



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

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Abstract

The Kilopower project aims to develop and demonstrate scalable fission-based power technology for systems capable of delivering 1 to 10 kW of electric power with a specific power ranging from 2.5 to 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 U.S. Department of Energy's National Nuclear Security Administration, Los Alamos National Laboratory, Nevada National Security Site (NNSS), 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 calendar year (CY) 2017 at the NNSS.

The 1-kWe variation of the Kilopower system was chosen for the KRUSTY demonstration. The concept for the 1-kWe flight system consists 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-E2s) 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 nonnuclear system-level testing using an electrically heated depleted uranium (DU) (nonfissioning) reactor core simulator at the NASA Glenn Research Center. System-level testing 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 NNSS. Fabrication, assembly, and testing of the DU core has allowed for higher fidelity system-level testing at Glenn, and has validated the fabrication methods to be used on the highly enriched uranium core that will supply heat for the DAF KRUSTY demonstration.

1.0 Introduction

The Kilopower project aims to develop and demonstrate scalable fission-based power technology for systems capable of delivering 1 to 10 kW of electric power with a specific power ranging from 2.5 to

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 U.S. Department of Energy’s National Nuclear Security Administration, Los Alamos National Laboratory (LANL), 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 calendar year (CY) 2017 at the Nevada National Security Site (NNSS).

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 exploration needs (Refs. 1 and 2). The 1 to 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 that was designed, built, and tested in the last decade (Refs. 3 to 8). The reduction in power level from 40 kW class to the 1 to 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 (Refs. 9 and 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 concept (Figure 1), which consists 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

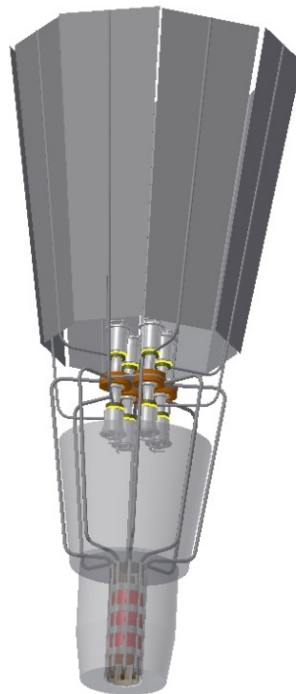


Figure 1.—The 1-kW_e Kilopower flight concept.

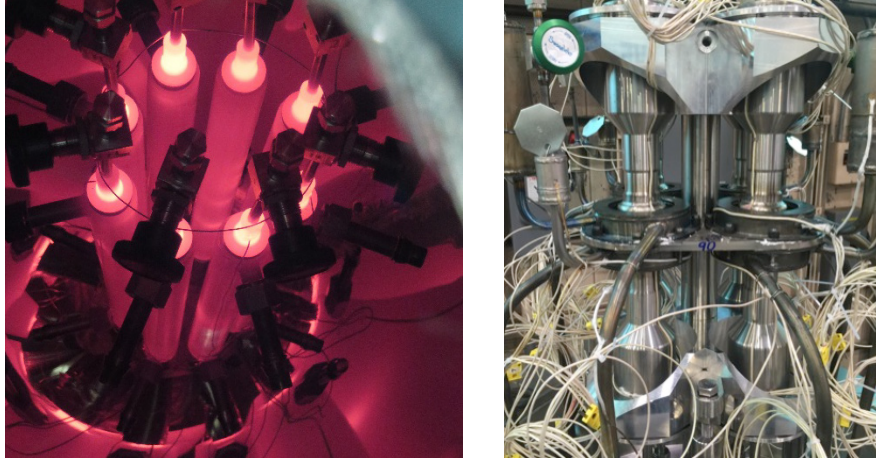


Figure 2.—System-level testing of Kilowatt Reactor Using Stirling Technology at NASA Glenn Research Center.

enriched uranium-molybdenum core coupled to prototypic sodium heat pipes. The heat pipes transfer heat to two existing 80-W Advanced Stirling Convertors (ASC) and six thermal simulators, which simulate the thermal draw of full-scale power conversion units. Thermal simulators and Stirling engines are gas cooled. While the ASC does not meet the 125 W specification of the Kilopower concept, this pair of units was available from the Radioisotope Power System project at no additional project cost and are sufficient to demonstrate integration and functionality.

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). Figure 2 shows the KRUSTY test hardware being tested at NASA Glenn Research Center with the stainless steel core. The focus of this paper is recently completed testing in which the stainless steel core was replaced 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 NNSS.

2.0 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.

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, LANL, and the Device Assembly Facility (DAF) visited Glenn 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 ring clamps being assembled during the core installation process at Glenn. Figure 4 shows the KRUSTY test hardware inside of the vacuum chamber. The core is in the bottom section of the vacuum chamber with sodium heat pipes clamped to the outside diameter using shrink fit rings. The sodium heat pipe condensers are located on a conduction plate that shares heat between the convertors and simulators. The Stirling convertors are in a dual-opposed configura^{tion} for vibration cancellation.

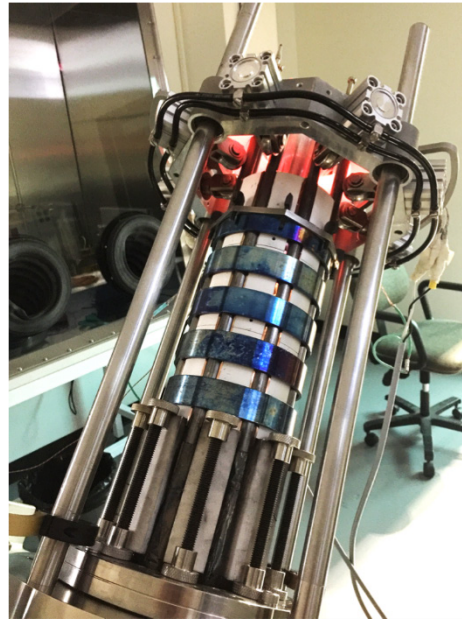


Figure 3.—Ring clamps being installed around core and heat pipes.

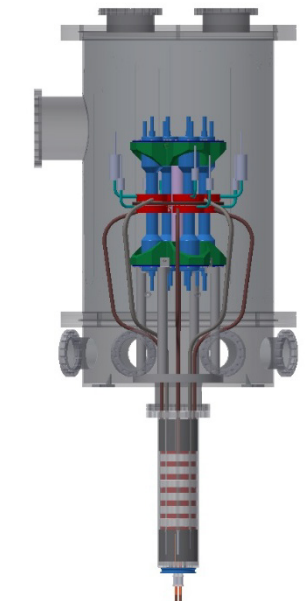


Figure 4.—Photograph and CAD rendering of Kilowatt Reactor Using Stirling Technology (KRUSTY) hardware inside of vacuum chamber.

The test setup at Glenn 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 Glenn 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 electric heaters on the HEU core. This will guarantee easily controlled heating rates for all components and allow for a check on all thermal interfaces. This test was replicated using the DU core at Glenn. 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. When the Stirling hot end temperatures reach 650 °C, the engines and simulators are turned on, dropping the hot

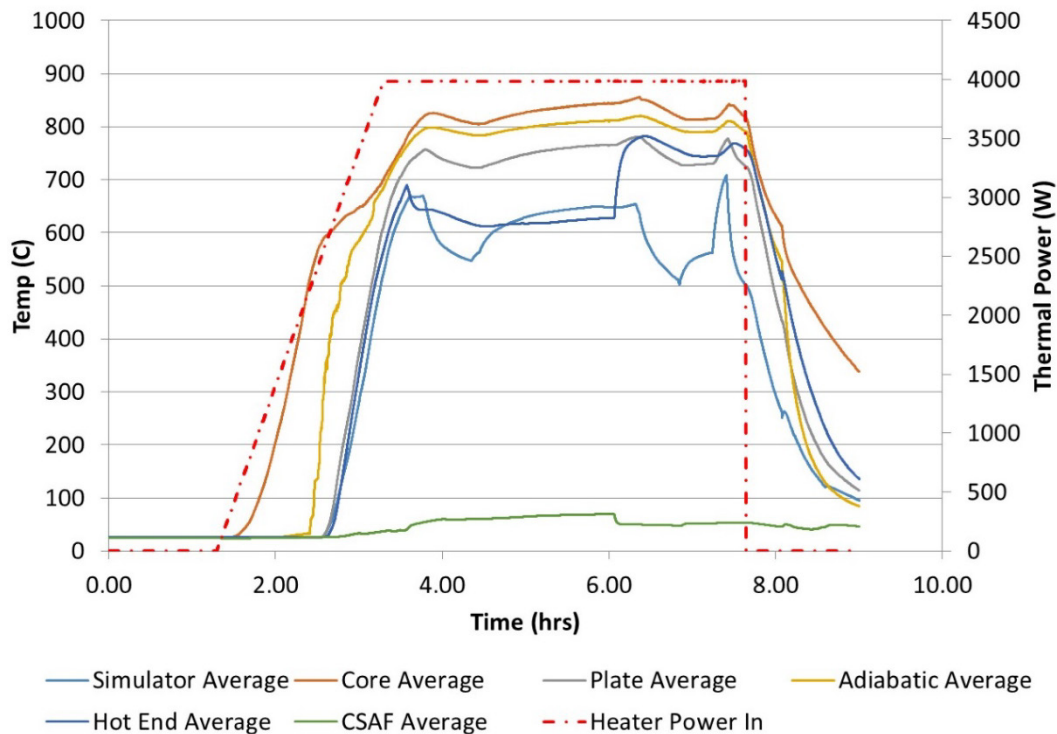


Figure 5.—Temperature and heater power data from thermal break-in test at NASA Glenn Research Center.

end temperatures of both. The system is then allowed to reach steady state over 2 to 3 hr. Prior to shutdown, 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 cooling 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, and the simulators are turned back on and the electric heater is turned off to initiate shutdown. Steady-state heat flow was determined to be acceptable to achieve 120 W of electrical power out of the two convertors. It was determined that a total heat draw of more than 2,500 W is possible from the combination of convertors and simulators.

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 neutronics models. These tests were simulated at Glenn using the current neutronics models to estimate core response to various reactivity insertions. Figure 6 shows the core power and 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.

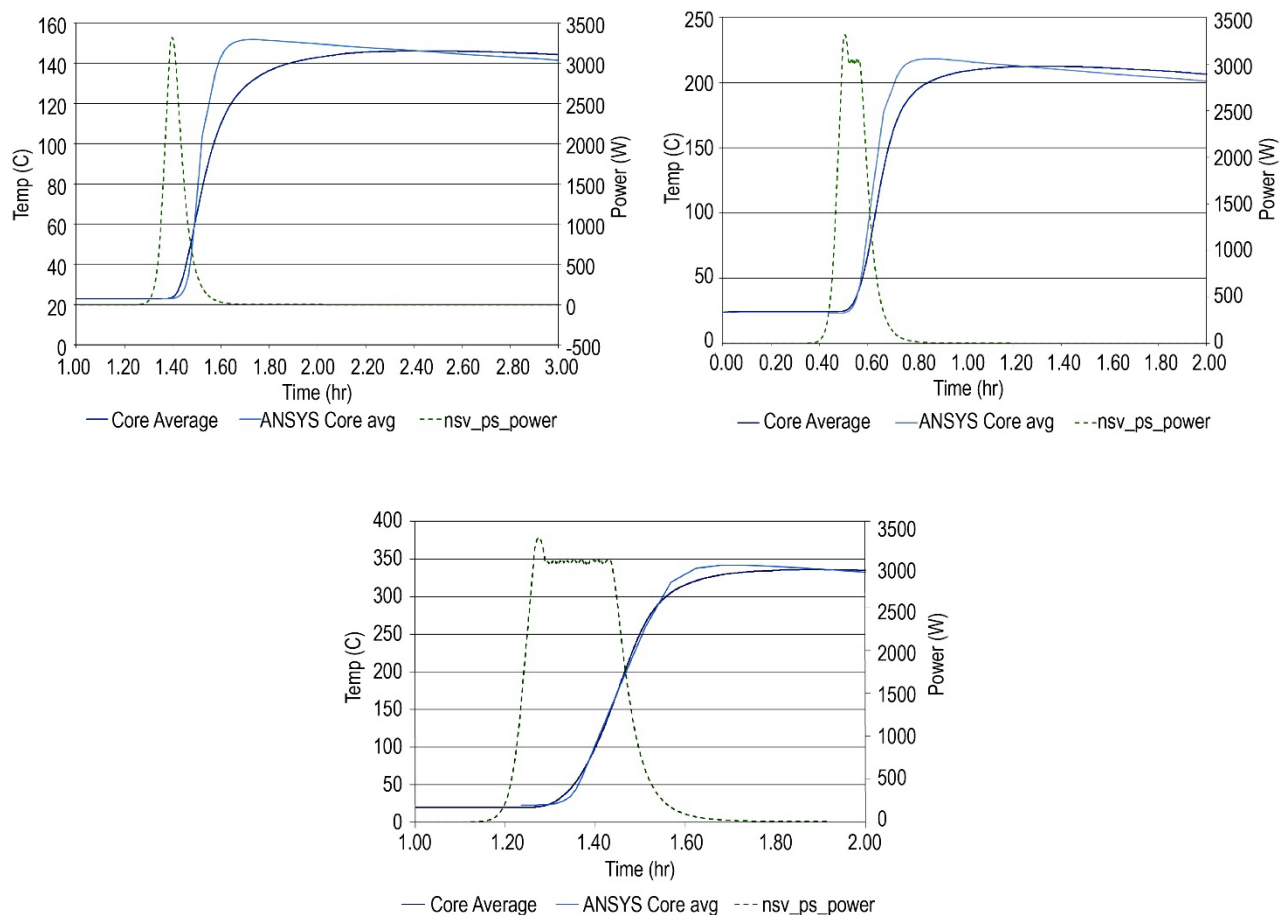


Figure 6.—Core power and measured and predicted core temperatures for three different reactivity insertion scenarios.

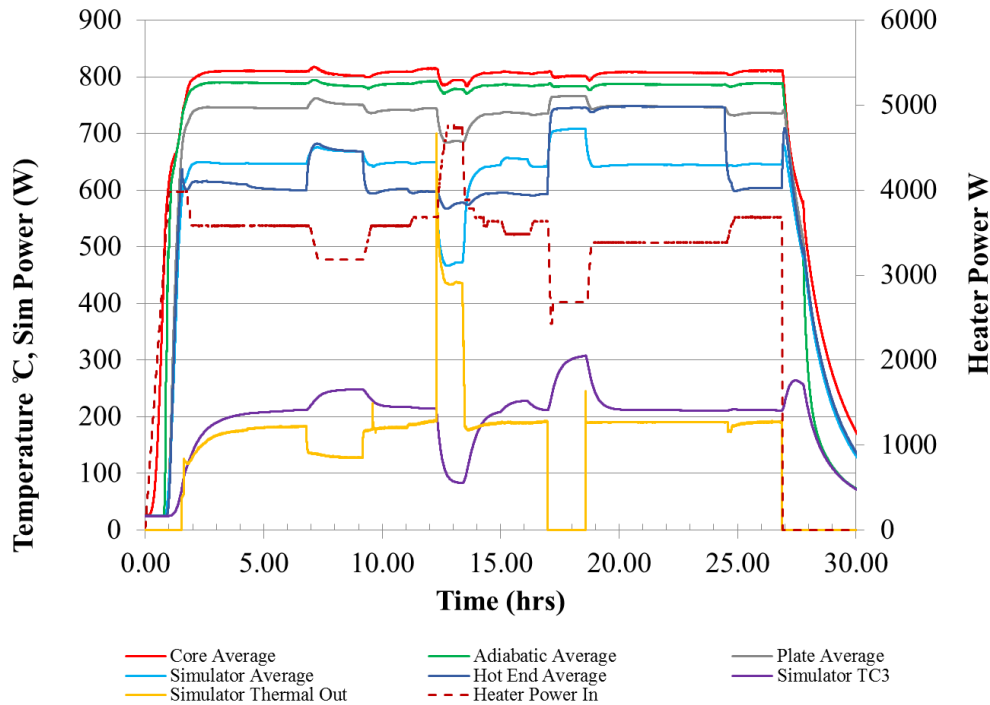


Figure 7.—Full-power testing of the depleted uranium core using electric heaters.

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 to 48 hr. This test was simulated at Glenn 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 perturbations.

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 1.5-hr mark, at which point the convertors and simulators are turned on and the system is allowed to reach steady state over the next 5.5 hr. Next, the convertors were reduced to half power and operated for 2 hr 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 while reducing core power to determine the negative feedback required to maintain core operation at 800 °C in the absence 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.

3.0 Conclusions

Fabrication of and testing of a 1-kW space fission power technology at the subsystem level in a relevant environment, with the depleted uranium (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 highly enriched uranium (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 Nevada National Security Site (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 Advanced Stirling Convertors (ASCs) heat acceptor, both of which can be eliminated in future design iterations if money becomes available for customized convertors and interfaces. The system as it stands is capable of delivering 120 W electric from two ASCs with a maximum thermal power draw of roughly 3,000 W, which is sufficient to verify neutronics models at the nominal Kilowatt 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 configuration in which convertor vibration is actively canceled using balancers, allowing for simpler heat pipe interfaces and further redundancy that could potentially 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 Kilowatt Reactor Using Stirling Technology (KRUSTY) nonnuclear assembly will be shipped to the NNSS, where the HEU core will be installed and checkout testing will begin.

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