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RESULTS OF THE KRUSTY WARM CRITICAL EXPERIMENTS

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The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) was a prototypic nuclear-powered test of a 5-kWt Kilopower space reactor. This paper presents results from the KRUSTY critical experiments, which were completed prior to the final system test. The first set of criticals were "cold" or zero-power criticals; i.e. the core was not heated by fission power. These were followed by three "warm" criticals, where fission power heated the core to 200, 300 and 450 C respectively. These criticals provided the data and confidence required to proceed with the KRUSTY nuclear system test. The criticals also provided valuable data for the benchmarking of codes applicable to all nuclear systems. Overall, the results of the KRUSTY criticals, cold and warm, matched extremely well with the pre-test predictions

I. INTRODUCTION

The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) was designed to be representative of a 5-kWt Kilopower[1,2] space reactor. KRUSTY was designed, developed, manufactured, and tested for <$20M, with final testing completed in March 2018 at the Nevada National Security Site (NNSS).

The KRUSTY design is described in papers by Gibson[3] and Poston[4]. The reactor design is remarkably simple – a solid cylindrical core of UMo is cooled by Na heat pipes, and surrounded by a BeO neutron reflector. Metal rings clamp the heat pipes to the fuel via a shrink fit. Reactivity control is provided by moving the reflector on a lift table device. The heat pipes transfer the power to Stirling convertors, although for the critical experiments the temperature is not high enough to thermally couple the power conversion to the reactor.

II. KRUSTY TESTING

There were several testing phases during the 3-year KRUSTY project. In year one, mechanical prototyping and testing was performed in tandem with system design. In year two, electrically-heated testing was performed on various components and system mockups, which were used to inform the final design and component procurement. Year three started with a full electrical test of the final KRUSTY design using depleted uranium fuel. Next the system was sent to the NNSS Device Assembly Facility (DAF) to be mated with the HEU fuel, which was manufactured and shipped from the Y-12 National Security Complex. KRUSTY was then assembled and installed on the COMET lift table, which is operated by the Nuclear Criticality Experiments Research Center (NCERC). The nuclear testing campaign at NCERC lasted from November 2017 to March 2018. A companion paper in these proceedings documents the full nuclear system test[5].

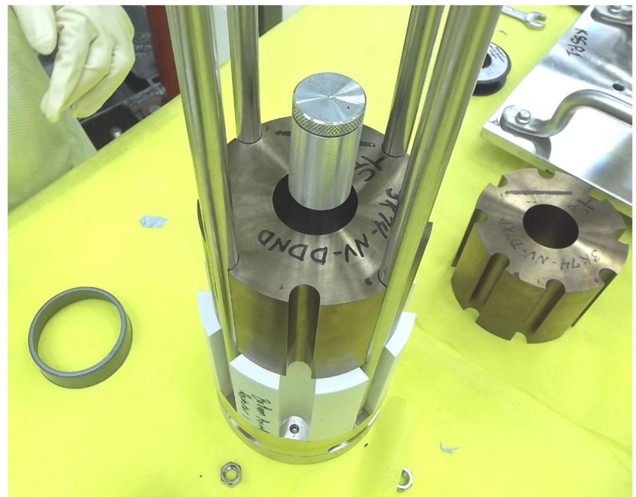

Fig 1. Partially assembled configuration for the component criticals. The first (of 3) HEU UMo core segments rests on top of the lower BeO axial reflector. The central cylinder aids assembly and alignment, and is later removed.

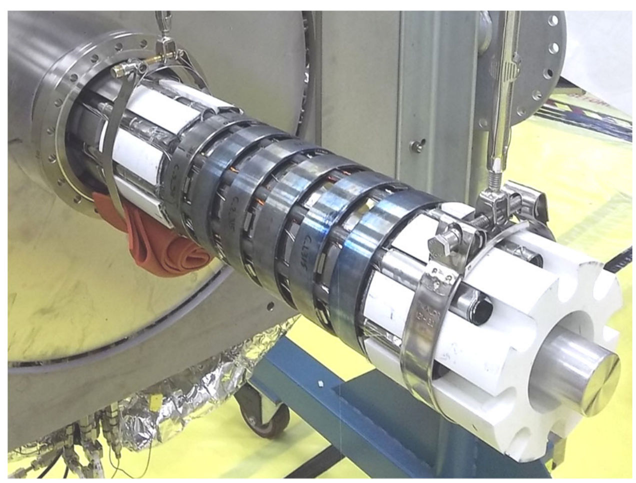

Fig 2. The assembled KRUSTY reactor core, ready to be enclosed within the vacuum vessel. Six Haynes 230 rings are clamping the Na heat pipes to the HEU UMo core, with white BeO axial reflectors on both ends. A temporary fixture to aid assembly (soon to be removed) protrudes from the bottom and surrounds each reflector. The vacuum flange is on the far left.

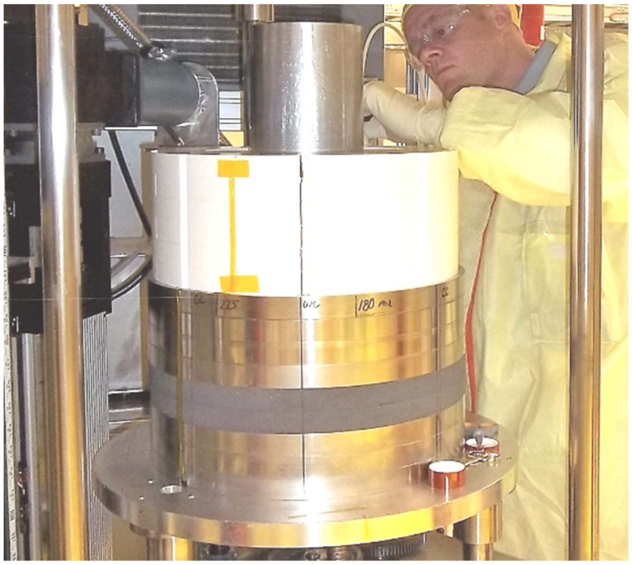

Fig 3. The lower shielding and radial reflector being installed on the COMET platen, which consists of stacked 1"-thick rings of SS-304 (shiny), B_4C (dark grey), and BeO (white). Yellow tape holds thermocouple wires.

III. ZERO-POWER CRITICALS

There were two distinct sets of zero-power "cold" criticals. The "component" criticals and the "KRUSTY" criticals. The component criticals removed the heat pipes, core clamps, insulation, and vacuum vessel to provide cleaner data for criticality benchmarking. KRUSTY was not specifically designed to be a highly precise benchmarking experiment; i.e. there was enough uncertainty in fuel and reflector position to potentially cause 10-20 cents of uncertainty in integral k-eff. However, the relative perturbations in reactivity are likely accurate to a few cents. The second set of zero-power criticals evaluated the fully assembled KRUSTY configuration, which was used for the full system test. The primary goal of these criticals was to get an accurate correlation of system reactivity versus BeO stack height and platen position.

A total of 91 criticality measurements were taken. In each case, the platen was raised to make the reactor slightly supercritical (keff >1) and the rate of power increase was measured to provide a relatively accurate calculation of the reactivity (within a cent or two). Soon after these measurements were recorded, they were compared to predictions from the neutronics code MCNP[6]. The MCNP model was tweaked (by adjusting gap tolerances, densities, unspecified impurities) to best represent the entire suite of criticality results. The updated model was then used to determine what thickness of BeO radial reflector to load onto Comet for the warm criticals and the final reactor test. Note that the initial, unadjusted MCNP model predicted the first critical very well (within 30 cents) using ENDF/B7.1 data. Apart from the integral k-eff, the model predicted each incremental reactivity change (e.g. adding or subtracting BeO) within a few cents.

Fig 4. B_4C (dark grey) pucks stacked on top of BeO (white) axial reflector pieces.

Several criticals were performed to determine the worth of an internal B_4C rod, which is the proposed reactivity control for a flight system. Boron carbide "pucks" (~95% enriched in ^{10}B) were incrementally stacked onto a mock "control rod" assembly, which was manually inserted into the core though a penetration in the lower vacuum vessel. Figure 4 shows four 1.27-cm enriched B_4C pucks stacked on top of the lower axial reflector plugs. Above the B_4C stack is the SS316 conical, thin-walled washer and the centering rod. The reactivity worth of the B_4C ranged from ~3 cents/mm near the bottom of the core to ~6 cents/mm near the axial center of the core. These results also agreed very well with the MCNP model.

IV. 15-CENT WARM CRITICAL

The nuclear-heated or "warm" criticals began in the same manner as the cold criticals, but the power is allowed to increase unabated until sensible power heats the fuel and provides reactivity feedback. The controls are then left untouched to monitor the temperature and power as the passive transient proceeds.

The fission power and fuel thermocouple (TC) temperature readings from the 15-cent run are shown in Fig. 4.

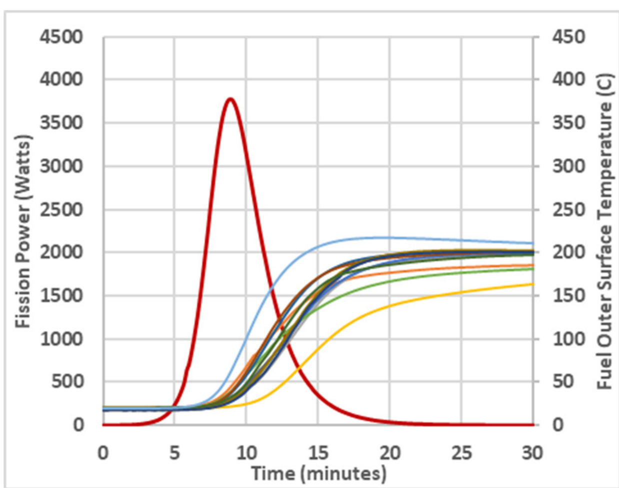

Fig. 4. Power and temperature data from 15-cent run.

The fission power that is plotted in Fig. 4, and all graphs in this report, is actually the normalized neutron detector reading. The neutron detector is a He-3 detector, for which the readout is Amps. The flux at the neutron detector location is almost directly proportional to the flux/fission in the core. Movement of the platen, which effects neutron leakage from core, might have a significant impact, but the platen does not move during this transient (i.e. after the 15 cents is inserted). Changes in system temperature will also have a minor effect on leakage, but nothing significant. Given that the red curve represents fission rate, the integral of that curve can then be normalized to the number of Joules needed to heat the fuel to the measured temperature (based on the fuel specific heat and MeV/fission). Second order effects such as heat leakage from the core and the time dependent nature of decay power affect this normalization, but the initial guess based on adiabatic heat up and "constant" decay power was very close based on subsequent benchmarking efforts.

The peak power reached during the 15-cent free run was ~3.8 kWt. This was within the expected range, but a bit higher than the predicted value of 3.4 kWt. This is apparently because the actual insertion was 15.7 cents, as indicated by the measured reactor period (ramp rate), which would explain this difference.

The core temperature rise for the 15-cent run was also well within the predicted range; however, the TC readings were not in sync. It appears that some TCs had better thermal bonding than others, and that only one TC was well bonded (the blue line on Fig.2), which reached ~220 C. As the subsequent tests went to high temperatures, the thermal-bonding appeared to get much better; which is to be expected, since the TCs are spring-loaded against the fuel (not physically attached). It was decided not to weld or braze the TCs directly to the fuel to avoid potential fuel damage, but unfortunately this caused significant lag in most of the core temperature TCs.

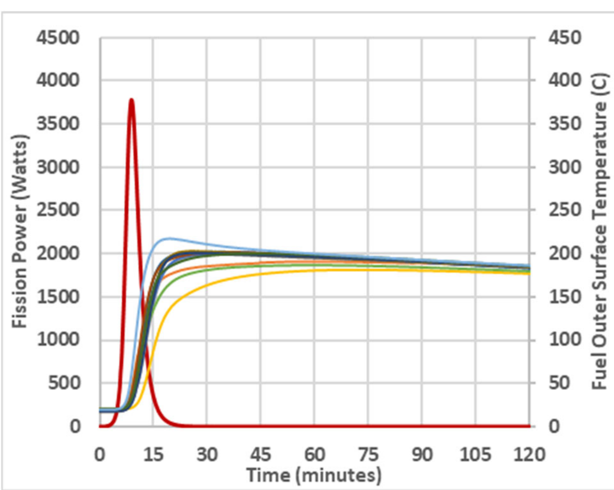

Fig. 5. Power and temperature data from 15-cent run.

Figure 5 plots the 15 cent run on a longer time scale. After an hour or so, all the TCs reach an equilibrium value, because radiation heat transfer across the poorly bonded gaps has brought the temperatures together. It was important to run this and the other warm criticals long enough to monitor long-term temperature drop (indicating passive power loss). This provided data to benchmark the modeling tools in conjunction with the final system test.

V. 30-CENT WARM CRITICAL

Next, the 30-cent critical was performed. The initial reactivity insertion was again ~15 cents, but after the power peaked and began to drop, the operator incremented reactivity (lifted the platen) until a total of 30 cents had been inserted. It was decided to start every nuclear-powered test with a 15-cent free run, to ensure that the configuration had not changed since the last test, and that nothing else might be going wrong. Reactivity was inserted at a rate to keep the power at ~3 kWt – actually the neutron detector Amps that corresponded to 3 kWt. This transient is plotted in Fig 6.

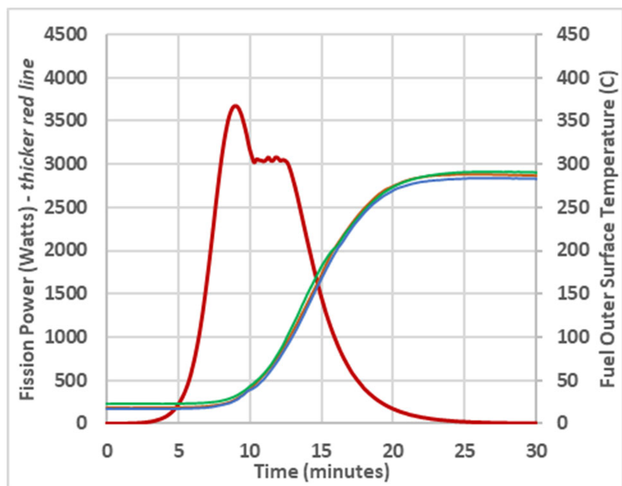

Fig. 6. Power and temperature data from 30-cent run.

The power in Fig. 6 rises to a peak similar to the 15-cent free run, but it is slightly lower because the actual insertion is indicated to be 15.5 cents as opposed to 15.7 cents. The point at which the operator inserts additional reactivity to keep power constant can be clearly seen, starting at 10 min. and ending at ~12.5 min. At that time the platen was at a position predicted to have inserted 30 cents (note: post-test modeling indicates an actual insertion of 29.9 cents, so the prediction was very good).

In the 30-cent run, the TC readings are much more uniform than the 15-cent run, but there is still clearly a lag in TC response time; i.e. the fuel should start heating significantly when the power becomes >1 kWt (at 7 min). It is possible that the time stamps of the two data sets (power and temperature) were not properly overlaid, but this lag was noticed in real time during each of the tests.

During the test, the TC lag created unease in the control room because the neutron detectors indicated high power but the core was not heating up. Fortunately, due to the simple nature of the system, it was decided to continue because there was no possibility for the core to overheat.

Figure 7 plots the 30-cent run on a longer time scale.

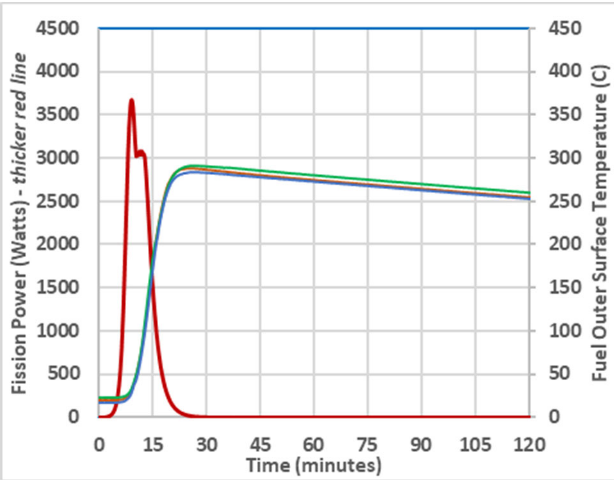

Fig. 7. Power and temperature data from 30-cent run.

The long-term temperature drop in Fig. 7 indicates the heat loss from the fuel is ~30 W, which is very useful data to benchmark the heat transfer mechanisms from the fuel, in particular the effectiveness of the multi-layer insulation (mli). If this case was allowed to run for 10s of hours, the fuel would have eventually cooled enough to produce positive reactivity. Then the power would have risen to ultimately match the heat loss and the core would have coasted at ~200 C. Instead, this passive behavior was demonstrated in the 60 cent run.

V. 60-CENT WARM CRITICAL

The final warm critical was conducted in the same fashion as the 30-cent run, except that the operator continued to insert reactivity until 60 cents was inserted. This test was crucial to the success of the KRUSTY campaign. First, it would confirm the passive dynamic response predicted for the system. Second, it provided the authorization basis to proceed with the full system test. The latter was a novel approach to providing the safety basis for a nuclear test. The ability to adequately model the dynamic performance of KRUSTY existed only within the design team (using the code FRINK[7]). Safety reviewers could rely on simplified nuclear calculations (due to the neutronic simplicity of KRUSTY) but an independent transient system model would have taken substantial time and effort. Thus, it was proposed that the design team would predict the peak TC reading for the 60-cent run, and if the result was within 10% then the final test could proceed, otherwise KRUSTY would not be given authorization for the final full-system test. An official predicted value of 447 C (720 K) was submitted the day before the test.

The power and fuel temperatures from the 60-cent run are shown in Fig. 8.

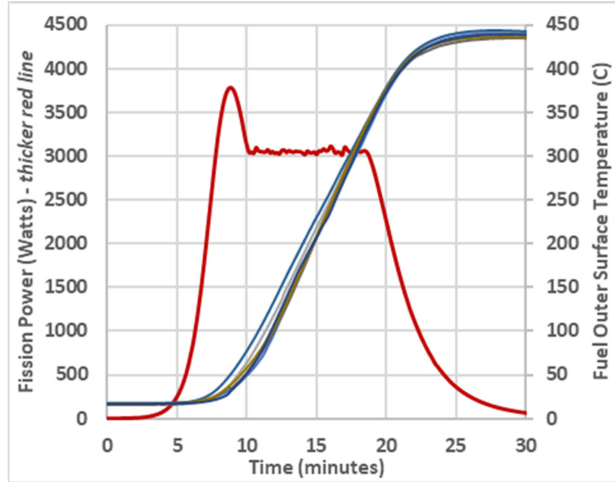

Fig. 8. Power and temperature data from 60-cent run.

The power in Fig. 8 once again rose to a peak similar to the other warm criticals, corresponding to a 15.5 cent insertion. As with the 30-cent run, the operator began to insert additional reactivity at 10 min. to keep power at ~3kWt. In this case reactivity was inserted to a predicted value of 60 cents, which occurs at 18 min. on Fig. 8 (note: post-test modeling indicates an actual insertion of 58.5 cents – not as well predicted as the 30-cent run, but not surprising because there wasn't as much zero-power criticals data to help predict this magnitude of insertion).

The key value on Fig. 8 is the peak TC reading. The peak recorded temperature was 446 C, only 1 degree from the safety basis prediction, so clearly within 10%. In the best scenario, this prediction might have been +/-2% (or 9 C), so nailing it within 1 C was sheer luck. Regardless, it checked the box for proceeding with the full system test.

Figure 9 plots the 60-cent run on a much longer time scale, in this case 6-hours to let the transient fully evolve.

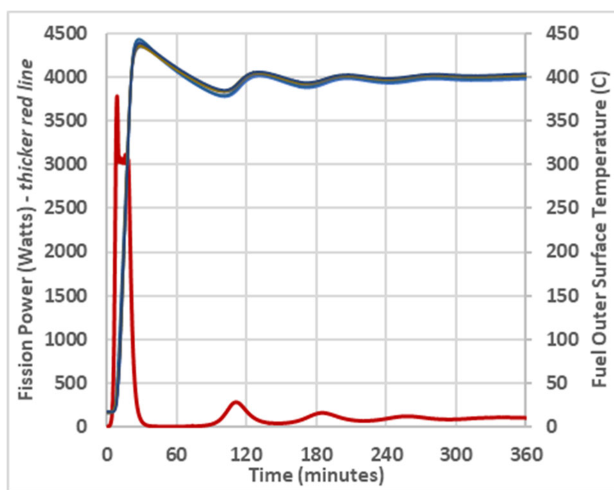

Fig. 9. Power and temperature data from 60-cent run.

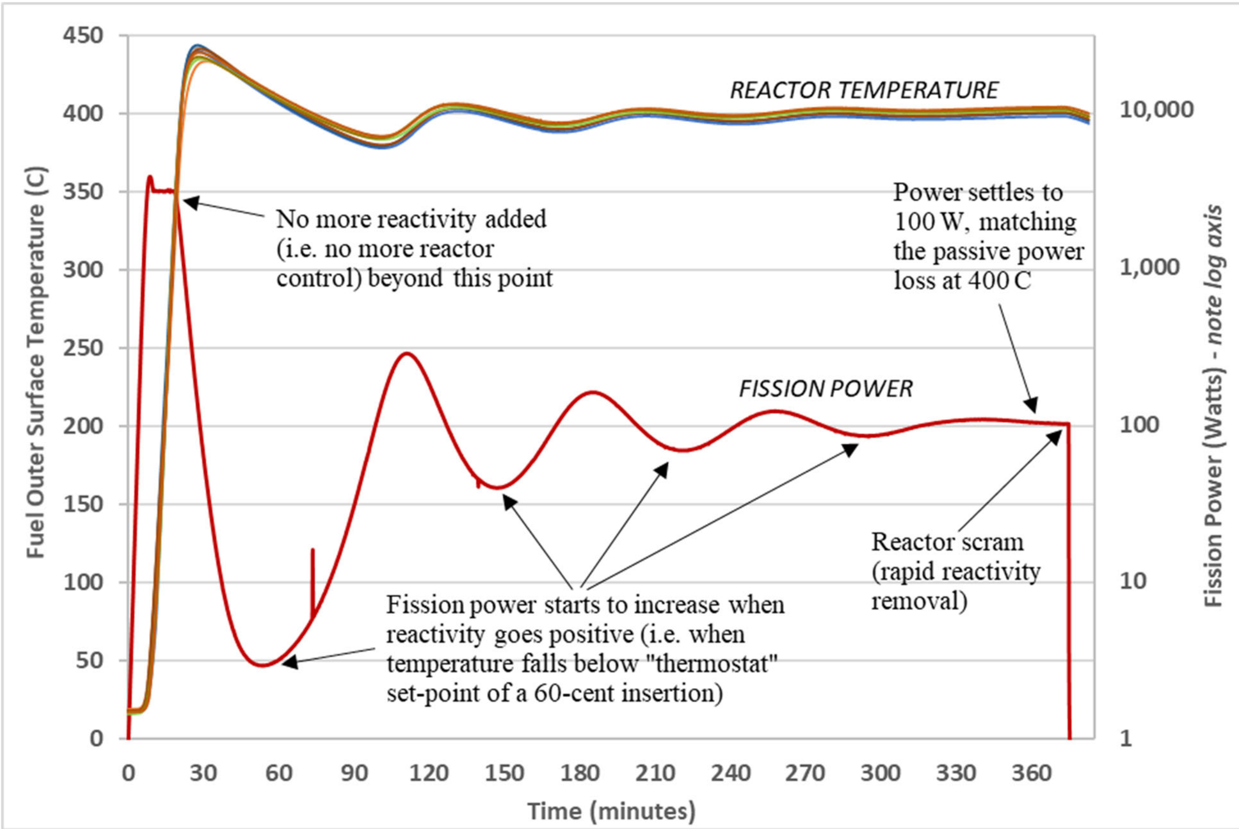

Fig. 10. Power and temperature data from the 60-cent run.

The results in Figure 9 provided the first validation that KRUSTY, and all similar Kilopower reactors, would provide stable operation and provide a power level equal to the power drawn from the core. Figure 10 replots the data in Fig.9 with the power on a log scale (and in larger format), to better show this dynamic. The passive response of the reactor is the same as a household thermostat – if the temperature gets too cold the power/heat kicks on and vice-versa. In a reactor, the temperature "set-point" is determined by the level of reactivity insertion and the passive temperature feedback of the reactor.

V. CONCLUSIONS

The KRUSTY criticals were successful, and the passive, self-regulating dynamics of the KRUSTY reactor were demonstrated. More-so, both the static and kinetic results were remarkably close to the pre-test modeling, which underscores that this kind of reactor can be designed without significant uncertainty in how it will actually operate. This is extremely important for Kilopower systems with powers >>5 kWt, which will generally preclude the opportunity for inexpensive testing like was done for KRUSTY. The key of the Kilopower program, is that all reactor designs will have the same basic physics and heat transfer as KRUSTY, and thus they should all operate in the same manner. If the physics can be kept simple, i.e. a compact, fast-spectrum reactor, then even at much higher powers the same passive, load-following response might remain – even with a different power conversion system or even gas-cooling of the reactor.

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