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Title: Kilowatt Reactor Using Stirling TechnologY (KRUSTY) Demonstration: CEDT Phase 1 Preliminary Design Documentation

Author(s): Sanchez, Rene Gerardo
Hutchinson, Jesson D.
Mcclure, Patrick Ray
Myers, William L.

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Los Alamos
NATIONAL LABORATORY
EST. 1943

Research Note

Nuclear Engineering and Nonproliferation Division
Advanced Nuclear Technology Group NEN-2

To/MS: David K. Hayes, NEN-2, MS B228
Thru/MS: William L. Myers, NEN-2, MS B228
From/MS: Rene G. Sanchez, NEN-2, MS B228
Patrick McClure, NEN-5, MS C921
Jesson Hutchinson, NEN-2, MS B228
Phone/e-mail: 505-665-5343/rgsanchez@lanl.gov
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The following information is to be distributed for review as part of the Department of Energy's Nuclear Criticality Safety Program (NCSP) Critical Experiment Design (CED) process requirements. This Research Note is to serve as documentation for IER 299 CED phase 1 preliminary design which is the information that represents the preliminary planning, design, and analysis for the KRUSTY experimental measurements to be executed to obtain the requested data.

IER 299: Kilowatt Reactor Using Stirling TechnologY (KRUSTY)
Requestor: Don Palac
Affiliation: NASA Glenn Research Center

The CEDT members for IER-299 include:

CEDT lead: Bill Myers, LANL
Experiment member: Rene Sanchez, LANL
NDAG member: Skip Kahler, LANL
Methods member: Bob Little, LANL
Publication member: Rene Sanchez, LANL
CedT Member: Jeffrey Lewis, NSTec
CedT Member: Rashelle Will, NSTec
CedT Member: Steve Clement, LANL

CEDT Phase-1 Preliminary Design: The intent of the integral experiment request IER 299 (called KiloPower by NASA) is to assemble and evaluate the operational performance of a compact reactor configuration that closely resembles the flight unit to be used by NASA to execute a deep space exploration mission. The reactor design will include heat pipes coupled to Stirling engines to demonstrate how one can generate electricity when extracting energy from a "nuclear generated" heat source. This series of experiments is a larger scale follow up to the DUFF series of experiments[1,2] that were performed using the Flat-Top assembly.

[1] D. Poston, et. al., "Experimental Demonstration of a Heat Pipe/Stirling Engine Nuclear Reactor," Los Alamos National Laboratory Report: LA-UR-13-23137 (2013).
[2] P. McClure, et. al., "Final Results of Demonstration Using Flattop Fissions (DUFF) Experiment," Los Alamos National Laboratory Report: LA-UR-12-25165 (2012).

The critical assembly chosen to perform this set of experiments is the Comet assembly which located in the National Criticality Experiments Research Center (NCERC) at the Device Assembly Facility (DAF) at the Nevada National Security Site (NNSS). The compact reactor design to be assembled on Comet is called KRUSTY (Kilowatt Reactor Using Stirling TechnologY). The KRUSTY design will incorporate use of a vacuum chamber to simulate some parameters of the operating environment to be encountered in space. Data from the experiments can be used to benchmark the static neutron transport calculations and the dynamic nuclear simulation tools used to generate the reactor concept design. The thermo-mechanical performance of the reactor will be assessed and compared to data obtained from electrically heated system tests that are to be performed at NASA's Glenn Research Center sometime in the fall of 2015.

Y-12 will be responsible for casting and machining the uranium components to be used to assemble both the KRUSTY core and surrogate core to be used for the electrically heated system tests. The uranium parts are to be made using a uranium metal alloy (8wt%Mo). The uranium isotopic composition of the KRUSTY core will be highly enriched uranium (HEU, 93wt% ^{235}U). The uranium isotopic composition of the surrogate core will be depleted uranium (DU, 0.12 wt% ^{235}U). The same equipment (i.e., heat pipes, Stirling engines, and vacuum chamber) that are to be used in the electrically heated system tests at NASA's Glenn Research Center will be the same hardware that will be used as part of KRUSTY. The electrically heated system tests will use an electrical resistance heater to simulate nuclear power generated by the core.

The goals of the electrically heated system tests are:

1) to model and then measure the heat transfer properties from the reactor core through the heat pipes to the hot side of the Stirling engines; and
2) to evaluate the thermal and mechanical performance of reactor components (heat pipes, Stirling engines, uranium core, and vacuum chamber) at the design temperature (800 °C).

Major goals of the KRUSTY measurements are:

1) to re-affirm the heat transfer data obtained in the electrically heated system tests;
2) to model and then confirm the excess reactivity needed to reach the design temperature;
3) to measure the power output of the Stirling engines to see if they are operating at their optimal performance levels;
4) to perform a transient test by lowering the power demand of the Stirling engines to confirm the self-regulating physics of the reactor; and
5) to re-affirm the thermal and mechanical performance of the reactor components that were obtained in the electrically heated system test but this time in a high neutron fluence field.

Figure 1 shows the basic setup for the preliminary design of the experiment. One end of each heat pipe will be attached to the core and the other end will be attached to a flat plate that serves as the interface to transfer energy to all of the Stirling engines. This design feature is intended to ensure that all of the Stirling engines continue to generate electricity in case one of the heat pipes is not functional. As illustrated, the core, heat pipes, and Stirling engines will be enclosed inside a stainless steel vacuum chamber. The vacuum chamber enclosure, along with the core, heat pipes, and Stirling engines will sit upon a shield made from stainless steel that is to be attached to the top platform of the Comet assembly. Changes to the state of criticality for KRUSTY will be made by adjusting the reflector geometry that surrounds the core. Beryllium Oxide reflector rings will be placed on the movable platen and raised up to surround the portion of the vacuum chamber enclosure where the core resides to achieve critical and super-critical configurations.

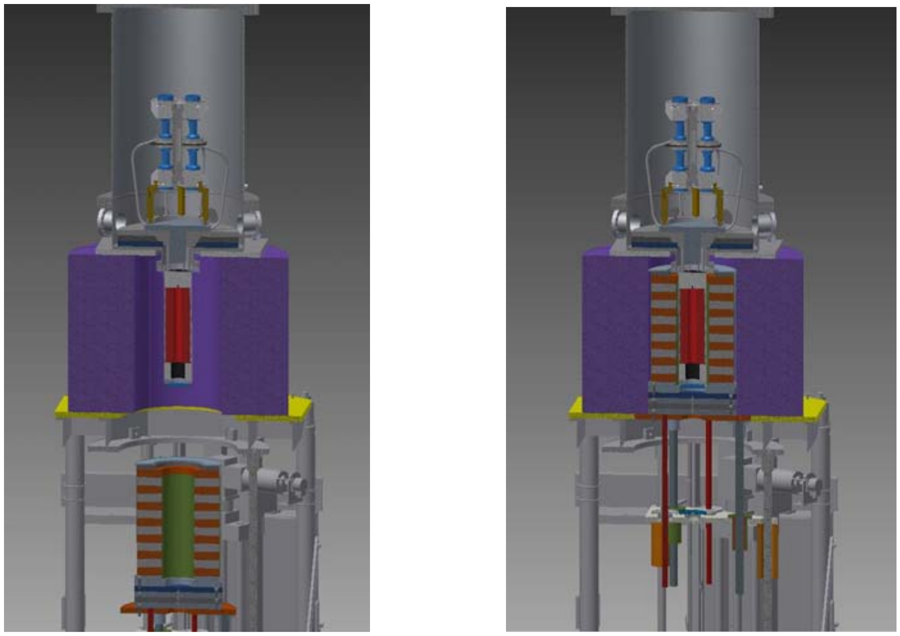
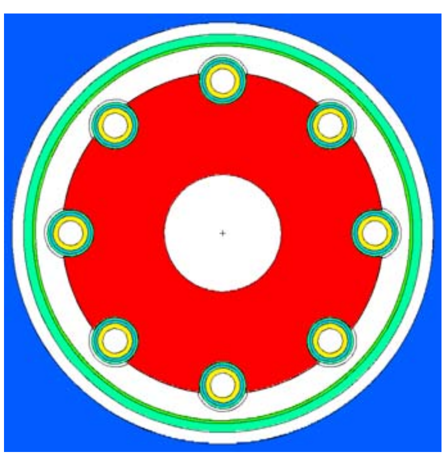


Figure 1. KRUSTY experiment mounted on the Comet assembly.

Description of KRUSTY core configuration: The preliminary design for the KRUSTY core is comprised of approximately 32 kg of uranium metal alloy (8 wt% Molybdenum) with a density of 17.476 g/cc at room temperature. The uranium is isotopically enriched to 93 wt% ^{235}U. The uranium core components form the shape of an upright cylindrical annulus with an inner diameter (ID) of 4 cm and an outer diameter (OD) of 11 cm. The current core design has a height of 25 cm. The inner cavity of the core is called the central hole. Eight Haynes 230 heat pipes are attached to the outside of the core using stainless steel rings. A schematic of the radial view of the components of KRUSTY inside the vacuum chamber (including the vacuum chamber enclosure) in the vicinity of the core is shown in Figure 2.



4.0	Central Hole OD (cm)
11.0	Core OD (cm)
10.4	HP "Ring" Dia (cm)
1.588	Heat pipe OD (cm) 0.625"
1.410	Heat pipe ID (cm) 0.035" wall
0.003	Fuel liner/can thickness (cm)
3.050	Vacves thickness (cm) 0.120"
12.597	Vacves ID
13.607	Vacves OD
14.410	Radref ID (cm)

Figure 2. A radial view of KRUSTY showing the core, heat pipes, and outer vacuum enclosure in the vicinity of the core.

Each heat pipe will contain approximately 15 cc of sodium to be used as the working fluid for heat transfer. Each heat pipe extends vertically from where it is attached to the core and bows outward and upward (after passing through the portion of the vacuum chamber enclosure where the core resides) to connect to a flat plate that serves as the energy transfer interface between all of the heat pipes and all of the Stirling engines. The KRUSTY design will utilize two Stirling engines and six mock Stirling engines, all with identical heat removal capabilities. This configuration is shown in Figure 3.

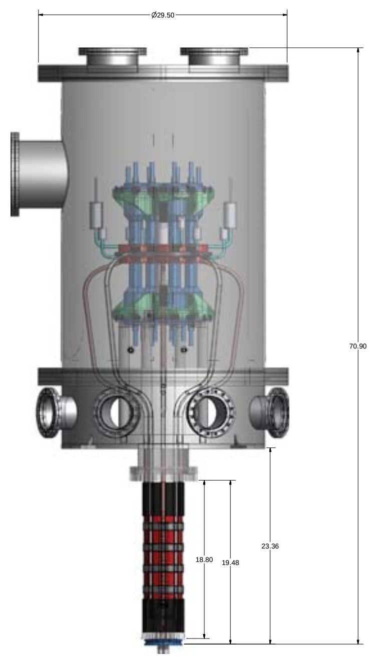


Figure 3. The core, heat pipe, flat plate, Stirling engine coupling configuration for KRUSTY.

As mentioned earlier, changes to the state of criticality for KRUSTY will be made by adjusting the reflector geometry that surrounds the core. Approximately twelve annular BeO plates (or rings) with thickness of 2.5 cm are available to be stacked on the lower movable platen to allow for a step-wise approach to critical. Some extra annular BeO plates that are of lesser thickness will also be available to enable smaller adjustments to the reflector geometry during the approach to critical measurements and to enable a means to adjust the excess reactivity available in the experiment in smaller increments.

A full power test of the KRUSTY design is assembled by slowly raising the BeO reflector to surround the vacuum enclosure where the core resides until the final design operating temperature is achieved. For this experiment, the final design temperature will be approximately 825 °C peak core temperature, approximately 800 °C at the edge of the core, approximately 775 °C at the hot end of the heat pipe, and approximately 750 °C at the hot end of the Stirling engine. To accomplish this task, it has been estimated that the KRUSTY design will need approximately 3.00$ of excess reactivity.

The necessary excess reactivity (3.00$) needed for successfully achieving the goals for this experiment is larger than the current authorized limiting condition of operations (LCO) limit of 0.80$ for Comet. Getting authorization to change this limit will require a facility safety basis change and approval from DOE to proceed with the experiment.

Other instrumentation and balance of plant equipment installations will be required for successful execution to the experiment. Twelve type H nitrogen bottles will be needed to provide cooling to the cold end of the Stirling engines. Extra thermocouples and other electronic equipment will be needed to record and monitor the temperatures, power, as well as to provide a means to control the Stirling engines.

MCNP model: The reference model for the preliminary KRUSTY design shown in Figure 4 was developed using the information David Poston provided during a conference call presentation that occurred April 16, 2015[3]. This reference model is actually quite similar to the final experiment design. The simulation results reported here were obtained using MCNP5 version 5 with ENDF/B-VI cross sections. As shown in Figure 4, the MCNP model is quite similar to the actual experiment shown in Figs. 1 and 2. The blue region in Figure 4 represents the stainless steel shield; the orange region represents the B_4C that will also be used as part of the shielding materials; the yellow region represents the BeO reflector; and the magenta region represents the fuel. The heat pipes are also modeled and are shown in the radial view of the model.

The MCNP computer code was operated in the KCODE mode to get an estimate of the multiplication factor, k_{eff}, for the reference case. The simulation yielded a k_{eff} of 1.04712 ± 0.00038. Assuming a β_{eff} of 650 pcm, the excess reactivity for the reference model is 6.92$, which is a bit higher than the 3.00$ needed for the experiment. This simulation indicates that less excess reactivity will be needed and this can be accomplished by changing the reflector geometry (i.e., by removing part of the BeO reflector).

Table I shows the densities that were used for the reference model and shows the calculated masses of the main components used in this experiment. It should be noted that the total mass that will be loaded on the Comet platform does not exceed the maximum authorized loading limit of 20,000 lbs (9090 kg).

Heat transfer, shielding, and sensitivity simulations will be performed as part of the final design and they will be documented in the CED phase 2 process.

[3] D. Poston, “KRUSTY Reference Concept,” Personal communications, April 16, 2015.

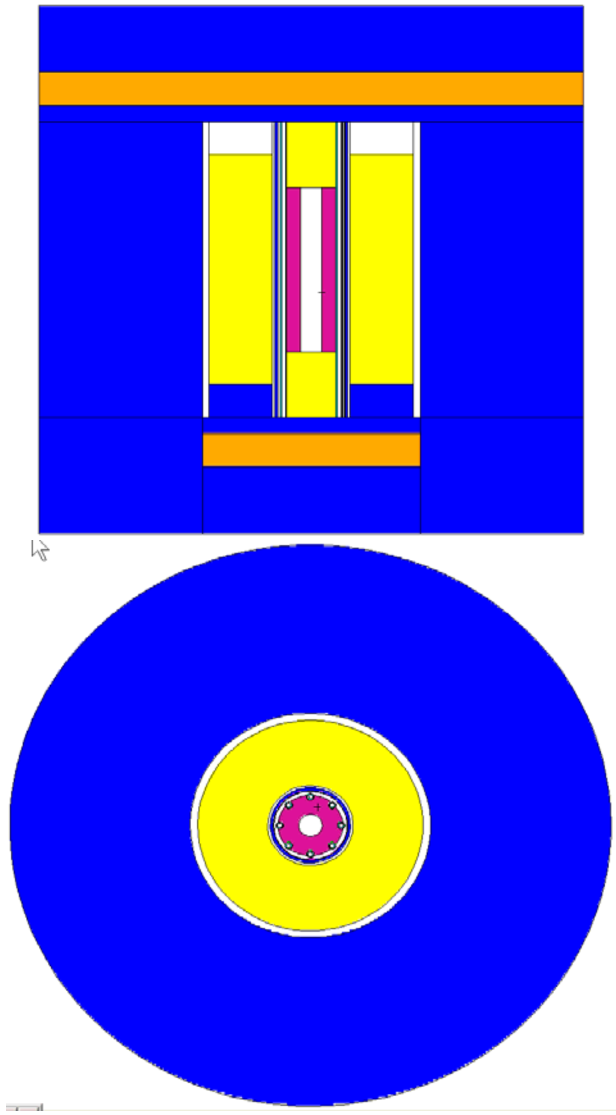


Figure 4. MCNP model of KRUSTY showing the cross sectional and radial views.

Table I. Densities and mass of the components in the reference model.

Component	Density (g/cc)	Mass (g)
Fuel	17.476	31,876
Top Stainless Steel Shield (Thick Plate)	7.92	652,373
Top B_4C Shield	2.51	103,375
Top Stainless Steel Shield (Thin Plate)	7.92	163,093
Stainless Steel Radial Shield	7.02	3,386,129
Top BeO Reflector	3.01	2,574
Bottom BeO Reflector	3.01	2,574
Total Weight on Comet Platform		4,341,994
Radial BeO Reflector	3.01	102,760
Bottom B_4C Shield	2.51	16,540
Bottom Stainless Steel Shield	7.92	169,101
Total Weight on Movable Platen		288,401

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Distribution:
D. K. Hayes, NEN-2, MS B228, dkhayes@lanl.gov
W.L. Myers, NEN-2, MS B228, bmyers@lanl.gov
R.G. Sanchez, NEN-2, MS B228, rgsanchez@lanl.gov
R.C. Little, XCP-DO, MS B259, rcl@lanl.gov
R.W. Margevicius, NEN-DO, MS F650, margevicius@lanl.gov