidt, G.R., “Limitations of Nuclear Propulsion for Earth to Orbit,” AIAA 2001-3515.
4. Bussard, R.W. and DeLauer, R.D., Fundamentals of Nuclear Flight. © 1965, McGraw-Hill, Inc.
5. CHEMKIN Collection III: Thermodynamic Database User Manual.
6. Crouch, H.F., Nuclear Space Propulsion. © 1965, Astronuclear Press.

7. El-Genk, M.S., A Critical Review of Space Nuclear Power and Propulsion. American Institute of Physics. © 1994.
8. Finseth, J.L., “Rover Nuclear Rocket Engine Program: Overview of Rover engine Tests, Final Report,” Contract NAS 8-37814.
9. Fowler, J.M. and Warner, C.F., “Measurements of the Heat Transfer Coefficients for Hydrogen Flowing in a Heated Tube.” ARS Journal, p.266-267, March 1960.
10. Furman, E. "Thermal Hydraulic Design Analysis of Ternary Carbide Fueled Square-Lattice Honeycomb Nuclear Rocket Engine," in 16th Symposium on Space Nuclear Power and Propulsion, edited by M.S. El-Genk et al., New York, AIP Conference Proceedings, 1999.
11. Given, J.A. and Anghaie, S., “A Computational Model For Thermal Fluid Design Analysis of Nuclear Thermal Rockets,” Nuclear Technology, Vol. 117, Jan. 1997, pp. 87-108.
12. Glasstone, S. and Sesonske, A., Nuclear Reactor Engineering. ©, 1967, Litton Educational Publishing, Inc.
13. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion. 2nd Edition, © 1992, Addison-Wesley Publishing Company, Inc.
14. Howe, S.D., “Assessment of the Advantages and Feasibility of a Nuclear Rocket for a Manned Mars Mission,” Proceedings from Manned Mars Mission Workshop, Marshall Space Flight Center, Huntsville, Alabama. June 10-14, 1985.
15. Howe, S.D., “High Energy Density Propulsion – Reducing the Risk to Humans in Planetary Exploration.”
16. Howe, S.D., “Reducing the Risk to Mars: The Gas Core Nuclear Rocket.” Los Alamos National Laboratory.
17. Howe, S.D., Travis, B., and Zerkle, D.K., “SAFE Testing Nuclear Rockets Economically,” Los Alamos National Laboratory.
18. Incropera, F.P., and De Witt, D.P., Introduction to Heat Transfer. 2nd Edition, © 1990, John Wiley & Sons, Inc.
19. King, C.R., “Compilation of Thermodynamic Properties, Transport Properties, and Theoretical Rocket Performance of Gaseous Hydrogen.” NASA TN D-275. April 1960.
20. Kubin, R.F. and Presley, L.L, “Thermodynamic Properties and Mollier Chart for Hydrogen from 300 °K to 20,000 °K.” NASA SP-3002. 1964.
21. Lawrence, T.J., Witter, J.K., Humble, R.W., Nuclear Rocket Propulsion Systems. Space Propulsion Analysis and Design, Chapter 8.
22. McCarty, R.D., “Hydrogen Technological Survey – Thermophysical Properties,” NASA SP-3089, 1975.
23. Nuclear Thermal Propulsion: A Joint NASA/DOE/DOD Workshop. NASA Conference Publication 10079. 1991.
24. Patch, R.W., “Thermodynamic Properties and Theoretical Rocker Performance of Hydrogen to 100,000 K and 1.01325×10^8 N/m^2.” NASA SP-3069. 1971.
25. Powell, J., et al., “MITEE: An Ultra Lightweight Nuclear Engines for New and Unique Planetary Science and Exploration Missions,” Plus Ultra Technologies, Inc. Report No. PUR-1, July 24, 1998.
26. Schmidt, H.R. (Chairman), Guidebook for the Application of Space Nuclear Power Systems. Report of the Committee on The Nuclear Space Program. January 1969.
27. Zinn, S., and Semiatin, S. L., “Coil Design and Fabrication: Basic Design and Modifications.” Journal of Heat Treating. June 1988, p.32-36.