Electrically Heated Testing of the Kilowatt Reactor Using Stirling TechnologY (KRUSTY) Experiment Using a Depleted Uranium Core

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The Kilopower project aims to develop and demonstrate scalable fission-based power technology for systems capable of delivering 1 – 10 kW of electric power with a specific power ranging from 2.5 - 6.5 W/kg. This technology could enable high power science missions or could be used to provide surface power for manned missions to the Moon or Mars. NASA has partnered with the Department of Energy's National Nuclear Security Administration, Los Alamos National Laboratory, Nevada National Security Site, and Y-12 National Security Complex to develop and test a prototypic reactor and power system using existing facilities and infrastructure. This technology demonstration, referred to as the Kilowatt Reactor Using Stirling TechnologY (KRUSTY), will undergo nuclear ground testing by the end of CY 2017 at the Nevada National Security Site.

The 1 kWe variation of the Kilopower system was chosen for the KRUSTY demonstration. The concept for the 1 kWe flight system consist of a 4 kWt highly enriched Uranium-Molybdenum reactor operating at 800 °C coupled to sodium heat pipes. The heat pipes deliver heat to the hot ends of eight 125 W Stirling convertors producing a net electrical output of 1 kW. Waste heat is rejected using titanium-water heat pipes coupled to carbon composite radiator panels. The KRUSTY test, based on this design, uses a prototypic highly enriched uranium-molybdenum core coupled to prototypic sodium heat pipes. The heat pipes transfer heat to two Advanced Stirling Convertors (ASC-E2's) and six thermal simulators, which simulate the thermal draw of full scale power conversion units. Thermal simulators and Stirling engines are gas cooled. The most recent project milestone was the completion of non-nuclear system level testing using an electrically heated depleted uranium (non-fissioning) reactor core simulator. System level testing at the Glenn Research Center (GRC) has validated performance predictions and has demonstrated system level operation and control in a test configuration that replicates the one to be used at the Device Assembly Facility (DAF) at the Nevada National Security Site. Fabrication, assembly, and testing of the depleted uranium core has allowed for higher fidelity system level testing at GRC, and has validated the fabrication methods to be used on the highly enriched uranium core that will supply heat for the DAF KRUSTY demonstration.

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Introduction

The Kilopower project aims to develop and demonstrate scalable fission-based power technology for systems capable of delivering 1 – 10 kW of electric power with a specific power ranging from 2.5 - 6.5 W/kg. This technology could enable high power science missions or could be used to provide surface power for manned missions to the Moon or Mars. NASA has partnered with the Department of Energy's National Nuclear Security Administration, Los Alamos National Labs, and Y-12 National Security Complex to develop and test a prototypic reactor and power system using existing facilities and infrastructure. This technology demonstration, referred to as the Kilowatt Reactor Using Stirling TechnologY (KRUSTY), will undergo nuclear ground testing in by the end of CY 2017 at the Nevada National Security Site.

The Kilopower project began with studies examining the possibilities of using small reactors with common technology over a range of powers that could satisfy both science and exporation needs (Ref 1-2). The 1-10 kW power level was a substantial reduction from the 40 kW Affordable Fission Surface Power system which was studied a decade ago, culminating in a 10 kW demonstration unit which was designed built, and tested in the last decade (Ref 3-8). The reduction in power level from 40 kW class to the 1-10 kW power range allowed for several design simplifications including the use of monolithic cores and eliminating the need for pumped liquid metal loops. Another benefit of the lower power systems is that existing government facilities can be used to perform full system nuclear ground tests, which would have required building new facilities at great cost for higher power systems. An initial nuclear ground test referred to as the Demonstration Using Flattop Fissions (DUFF) was completed in 2012, and showed proof of concept for the Kilopower design and proved that nuclear ground testing in this power level could be achieved at reasonable cost (Ref 9-10). However, the DUFF test was not a high fidelity representation of the Kilopower system, so the team began work on the higher fidelity KRUSTY test. The KRUSTY test is based on the 1 kWe version Kilopower design (Fig 1.) which connsists of a 4 kWt highly enriched Uranium-Molybdenum reactor operating at 800 °C coupled to sodium heat pipes. The heat pipes deliver heat to the hot ends of eight 125 W Stirling convertors producing a net electrical output of 1 kW. Waste heat is rejected using titanium-water heat pipes coupled to carbon composite radiator panels. The KRUSTY test, based on this design, uses a prototypic highly enriched uranium-molybdenum core coupled to prototypic sodium heat pipes. The heat pipes transfer heat to two 60 W Advanced Stirling Convertors and six thermal simulators, which simulate the thermal draw of full scale power conversion units. Thermal simulators and Stirling engines are gas cooled.

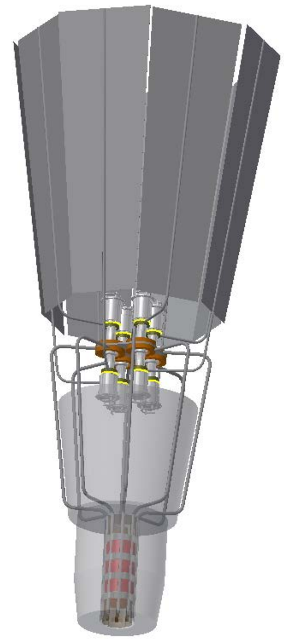

Figure 1. 1 kW$_e$ Kilopower Flight Concept.

Previously completed work on the KRUSTY test includes conceptual design, material studies, component fabrication, component testing, and system level testing using a stainless steel surrogate core (Ref 11). Fig. 2 shows the KRUSTY test hardware being tested at NASA GRC with the stainless steel core. The focus of this paper is recently completed testing in which the stainless steel core was replaced

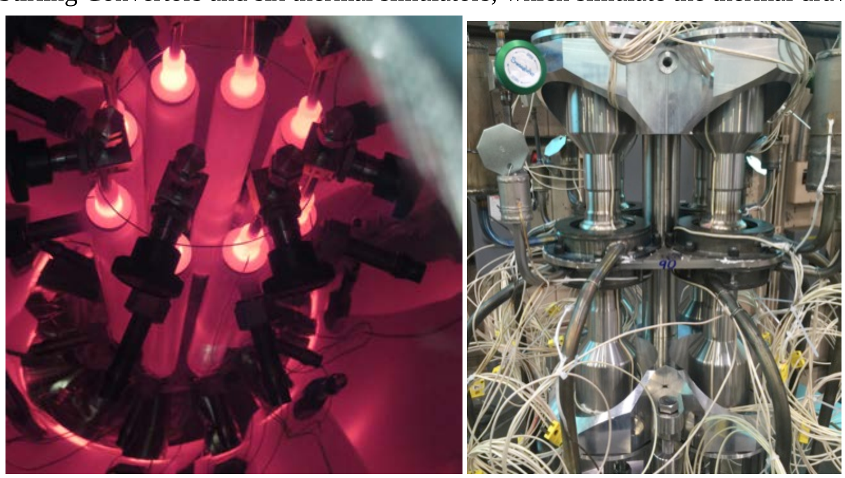

Figure 2. System level testing of KRUSTY at NASA GRC.

with a Depleted Uranium (DU) core in order to replicate the chemistry and properties of the Highly Enriched Uranium (HEU) core to be used during nuclear ground testing at the Nevada National Security Site (NNSS).

Depleted Uranium Testing

The DU core was fabricated by Y-12 and provided them the opportunity to develop their fabrication processes in preparation for the HEU core needed for nuclear testing. The DU core is exactly the same material as the HEU core with the major difference being the depletion of the 235 isotope. The DU core allowed the research team to evaluate the mechanical and material interfaces to the Haynes 230 heat pipes as well as any differences in thermal performance.

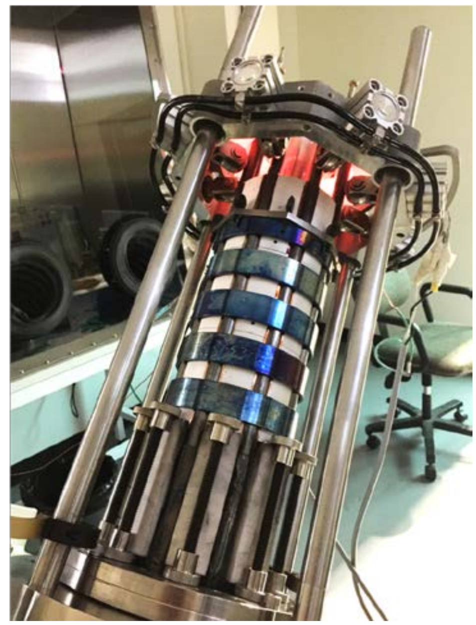

Figure 3. Ring Clamps being installed around the core and heat pipes

The DU material also provided a unique opportunity for the Kilopower team to perform training exercises regarding fueling the reactor. Team members from the Marshall Space Flight Center (MSFC), LANL, and the Device Assembly Facility (DAF) visited GRC to undertake the first KRUSTY dress rehearsal to perform the assembly process without the security and criticality requirements associated with the HEU material. This exercise allowed the processes to be evaluated and modified before moving into HEU operations at DAF for the KRUSTY test. The DU material is slightly radioactive and requires radiological work procedures for safe handling, making the training as close to the HEU process as possible. Anytime fissionable materials are being handled, criticality safety is a major concern to make absolutely sure that specific geometries and moderators cannot combine to make the material critical throughout the manufacturing, machining, and assembly processes. New designs, such as Kilopower, require additional efforts in criticality safety, and performing the procedures with DU ensures a well-prepared operation. Figure 3 shows the the ring clamps being assembled during the core instalaiton process at GRC. Figure 4 shows the KRUSTY test hardware inside of the vacuum chamber.

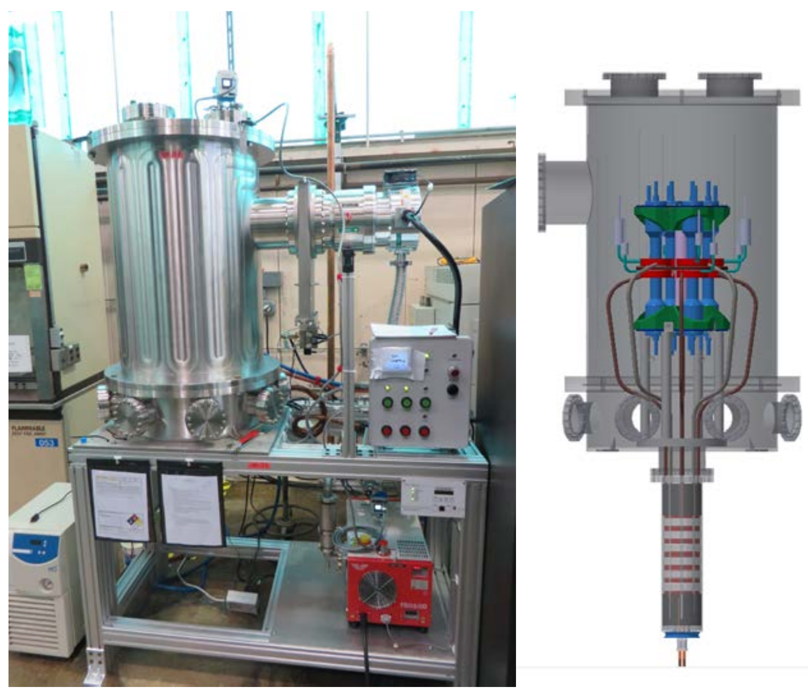

Figure 4. Photograph and CAD rendering of KRUSTY hardware inside of the vacuum chamber

The test set up at GRC is meant to mimic, as closely as possible, the configuration to be used while testing at the NNSS. This includes all of the test hardware, and also all facility systems, data, and control. Nuclear ground testing in existing facilities brings unique challenges such as the presence of radiation, limitations of signal quantity and type, and remote location of data and control systems. Although there is no way to simulate the radiation environment prior to the nuclear test, the other facility based restrictions were simulated during GRC testing. Gas systems, signal processing, and control systems are all remotely located using the same wire and tubing runs that will be required during nuclear testing. Electrically heated testing of the DU core follows the exact same test sequence as will be used during nuclear testing. The testing phases are thermal break-in, warm criticals, steady-state testing, and transient testing. The anticipated thermal response of the reactor has been modeled and the output of those models is fed into the electric heater controller to match power and temperature profiles as closely as possible.

The first test to be run at the NNSS is a thermal break-in test, which will be done using electic heaters on the HEU core. This will guarantee easily controlled heating rates for all componenets and allow for a check on all thermal interfaces. This test was replicated using the DU core at GRC. Figure 5 shows the average temperatures of various components during the thermal break-in test on the DU core. Initially, the heaters are turned on and core temperatures increase, but no heat is transferred to the upper surfaces because the sodium in the heat pipes has not started to boil. Once the sodium begins to boil and the vapor front moves to the conduction plate and Stirling hot ends all of the temperatures begin to increase. Once the Stirling hot end temperatures reach 650 °C the engines and simulators are turned on, dropping the hot end temperatures of both. The system is then allowed to reach steady-state over 2-3 hours. Prior to shut down, the Stirling convertors are stalled with the simulators on to analyze the response of the core to a loss of engine cooling. Next, with the convertors stalled, the simulators are turned up to maximum flow to determine if they can provide sufficient colling to account for the lost convertors. Finally the simulators are turned off to determine the response of the core to a total loss of cooling. Finally, the the simulators are turned back on and the electric heater is turned off to initiate shut down. Steady-state heat flow was determined to be acceptable to achieve 120 W of electrical power out of the two convertors convertors. It was determined that a total heat draw of more than 2500 W is possible from the combination of convertors and simulators.

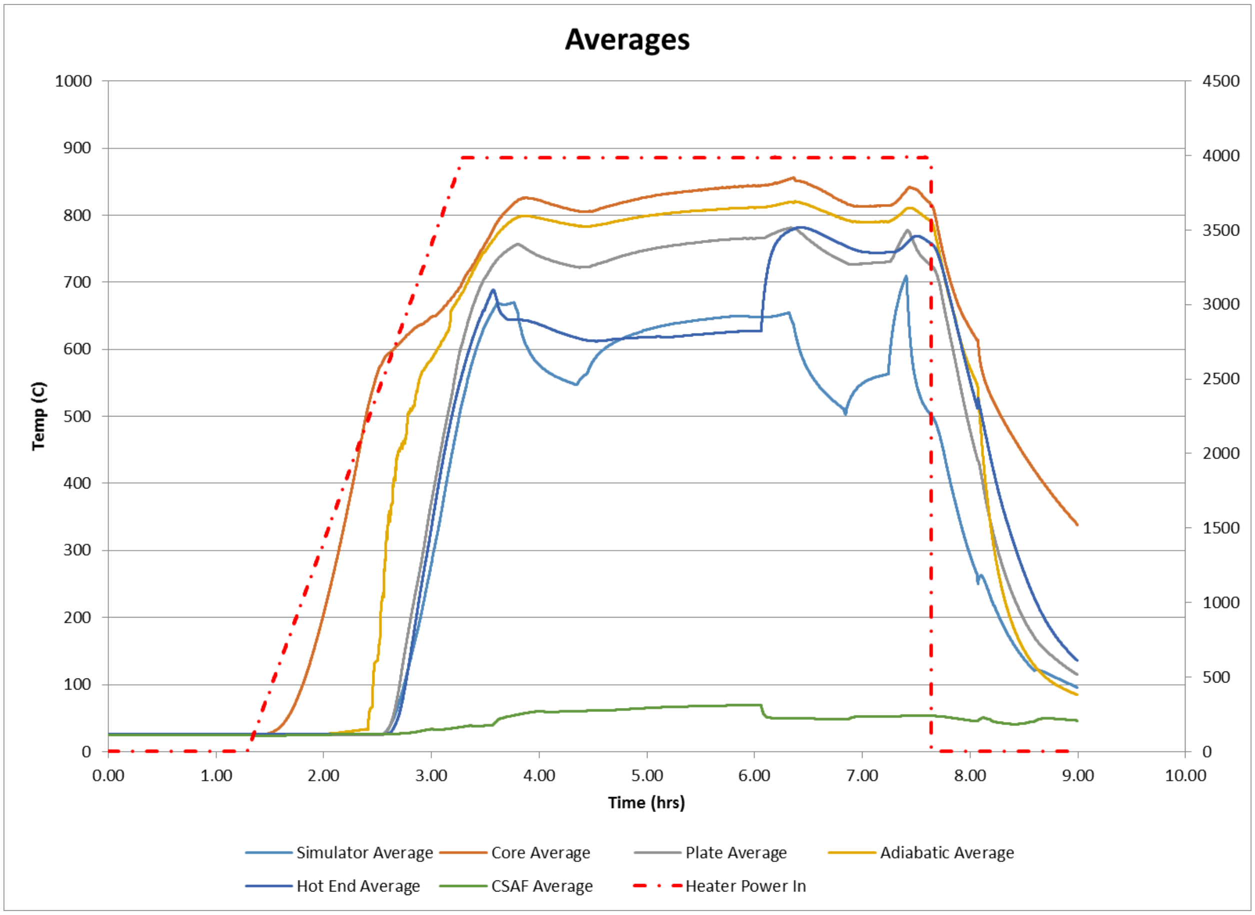

Figure 5. Temperature and heater power data from the thermal break-in test at GRC

After electrically heated break in testing, the HEU core will be put through a series of warm criticals which do not heat the core enough to activate the heat pipes or turn on the convertors, but give valuable information to validate nuetronics models. These tests were simulated at GRC using the current nuetronics models to estimate core response to various reactivity insertions. Figure 6 shows the core power, predicted, and measured core temperatures for each insertion case. Peak temperatures, time constants, and decay rates were all similar to model predictions, suggesting that the thermal properties of the system are well understood and modeled.

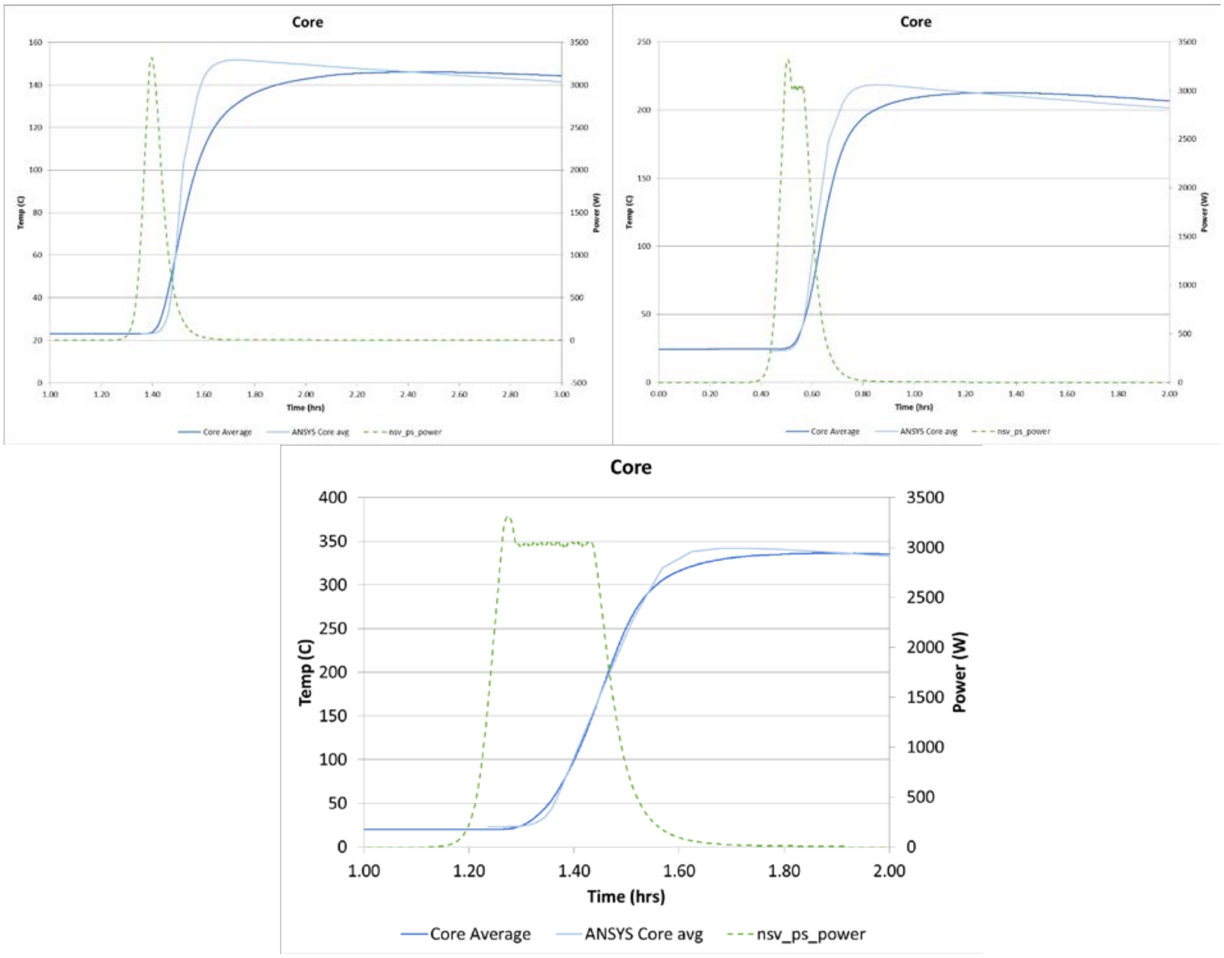

Figure 6. Core power, measured and predicted core temperatures for a 15 cent, 30 cent, and 60 cent reactivity insertions.

Following warm critical testing the HEU core will be run at full power for steady-state operation and transient response over the course of 24-48 hours. This test was simuilated at GRC using the electric heaters. Figure 7 shows heater power and system temperatures for the full power test which includes steady state operation and transient response to several system pertubations.

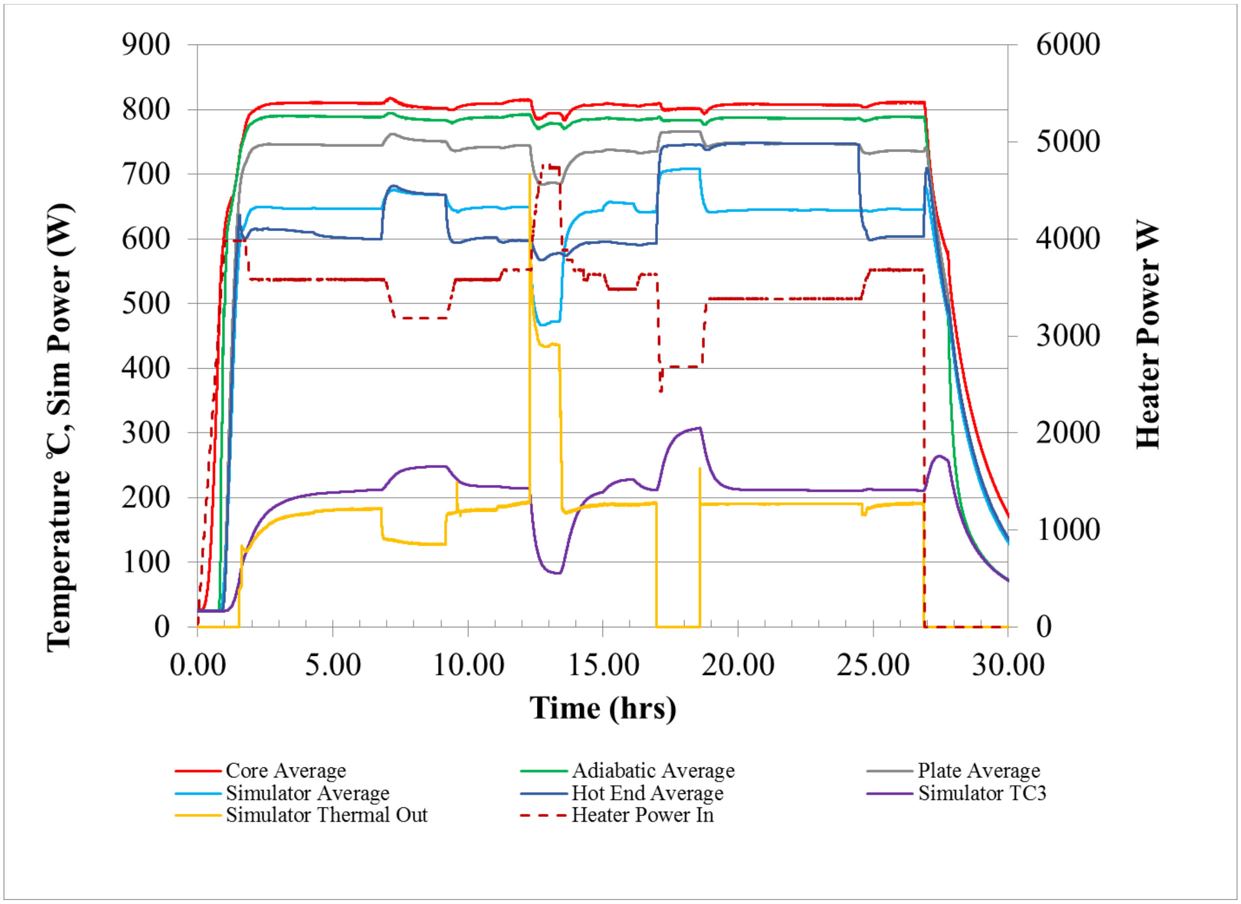

Figure 7. Full-power testing of the DU core using electric heaters

In these tests, reactor response was not simulated and the electric heaters were controlled to reach the desired condition. The data shows initial heat up with the convertor hot-end temperature reaching 650 °C at the one and half hour mark, at which point the convertors and simulators are turned on and the system is allowed to reach steady-state over the next five and a half hours. Next the convertors were reduced to half power and operated for two hours before being returned to full power operation. Next the convertors and simulators were commanded to maximum power to determine the maximum cooling load, then returned to nominal operation. The simulators and convertors were then turned off wheile reducing core power to determine the negative feedback required to maintain core operation at 800 °C in the abasence of cooling. The Simulators were then turned back on with the convertors stalled, then the convertors were restarted, and finally the heater power was turned off and the system was allowed to cool.

Conclusions

Fabrication of and testing of a 1 kW space fission power technology at the subsystem level in a relevant environment, with the DU core was a major milestone for the Kilopower project. Fabrication of the DU core sections allowed molds to be made and procedures put in place for fabricating the HEU core sections, which have recently been completed. Testing of the Kilopower technology demonstration with the DU core, using the test sequence and configuration for the final testing with the HEU core, has reduced the risk of any unexpected issues in fueling, assembly, or test operations at the NNSS. Testing of the DU core shows that at nominal operating conditions there is a 200 °C temperature drop between the core and the Stirling convertor hot end. The majority of this temperature drop takes place through the conduction plate and through the ASC heat acceptor, both of which can be eliminated in future design iterations if money comes available for customized convertors and interfaces. The system as it stands is capable of delivering 120 W electric from two ASC convertors with a maximum thermal power draw of roughly 3000 W, which is sufficient to verify neutronics models at the nominal Kilopower operating condition. There were no issues encountered during DU testing that caused unexpected operational issues which would need to be addressed prior to HEU testing.

Further work includes testing of a single engine configuration that could potentiall reduce temperature differences by eliminating the conduction plate used in the current dual-convertor configuration and dry runs for assembly of the test hardware at the NNSS. After completion of these tests the KRUSTY non-nuclear assembly will be shipped to the NNSS, where the HEU core will be installed and checkout testing will begin. .

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