The Deimos Experiment: Advanced Reactor Testbed

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INTRODUCTION

Advanced reactor initiatives are growing significantly through programs nationwide. This research area includes small modular reactors, microreactors, and space reactors. Many of the reactors being designed are untested concepts. They include unique moderators, varying fuel types, high temperatures, and compact configurations. The shift in fuel type, from highly enriched uranium (HEU) to high assay, low enriched uranium (HALEU), is particularly important as it has driven many of the other changes. For example, lower enrichment requires advanced moderators, which in turn require different reflectors to make the systems compact. The change in materials including the transition from HEU to HALEU affects the temperature feedback of the systems. Additionally, these advanced reactor concepts generally have a thermal neutron spectrum in contrast to earlier fast spectrum advanced reactor. With the extensive changes from previous reactor designs, validation experiments are needed. The National Criticality Experiments Research Center (NCERC) is uniquely equipped to perform such experiments. The Deimos experiment, designed for execution at NCERC, will serve as a testbed for advanced reactor concepts. It will use HALEU fuel in a graphite matrix, provide the ability to use advanced moderators, and allow measurements of temperature reactivity coefficients (TRCs).

BACKGROUND

NCERC has two general purpose vertical lift critical assembly machines — Comet and Planet – that can and have been used for experiments supporting advanced reactors, namely the Kilowatt Reactor Using Stirling Technology (KRUSTY) and Hypatia [1,2]. Both machines function with a stationary platform and a lower moveable platen. The lower portion is moved up remotely to the stationary platform to form a critical configuration. The primary differences between the two machines are the weight limits and overall size. Planet can support 2,000 lbs (907.2 kg) and 1,000 lbs (453.6 kg) on the stationary and moveable portions, respectively, whereas Comet can support 20,000 (9072 kg) and 2,000 lbs (907.2 kg) on each of these portions. Two experiments, Hypatia on Planet and KRUSTY on Comet, have been executed in support of advanced reactors at NCERC over the last decade. Both used HEU fuel and had primarily fast neutron spectra, as is shown in Fig. 1.

The KRUSTY experiment was completed in 2017 at NCERC on Comet. This experiment used HEU fuel and beryllium oxide (BeO) reflector; it achieved temperatures up to 800 °C using fission heating and demonstrated reactivity feedback for small space reactors, among many other purposes. While successful, the KRUSTY experiment limited other operations for months after its completion because of the high dose rate fission products created during the high power levels required to produce fission heating.

The Hypatia experiment was completed in 2020 on the Planet critical assembly machine. It also used HEU fuel and focused on demonstrating the benefit of electrically heated tests to remove the dose rate issues associated with fission heating. validation of nuclear data for a unique moderator, yttrium hydride, was accomplished. Electrically heated tests provide TRCs without requiring a high fission. As such, the room is immediately accessible, and the fuel can be handled a short time afterwards.

The Deimos project will build upon the success of both KRUSTY and Hypatia, this time focusing on HALEU fuel and concepts with a thermal neutron spectrum. It incorporates electric cartridge heaters for electrically heated tests to obtain TRCs.

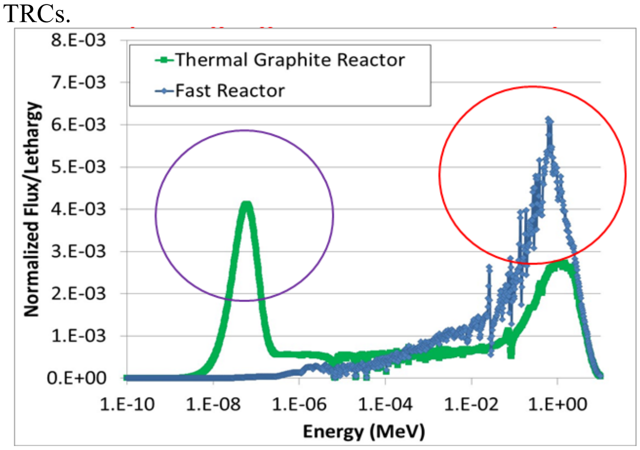

Fig. 1. Neutron spectra of thermal and fast reactors. The purple circle shows the desired validation operating region of most current advanced reactor concepts. The red circle shows the operating region of recent advanced reactor related experiments at NCERC.

EXPERIMENT DESIGN

The Deimos experiment design uses a large graphite moderator and HALEU fuel to achieve the desired thermal neutron spectrum shown in Fig. 1; Deimos has an 84% thermal neutron spectrum. The HALEU fuel is from the

Compact Nuclear Power Source (CNPS) experiment conducted at the Los Alamos Critical Experiments Facility. This fuel, known as the CNPS pellets or compacts, is TRi-structural ISOtropic (TRISO) embedded in a graphite matrix and is part of the current NCERC inventory. The graphite moderator will be comprised of two portions-- a movable core and a stationary reflector, both containing fuel. Fuel will be placed in graphite cups in stacks of 19 pellets and the filled cups will be inserted into holes in the large graphite monoliths. The pitch of the holes has been optimized to minimize the fuel mass required for criticality.

Fig. 2 shows an overall view of the Deimos experiment with a few major dimensions indicated. Electric cartridge heaters are used throughout the assembly, intermixed with the fuel, to provide the heating for TRC measurements. The full graphite portion of the assembly is heated to minimize uncertainty associated with temperature gradients. Thermocouples are used to monitor the temperature and provide data for transient analysis. The experiment is designed to reach an overall steady state temperature of 150 °C.

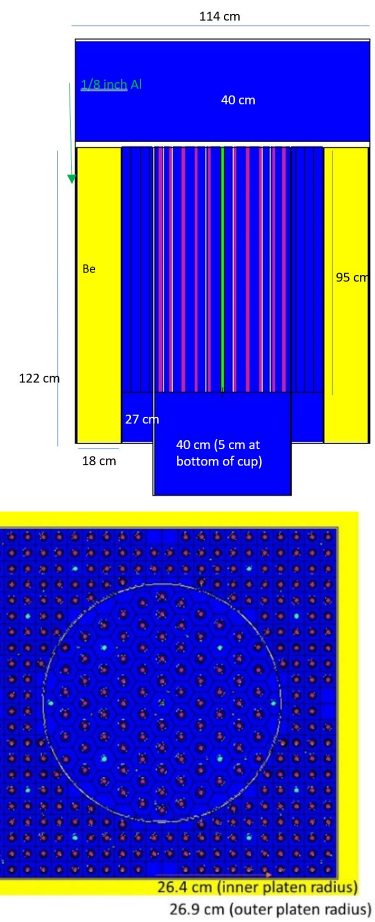

Fig. 2. Deimos experiment layout and overall design. Blue=graphite; yellow=Be; pink=fuel; cyan= heater

Fuel

The fuel compacts, shown in pink in Fig. 2, used for the Deimos experiment are the CNPS compacts from the NCERC inventory [5]. This fuel is composed of TRISO particles, about 500 microns in diameter, with 19.9 wt.% enriched ^{235}U embedded in a graphite matrix. The containers with this fuel were recently opened, and pellets were verified to be in good condition. Fig. 3 shows one compact from the recent opening, where a sample of the pieces was weighed and measured. This fuel has not been used since prior to moving to NCERC in the early 2000s. It was noted that some particles had separated from the individual pellets. This is believed to be due to a much larger packing fraction in the older fuel than what is made today (60 vs 40 vol.%). Given the national and global interest in HALEU and specifically TRISO HALEU, this fuel, even at a higher packing fraction, will provide essential data for advanced reactor validation.

Fig. 3. One CNPS compact, measured during the recent opening and inspection.

Moderator

The moderator material used for the Deimos experiment is graphite in several large pieces designed specifically to fit on the Comet critical assembly. One section, attached to the movable platen, is a 95 cm tall monolith with a diameter of 53.1 cm. Spanning the monolith are optimally spaced holes for fuel and heaters, based on an extensive pitch optimization study conducted with MCNP. To enable the removal of fuel, the compacts are loaded in graphite cups that are lowered in the holes in the moderator. There is a mating graphite monolith on the stationary platform. This monolith also has optimally spaced holes for fuel and heaters. The exterior dimensions of the stationary graphite monolith are 78.14 cm x 78.14 cm (length by width).

Outer Reflectors

Outside the stationary graphite moderator is a beryllium (Be) reflector made up of many smaller, stacked pieces from within the NCERC inventory. The Be reflector is shown as yellow in Fig. 2. Additionally, a thin layer of aluminum holds the pieces tightly together.

The outer axial reflectors are solid graphite pieces without holes for fuel or heaters. The bottom portion matches the diameter of the moderator monolith above it, 53.1 cm, and is 40 cm tall. The top portion matches the outermost dimensions of the Be reflector, 114 cm, and is also 40 cm tall. The top portion is made of many smaller pieces for handling.

Heaters

The heaters, composed primarily of stainless steel and shown in cyan in Fig. 2, are 90 cm tall and 1.27 cm diameter. They are placed in both the moveable and stationary portions and arranged to provide even heating of the assembly.

EXPERIMENT EXECUTION PLAN

To achieve the baseline goals of the Deimos experiment, a critical configuration will be built, and TRCs will be measured. To achieve the critical configuration, a 1/M approach to critical will be followed, following the guidance of ANS-1, *Conduct of Critical Experiments* [6]. Simulations have been performed to inform all aspects of the experiment, including determining the fuel pitch [7]. Simulations were performed using the MCNP6.2 ® neutron transport code, and ENDF/B-VIII.0 cross sections [8-9].

Simulation Overview

All materials were modeled as solid pieces. The TRISO fuel was modeled as homogenized pellets in a graphite matrix but verified with heterogeneous and equivalent calculations as well [10-12]. Radial gaps and most axial gaps were also modeled. Compositions, with the best-known information about isotopics and impurities, were included for all materials.

Simulations of the Initial Approach to Critical

The simulations were completed for the initial approach to critical, where fuel was incrementally added to all four quadrants of the outer reflector. It was determined that the center moveable portion, fully loaded with fuel, was sufficiently subcritical (k_{eff}=0.66) to be used as the starting configuration. Additions of fuel were done by adding four full cups (19 pellets each) at a time. Fig. 4 shows the simulated approach, based on this method.

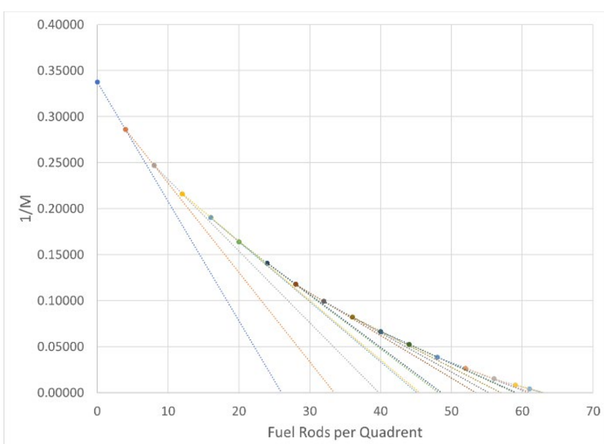

Fig. 4. 1/M Simulated Approach to Critical, as a Function of Fuel Rods per Quadrant.

Simulations of the Final Approach to Critical

For the expected number of fuel rods per outer quadrant, 63, an approach on separation distance, i.e. the distance from full out to full in, was simulated. Zero indicates the point where the two surfaces are even. An approach based on the insertion of one portion of fuel into another is generally non-conservative, so simulations are especially important in predicting the behavior. Fig. 5 shows the loading for this predicted critical configuration. Fig. 6 shows the 1/M plot as a function of separation distance. Once a critical configuration is found, reactivity will be added up to 80 cents excess so that configurations with negative TRCs can be measured.

The graphite was modeled as the exact type dictated by procurement specifications. Minimal impurities in the graphite, both the TRISO matrix and the cups/ monoliths, were selected to avoid complications uncertainties in the results associated with neutron absorbers. For the critical configurations, impurities are expected to have an effect on k_{eff} of less than 1000 pcm. They were modeled as boron and vanadium, the bounding impurities in Merson brand graphite.

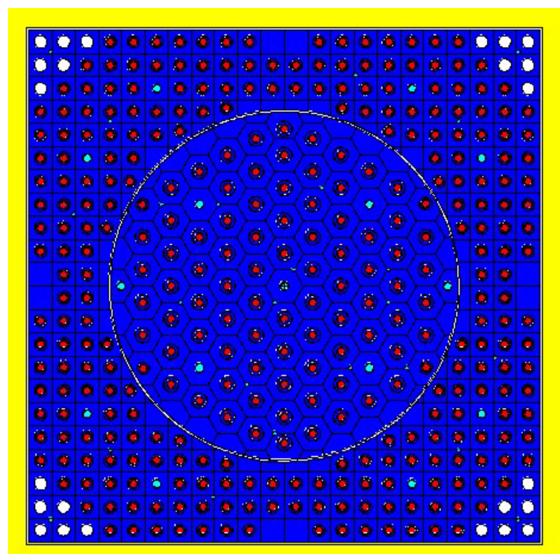

Fig. 5. Cross Sectional View of Predicted Critical Configuration, 63 Fuel Cups per Outer Quadrant.

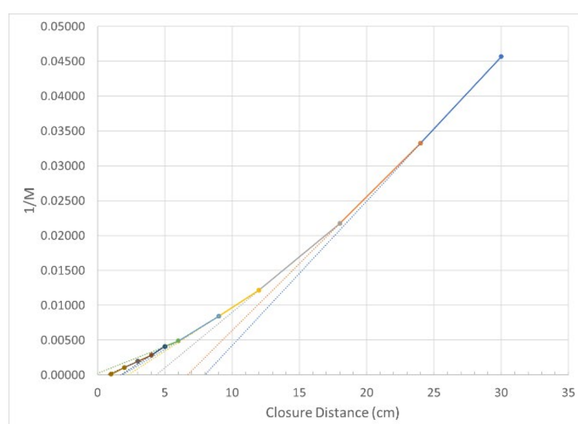

Fig. 6. 1/M Simulated Approach to Critical, as a Function of Separation Distance.

Heat Transfer Simulations

Once a critical configuration is achieved and measured, the heaters will be used to measure TRCs. This will be done by turning on all the heaters with the core in its full out position. Extensive multiphysics simulations have been completed to inform the heating profile, power needs, and expected results [13]. Heating will be conducted at a rate of 2 °C per minute in increments of 20 °C. Once a 20 °C increase is achieved, the heat will be held at a steady state to allow the temperature to equilibrate throughout the core. The exact time needed for equalizing the temperature will be determined during final component testing, which will occur once all parts have arrived at NCERC.

Once a steady temperature has been achieved across the core, the moveable portion will be reinserted into the outer reflector and reactivity will be measured. This process will be repeated and incrementally higher temperatures until the system can no longer reach critical. The experimental results will be compared to detailed heat transfer simulations. This process will determine a TRCs for the system which will apply to advanced reactors using HALEU TRISO fuel.

CONCLUSIONS

The Deimos experiment has been designed to be a testbed for advanced reactors. It has a thermal neutron spectrum, uses TRISO HALEU fuel, supports TRC measurements, and is reconfigurable. Predictive simulations have been completed for the approach to critical process and heat transfer using electrical heating. The results of the experiment will serve as a baseline for other advanced reactor designs with thermal neutron spectra. The demonstration will enable similar measurements for other advanced reactor designs and provide validation for these concepts

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