

## CNTR: Explanation of Propellant Flow and Description of Initial Experiments

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### INTRODUCTION

The Centrifugal Nuclear Thermal Rocket (CNTR) is one of few designs that could enable extremely rapid missions to Mars using currently available technologies. McCarthy conducted the first conceptual study of high performance nuclear thermal propulsion (NTP) and published his findings in 1954<sup>[1]</sup>. High performance NTP was further investigated by Princeton researchers in the early 1960s<sup>[2]</sup> and continued by other researchers throughout the 60s, 70s, and 80s. An interagency panel conducted in 1991 demonstrated the potential of liquid core nuclear rockets, such as the Liquid Annular Reactor System (LARS), to reach temperatures up to 5000 K and specific impulses ( $I_{sp}$ ) up to 2000 s<sup>[3]</sup>. A more recent study of versatile NTP asserts that a similar propulsion system, the Centrifugal Gas Core Reactor (CGCR), can reach an estimated  $I_{sp}$  of 1800 s<sup>[4]</sup>. An  $I_{sp}$  of that magnitude significantly reduces travel times and consequently health risks to flight crews<sup>[4]</sup>. The CNTR seeks to build on the work of previous liquid core NTP systems and aims to reach an  $I_{sp}$  in the range of 1500 s to 1800 s while using hydrogen as the propellant. However, the CNTR is not limited to hydrogen and can instead utilize other volatiles such as ammonia, methane, or water at about half the  $I_{sp}$  of hydrogen<sup>[4]</sup>. This flexibility expands the CNTR's mission range considerably by providing propellant storability and the potential for directly using volatiles available in-situ.

### CNTR Design and Propellant Flow Path

Before closely examining specific interfaces of the CNTR system, it is important to understand the CNTR design and propellant flow path. The CNTR utilizes a matrix of centrifugal fuel elements (CFEs) like the 19 CFE core block configuration displayed in Fig. 1. Each CFE consists of a molten uranium fuel source contained in a fritted centrifuge. The fritted surface is located along the length of the centrifuge and allows for radial propellant flow into the molten uranium. The 19 CFE configuration is tentative as further studies of the system's neutronics identify more mass and energy efficient CFE sizes and layouts. Another possible layout involves using several solid core rods to preheat the propellant to temperatures around 1200 K to 1700 K before

travelling into a single, larger CFE where the propellant is "superheated" to the desired temperature above 5000 K. This configuration could possibly improve propellant separation and heat transfer, but, for the purposes of this study the 19 CFE matrix will be discussed.

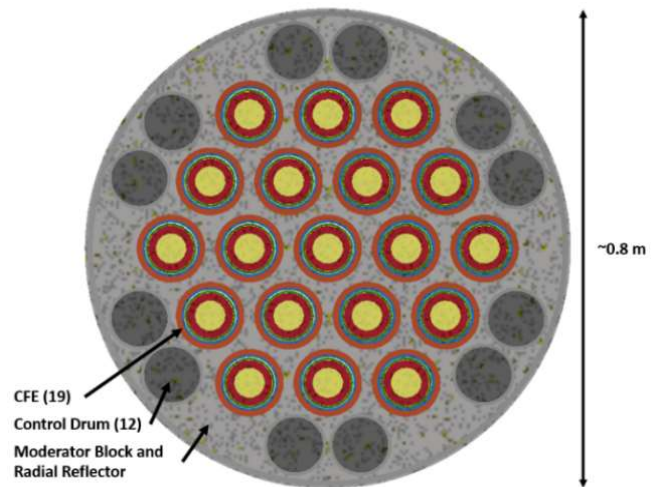


Fig. 1. Circular cross section of 19 CFE matrix.

The propellant flow in the CNTR is multipurposed. Before being heated by the molten uranium fuel source and ejected for thrust, the propellant is used to cool various system components and power the centrifuge rotation. The propellant flow path is depicted in Fig. 2. For clarity, the propellant being used in the following description is hydrogen but can be replaced by the other mentioned propellants. The hydrogen exits its storage vessel as a gas, enters the inlet plenum at the top of the assembly, and flows around the various external components of the system. This brings the propellant closer to the CFEs while also cooling the moderator block, radial reflectors, core drums, and other system components outside the CFEs to an acceptable temperature under 800 K. Then the hydrogen flows towards the nozzle end of the configuration, enters the gas inlet manifold, cools the nozzles, penetrates the moderator block via access paths below the centrifuges, and travels axially along the outside of the centrifuges.

The propellant then passes the turbines, generating power for the centrifuge. Past the turbines, the hydrogen path is rerouted by the redirection disk into perforations at the top of the centrifuge, as shown in Fig. 2. The hydrogen pushes axially downward, this time between the centrifuge outer wall and fritted silicon carbide layer. The hydrogen then passes through the fritted surface into the liquid uranium. Inside the liquid uranium, the hydrogen will be heated to a goal temperature exceeding 5000 K before entering the center cavity created by the centrifuge rotation. The hydrogen will then exit at a high exhaust velocity out the nozzle and create thrust.

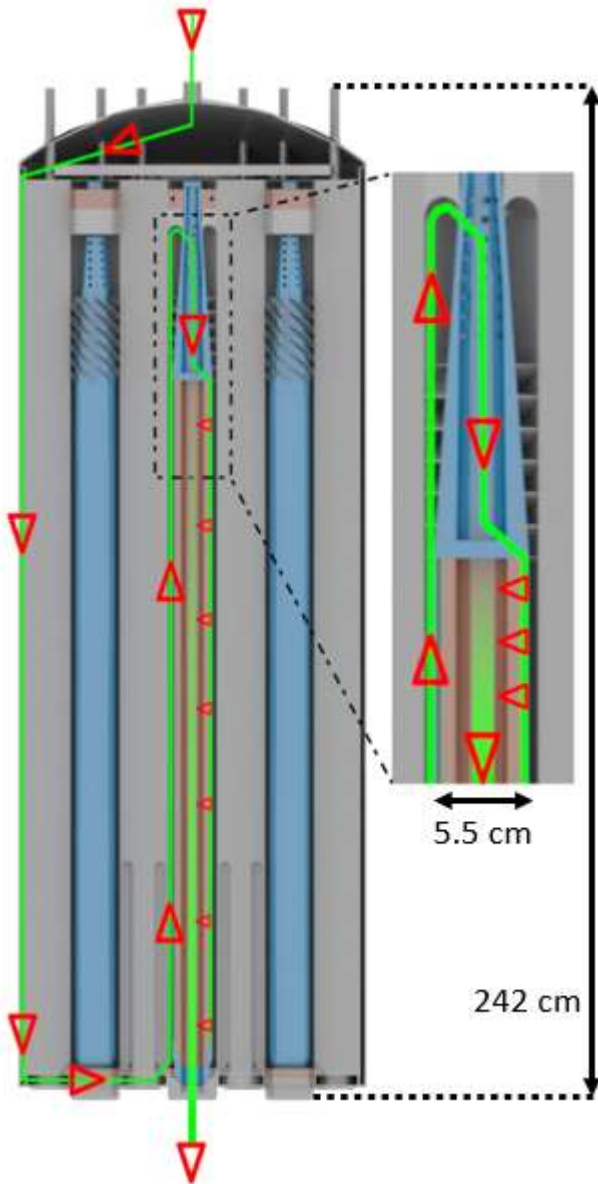


Fig. 2. Propellant flow path from inlet plenum to exhaust out the nozzle (left). View of propellant’s redirection and radial entry into a single CFE (right).

### CFE Temperature Profile

Each CFE undergoes nuclear fission to heat a propellant that is ejected out the nozzle, generating thrust. Thrust is related to exit velocity by equation [1], and exit velocity is related to exit temperature by equation [2].

$$F = \dot{m} V_e + (p_e - p_o) A_e \quad (1)$$

$$V_e = M_e \sqrt{\gamma R T_e} \quad (2)$$

Here,  $F$ ,  $\dot{m}$ ,  $V_e$ ,  $p_e$ ,  $p_o$ ,  $A_e$ ,  $M_e$ ,  $\gamma$ ,  $R$ , and  $T_e$  are thrust, mass flow rate, exit velocity, exit pressure, free stream pressure, exit area, exit Mach, specific heat ratio, gas constant, and exit temperature, respectively. Thus, maximizing the propellant temperature increases the exit velocity and thrust.

By utilizing a primarily liquid core system, the total heat transfer to the propellant is much higher than in a solid core system. A primarily liquid core element can push propellant temperatures to values exceeding 5000 K. While 5000 K is above the boiling point of molten uranium, the desired outlet pressure and centrifuge pressure of the system is expected to exceed the vapor pressure of the molten uranium, reducing uranium vaporization and increasing uranium condensation. Fig. 3 shows the desired temperature profile within a single CFE cross section.

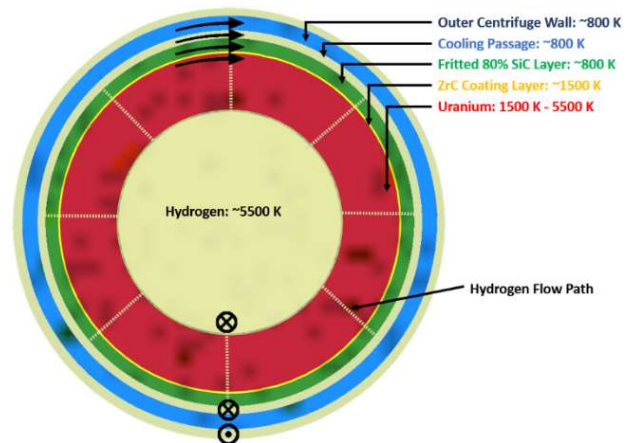


Fig. 3. Circular cross section of a single CFE with the desired temperature profile.

### Molten Uranium Leakage and Entrainment

While using liquid core elements increases the maximum temperature of the system, it poses many unique challenges such as uranium loss from leakage and entrainment. To counteract liquid uranium leakage from the nozzle, each fuel element is contained within a centrifuge, creating a CFE. The centrifuge rotates at a constant angular velocity and forms a vortex that displaces the liquid uranium towards the outer edges of the CFEs. This also creates a pocket for propellant flow at the center of each CFE. However, while the propellant

flows radially from the outer edge of the CFE into the center of the CFE, it is possible that some uranium liquid droplets, or even small amounts of uranium vapor, can become entrained in the propellant flow. To reduce uranium loss from entrainment, the ends of the CFE will be tapered. This rotating tapered region acts as a net, catching the liquid uranium droplets and uranium vapor as depicted in Fig. 4. This net area will be maintained at a lower temperature than the rest of the CFE, allowing condensation of the uranium vapor. The centrifugal force will push the condensed uranium vapor and liquid uranium droplets back into the main liquid uranium region, reducing or possibly eliminating uranium entrainment.

Maintaining the desired temperature distribution and reducing entrainment to acceptable levels will be a challenge due to the complex discrete-continuous fluid dynamics and lack of material properties in the extreme temperatures of the system. To begin to address the complex system, a series of experiments purposed with breaking down the complex propellant-uranium interface will be discussed in the following sections. These experiments focus on creating a reliable propellant flow channel in the center of each CFE, understanding propellant dynamics within the uranium, and quantifying the effects of temperature profiles within each CFE.

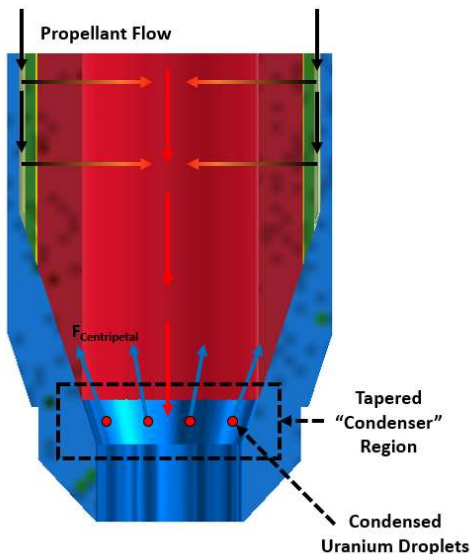


Fig. 4. Simplified centrifuge representation displaying the tapered "condenser" region used to catch liquid uranium droplets and uranium vapor.

### Material Analogs

As discussed, a series of simplified experiments for development of the CNTR are outlined in the following sections. To reduce safety complications and costs, early experiments will use more readily available materials comparable to the final hydrogen-uranium system. Initially,

gaseous nitrogen will replace the hydrogen as the propellant, and water will replace the uranium as the liquid medium. While these materials are not the best representations of the final system, the material analog serves multiple purposes. The primary reason is that conducting initial experiments with the nitrogen-water system will be safer while also providing key information about the propellant-liquid interface physics. Additionally, nitrogen and water are easily obtained and stored. This is essential to the workflow of the project, as it is likely that many revisions will need to be made over an extended time period.

The initial results obtained from these experiments illuminates the behavior of discrete-continuous fluid dynamics that can also be applied to the hydrogen-uranium interface, albeit with some inaccuracies. The system behavior can then be modeled with a computational fluid dynamic (CFD) software package such as OpenFOAM or ANSYS Fluent and validated with the nitrogen-water system. These models can then be adjusted to a more advanced, testable system, such as nitrogen and molten tin or gallium. This will more accurately reflect a gas and molten metal interface and provide information on the setup, testing, and performance of the hydrogen-uranium system.

### FIRST EXPERIMENT

There are many interactions in the proposed system and using an iterative testing scheme to add layers of complexity will aid in long term progression of the design. The first task will focus on accurately predicting surface profiles when rotating a CFE at different angular velocities. Increasing angular velocity will cause an increase in centrifugal pressure. In an environment with gravity, the centrifugal pressure will combat hydrostatic pressure and create a parabolic profile as seen in forced vortex behavior. In an environment without gravity, centrifugal pressure is the only force acting on the liquid. Thus, the liquid surface profile created is uniform because the centrifugal pressure is independent of the height of the liquid.

During use in a rocket, however, the thrust acting on the system will create an artificial "gravity" that will likely be weaker than earth's gravity, but still generate some hydrostatic pressure. As described previously, the bottom portion of the centrifuge will be designed as a conical section to act as a net, capturing some of the entrained uranium liquid or vapor created by turbulent flow of the propellant through the uranium layer, but may also help reduce the amount of uranium flowing out of the system due to the forces generated by thrust.

This initial experiment will provide data on water surface profiles and facilitate the creation and validation of a CFD model in ANSYS Fluent. If this model can reliably predict the surface profiles generated, then the model can be applied again but with a system that more accurately reflects the uranium-propellant system. Additionally, this model can become the baseline for future models that will monitor

entrainment based on different propellant inlet characteristics. Another area of interest will be the startup and shutdown processes for the centrifuge.

A prototype testing apparatus has been designed, and materials are being collected for assembly. The current prototype is displayed in Fig. 5. The outlet is currently oriented upward to prevent water from pouring out of the centrifuge prior to startup. The taper on the upper end of the cylinder forms the conical condensation section that will be used to reduce entrainment but is not particularly important for the initial experiment. The water in the centrifuge is expected to form a surface profile according to the following forced vortex equation, equation [3].

$$z - z_0 = \frac{\omega^2 r^2}{2g}, \quad (3)$$

The variables  $z$ ,  $z_0$ ,  $\omega$ ,  $r$ , and  $g$  represent height of fluid at a certain radius, lowest point of the vortex, angular velocity, radius, and gravitational acceleration, respectively.

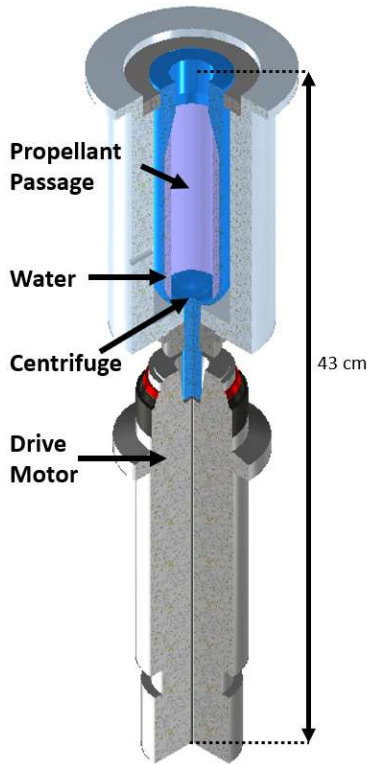


Fig. 5. Prototype of experiment setup. The drive motor rotates the centrifuge constrained by two bearings. A propellant passage is bored into the upper casing for future testing.

An example of case of this system with an angular velocity of 50 rad/s is shown in Fig. 6. Equation [3] predicts that at an angular velocity of 50 rad/s, the height of the fluid at the centrifuge wall relative to the bottom of the vortex should be 31.8 cm. A CFD model of this system constructed

in ANSYS Fluent using a coupled  $k-\omega$  Shear Stress Transport turbulence equation and a volume of fluids equation predicts the height of the fluid at the centrifuge wall relative to the bottom of the vortex to be 27.0 cm, as shown in Fig. 7.

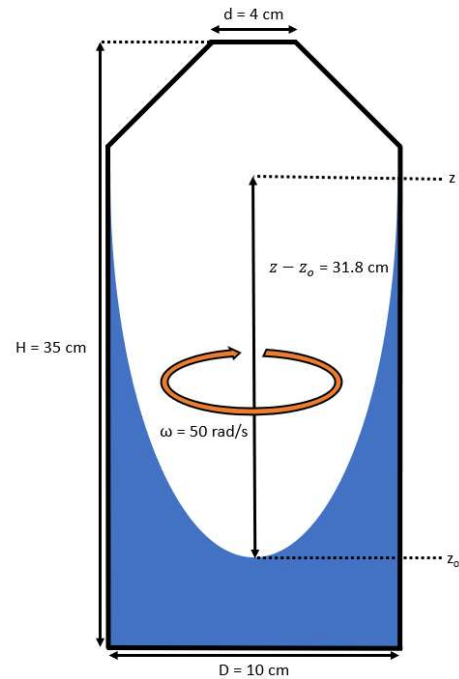


Fig. 6. Example surface profile of centrifuge spinning at 50 rad/s predicted using equation [3].

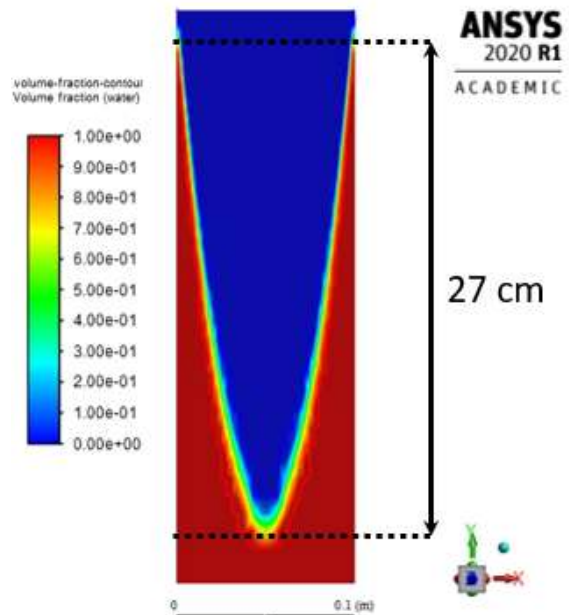


Fig. 7. ANSYS Fluent model predicting the surface profile of a vortex formed from a centrifuge spinning at an angular velocity of 50 rad/s.

## FUTURE EXPERIMENTS

The experiments to follow aim to create a one-way flow for radial propellant injection along the fritted surface. The current proposed method involves using a hydrophobic paper or spray. Once the propellant is reliably injected into the liquid with minimal backflow, the resulting bubbling or jetting behavior will be examined and quantified. Current models on bubble versus jet behavior in liquid core fuel elements are sparse in literature. The conceptual analysis conducted by Princeton in the early 1960s assert that the experimentally observed bubble shape in this sort of system is a spherical cap<sup>[2]</sup>. The current proposed method involves using a clear centrifuge and some visualization techniques and equipment to evaluate the bubble behavior. Varying the pore size and density, propellant entry velocity, and the method of application for the hydrophobic materials are all expected to affect the bubble behavior and size. Bubble behavior and size are important aspects of CFD multiphase calculations and obtaining this data will be essential to the accuracy of the models. These results will help deduce propellant action mechanisms in the propellant-uranium interface.

The final experiment to be discussed in this summary centers around the system behavior in increasing temperatures. Changing temperature profiles within the system will help quantify the heat transfer between the propellant and the liquid medium. It will also change the density and viscosity of the gaseous and liquid phases which will affect the discrete-continuous fluid interface although it is unclear to what degree. The effects of temperature change will be especially prominent with the molten metals due to the dramatic changes in viscosity. Other factors to consider will be bubble behavior, flow patterns, and exhaust temperatures for the propellant. The results from this task are essential, as there is little data on propellant-uranium interactions at high temperatures. The data collected with the nitrogen-water experiment will be essential to predicting the behavior of the uranium as the temperatures begin to reach levels of 3000 K – 5500 K.

## CONCLUSION

In summary, the CNTR is a complex system with many design challenges, particularly in the propellant-uranium centrifuge interface. Currently, there are several assumptions that will need to be confirmed or adjusted based on experiment results. One of the most important challenges in the CNTR is minimizing entrainments. The described basic experiments will help illuminate the physics of the system and begin to answer some prominent questions. One of these questions is how much vaporization can be expected? Another is how much cooling and area will be needed to capture any uranium that has vaporized? Will the vapor pressure be smaller than the centrifuge and outlet pressure

and if so can the model be reduced to only three phases: gaseous hydrogen, solid uranium, and liquid uranium? All these questions are essential to the formation of accurate models and the efficacy of the CNTR system. While the system does have some complex interactions, the overall concept is simple. By iteratively improving experiments such as the ones proposed in this paper, an accurate model representing the CNTR can be used to predict and optimize the final system's behavior. This will accelerate the CNTR's development and result in reduced mission times and increased mission success rates.

## ACKNOWLEDGMENTS

This work was supported by Universities Space Research Association, NASA Marshall Space Flight Center, and Argonne National Laboratory.

## REFERENCES

1. J. MCCARTHY, "Nuclear Reactors for Rockets," *American Rocket Society*, Vol. 24, No. 1, p. 36, (1954)
2. S. T. Nelson, "Conceptual Design Study of a Liquid-core Nuclear Rocket," Report No. 665, Princeton University, (1963).
3. J. S. CLARK, P. MCDANIEL, S. HOWE, I. HELMS, M. STANLEY, "Nuclear Thermal Propulsion Technology: Results of an Interagency Panel in FY 1991," NASA-TM-105711, NASA, (1993)
4. M. HOUTS, C. R. JOYNER, J. ABRAMS, J. WITTER, P. VENNERI, "Versatile Nuclear Thermal Propulsion," *IAC 70*, Washington D.C., Oct. 21-25, 2019. International Astronautical Congress (2019)