Title: Space Nuclear Reactor Engineering

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Intended for: Nuclear Engineering Capability Review

Issued: 2017-03-06

Space Nuclear Reactor Engineering

Nuclear Engineering Capability Review

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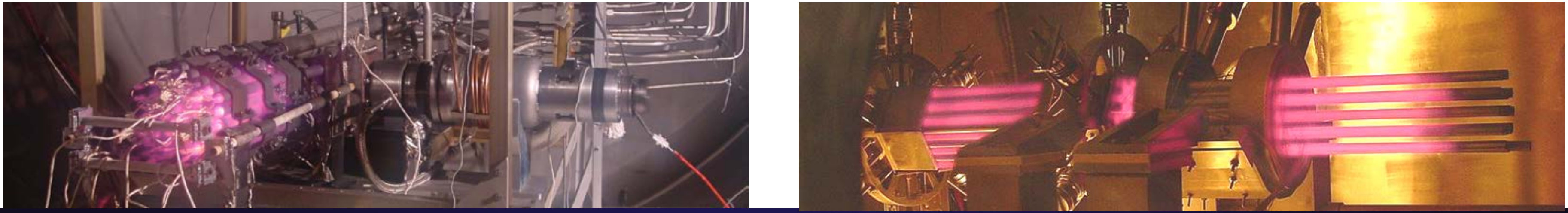
March, 2017

How Did We Arrive at Kilopower, DUFF and KRUSTY?

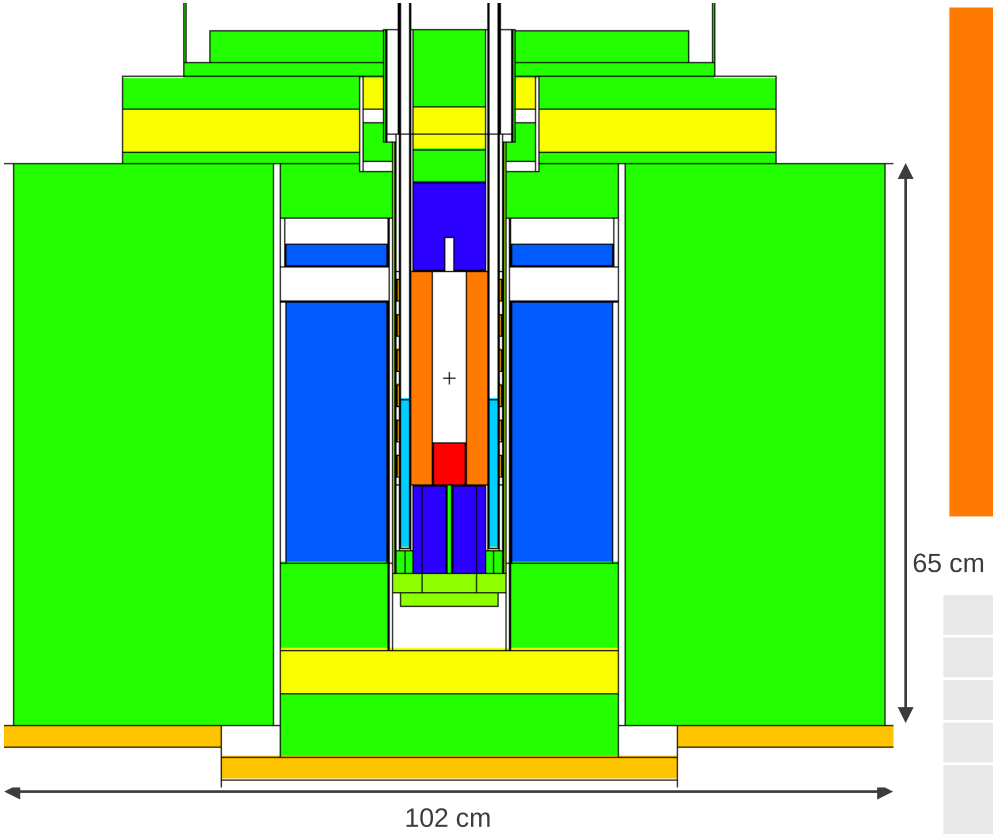
- We needed to find a space reactor concept that could be…
  - 1) Attractive to NASA for flight
  - 2) Proven with a rapid turnaround, low-cost nuclear test.
- Heat-pipe-cooled reactors coupled to Stirling engines long identified as the easiest path to near-term, low-cost concept.
- The idea, and completion of the DUFF experiment added the crucial testing component that finally sparked "real" interest.
- KRUSTY was designed to demonstrate a concept as close to flight-prototypic while remaining affordable and allowing "quick" completion.
  - Use fuel form that can be procured quickly and affordably (i.e. UMo at Y12)
  - Testable in existing facility with experienced operations, safety, compliance teams (i.e. NCERC at DAF)
  - Use existing critical assembly machine (e.g. COMET)
  - Provide adequate safety and asset risk – to machine, room, facility (limit power to ~5 kWt)
  - Use core dimensions that allow shipping in existing/approved container (i.e. 11-cm diameter)
  - Use Stirling simulators to reduce cost/schedule (i.e. 2 "real" converters and 6 thermal simulators)

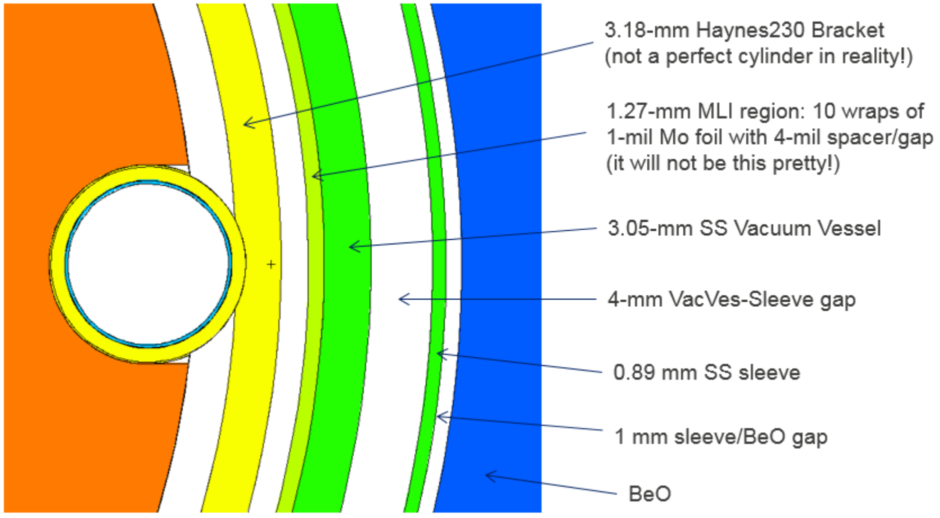
Initial goals to make KRUSTY the most valuable and “prototypic” to the customer; e.g. for a flight system (in order of importance)

- ✓✓✓✓ Thermal/neutronic coupling: dynamics, stability, load-following, heat-pipe cooling, etc.
- ✓✓✓✓ Core materials: all materials as close as flight prototypic as possible
- ✓✓✓ Power: deliver thermal power of similar magnitude and efficiency of flight system.
- ✓✓✓✓ Core Temperatures: thermal, structural, material/chemical, neutronic performance
- ✓✓✓✓ Reflector material: eliminate neutronic uncertainties with highly reflected beryllium
- ✓✓✓✓ Vacuum environment: for heat transfer, but required for materials/temps regardless
- ✓✓ Stirling Integration: demonstrate interfaces and representative dynamic response.
- ✓✓✓ Core geometry: resemble flight, in particular conduction paths to heat pipes
- ✓✓ Reactor control: Less important because flight system doesn’t have active reactor control (only startup), and system-dynamics is validated with either control approach.
- ✓ Reflector temperatures: Less important because substantially slower time constant.
- ✓✓ Shielding: hard to benchmark shielding characteristics with room/equipment scatter

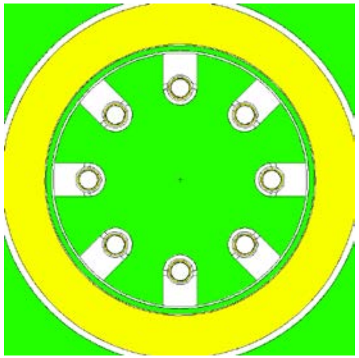


KRUSTY MCNP Model



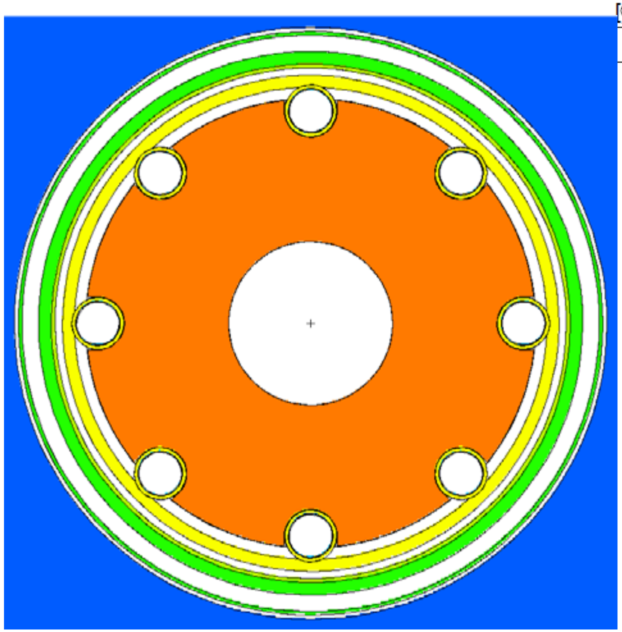


Orange	U8Mo
Blue	BeO
Green	SS316
Red	B4Cenr
Yellow (above)	Ha230
Yellow(left)	B4C
Light Orange	Al
Light blue	Na

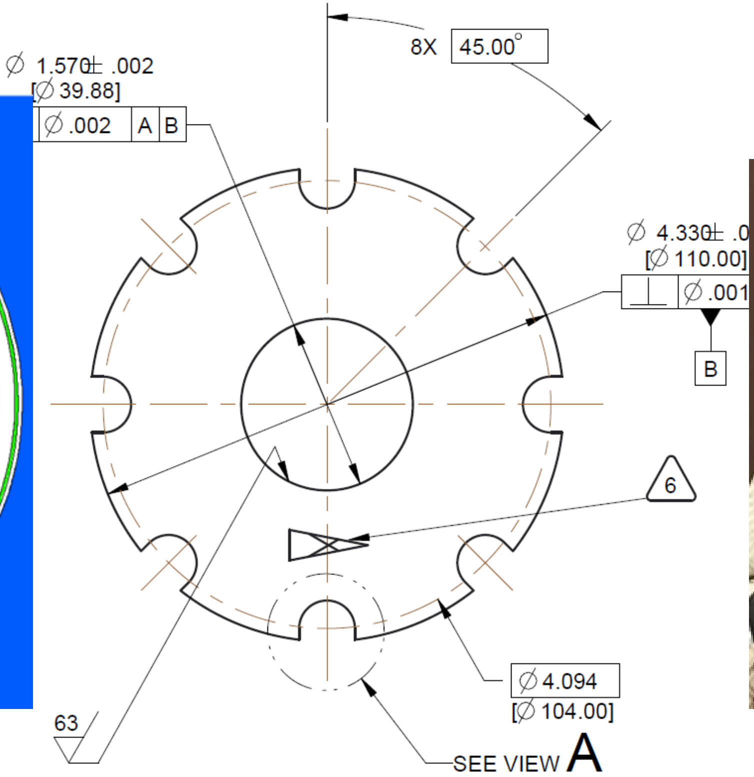


MCNP was the primary design tool.
MCNP was the first place KRUSTY ever "existed".

Iteration between model, design-drawings, and fabrication



MCNP model



Design Drawing

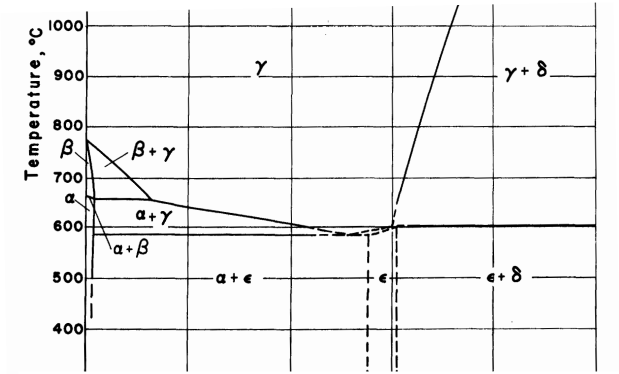
DU Core Piece

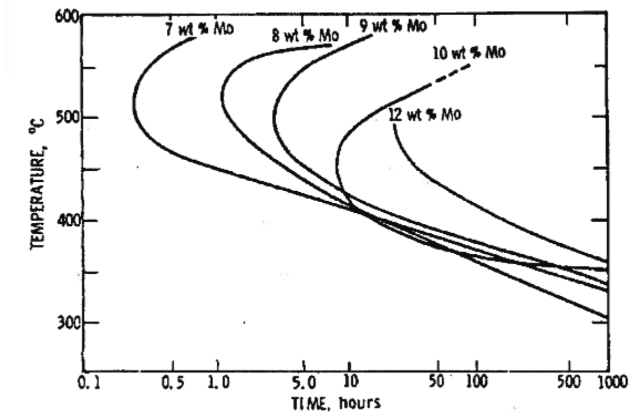
Parts modeled at spec – fuel tolerances +/- 0.002”

KRUSTY Reactor Parameters

HEU8Mo	Fuel Material
Haynes-230	Heat Pipe and Core Structure
BeO	Neutron Reflector Material
B4C	Internal Neutron Poison Rod
B4C/SS316	Neutron/Gamma Shielding
5.0	KRUSTY “Rated” Power (kWt)
3.0	Nominal Test Power (kWt)
28.0	Proposed Full-Power Test Hours (hr)
800	Core Ave Fuel Temperature (C) – 1073 K
~775	Heat Pipe Condenser Temperature (C) – 1048 K
1.60	Ave Test Fuel Power density (W/cc)
27.5	Total U235 Inventory (kg)
95.0%	Radref BeO theoretical density
0.00001%	Fuel Burnup (FIMA)
9.3E+11	Core Ave Neutron Flux (n/cm2-s)

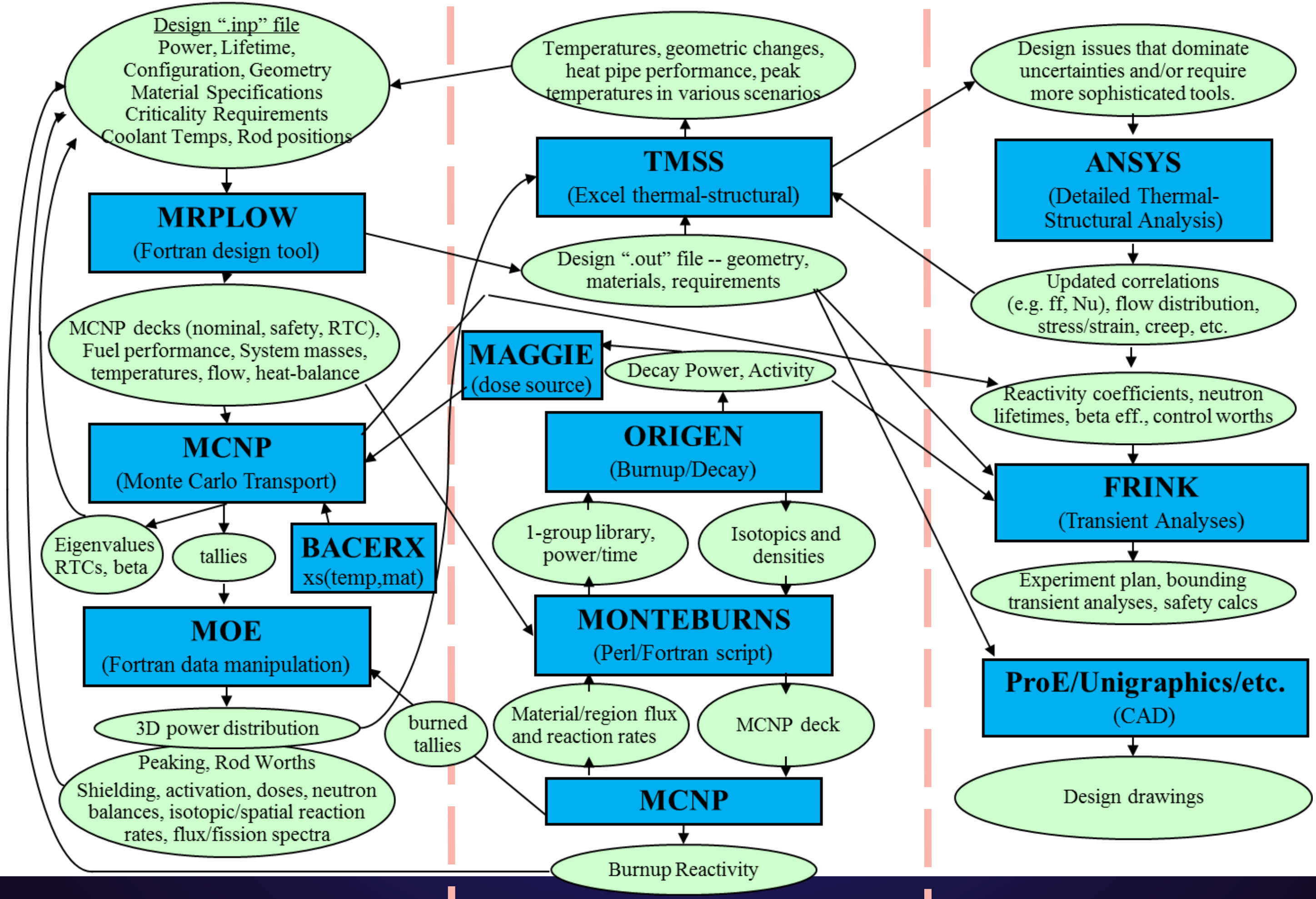
UMo alloy chosen for high fuel loading, good thermal conductivity, ease of fabrication, and ongoing development at INL and elsewhere. 8 w/o Mo chosen as balance between low mass and phase transition stability





LANL Reactor Design Process for Kilopower

Level 0 – Notional | Level 1 –Conceptual | Level 2 – Preliminary onward



Design ".inp" file
Power, Lifetime,
Configuration, Geometry
Material Specifications
Criticality Requirements
Coolant Temps, Rod positions

MRPLOW
(Fortran design tool)

MCNP decks (nominal, safety, RTC), Fuel performance, System masses, temperatures, flow, heat-balance

MCNP
(Monte Carlo Transport)

Eigenvalues RTCs, beta

tallies

BACERX
xs(temp,mat)

MOE
(Fortran data manipulation)

3D power distribution

Peaking, Rod Worths
Shielding, activation, doses, neutron balances, isotopic/spatial reaction rates, flux/fission spectra

burned tallies

Temperatures, geometric changes, heat pipe performance, peak temperatures in various scenarios

TMSS
(Excel thermal-structural)

Design ".out" file -- geometry, materials, requirements

MAGGIE
(dose source)

Decay Power, Activity

ORIGEN
(Burnup/Decay)

1-group library, power/time

Isotopics and densities

MONTEBURNS
(Perl/Fortran script)

Material/region flux and reaction rates

MCNP deck

MCNP

Burnup Reactivity

Design issues that dominate uncertainties and/or require more sophisticated tools.

ANSYS
(Detailed Thermal-Structural Analysis)

Updated correlations (e.g. ff, Nu), flow distribution, stress/strain, creep, etc.

Reactivity coefficients, neutron lifetimes, beta eff., control worths

FRINK
(Transient Analyses)

Experiment plan, bounding transient analyses, safety calcs

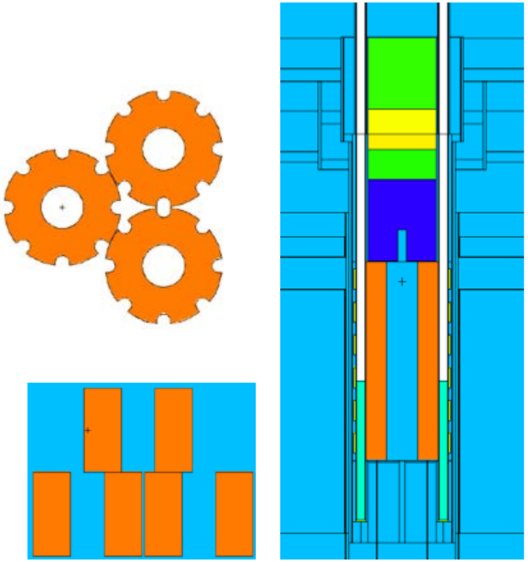
ProE/Unigraphics/etc.
(CAD)

Design drawings

Criticality Safety of Core/Assembly

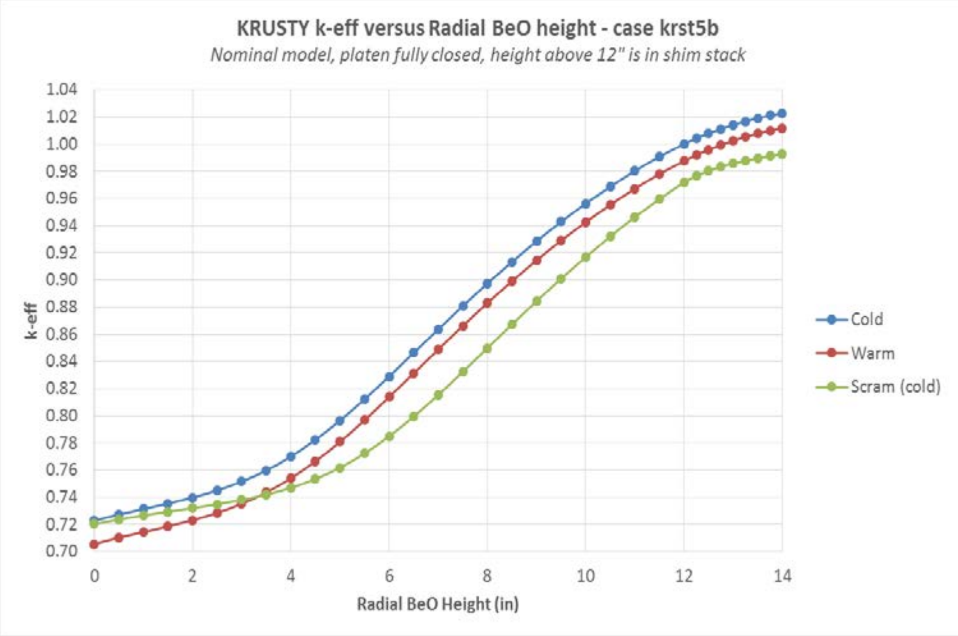
- **From a crit safety perspective, the KRUSTY core is neutronically similar to the Flattop HEU core and other existing NCERC material.**
- **Keff calculations are shown below.**

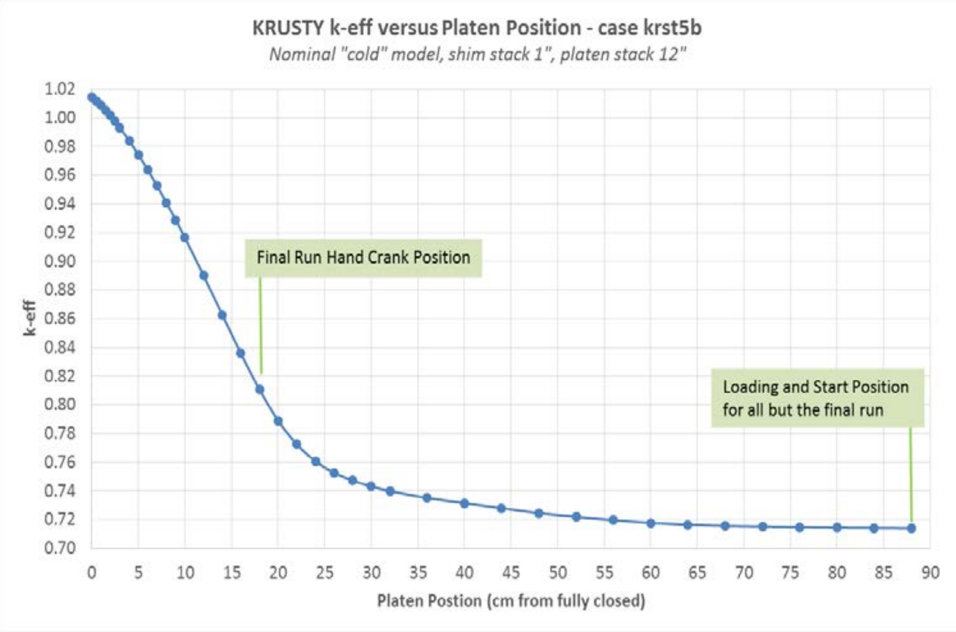
	bare	water	sand	wet-sand
Flattop HEU core ball	0.6576	0.8991	0.8166	0.8863
KRUSTY fuel 1 section	0.4577	0.7642	0.6034	0.7127
KRUSTY fuel 3-section column	0.5886	0.9591	0.8310	0.9346
KRUSTY fuel 3-section triangle pitch	0.5776	0.9710	0.8210	0.9368
KRUSTY fuel 3-section paint-can stack	0.5846	0.9806	0.8296	0.9446
KRUSTY assembly outside of vessel/shield	0.6148	0.9155	0.8311	0.9062
Same as above with central void not filled	0.6148	0.8612	0.8277	0.8881



- **There is no material that the fuel could be accidentally surrounded by that would take the fuel critical other than Be or another fissile material**
  - Academic caveat: a form fitting full (4pi) encasement of >1m thick of high-density/purity graphite could do the trick)

Worth of BeO Radial Reflector Stack

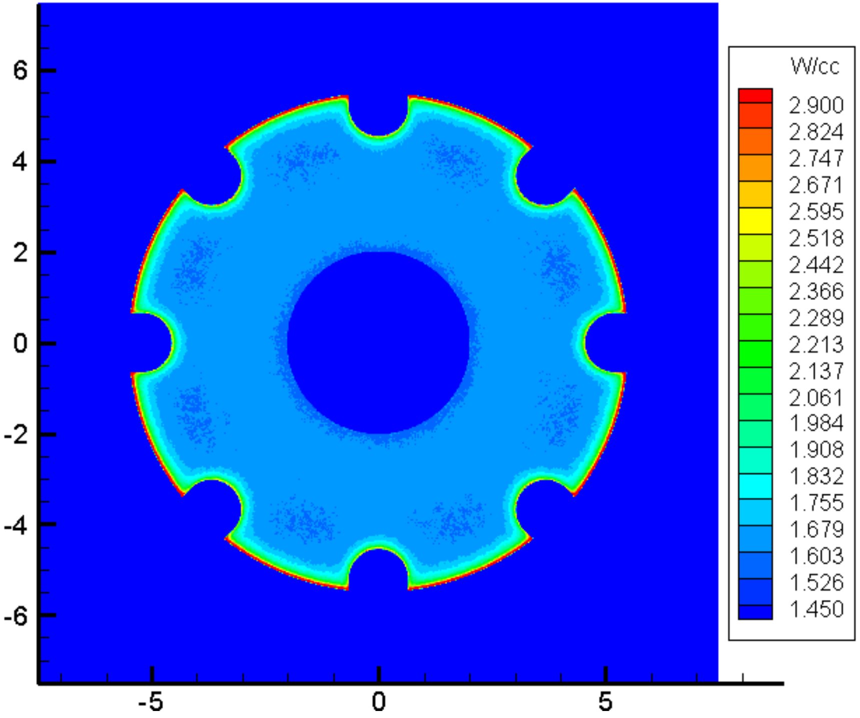


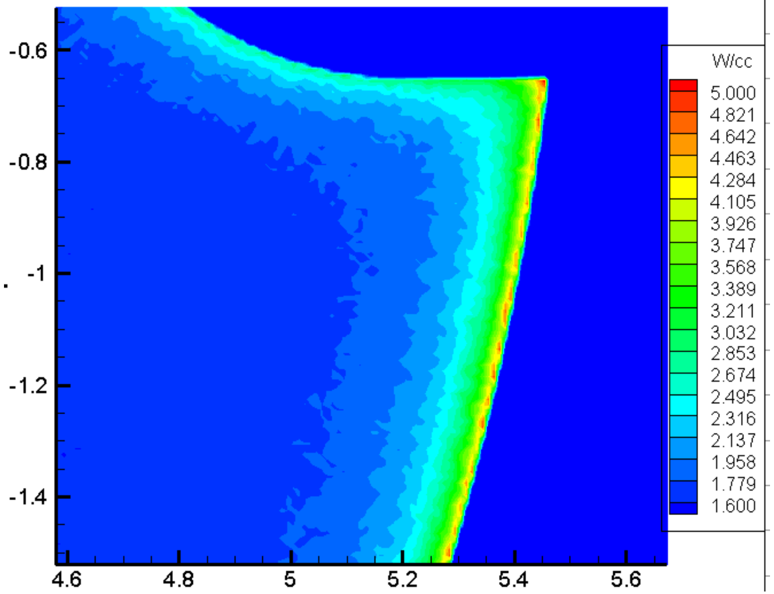


KRUSTY will not necessarily be loaded with the entire height of BeO for the powered runs, it will depend on the results of the preceding zero-power criticals, and the use of the B4C-poison stack.

The final “full-power” run uses a higher starting/ending platen position because this provides post-test shielding to room, and will allow personnel to reenter and perform work in the room sooner.

Radial Core Power Deposition





Good news: the power is pretty flat, and slightly tilted outward, which reduces delta-T in the nuclear test.

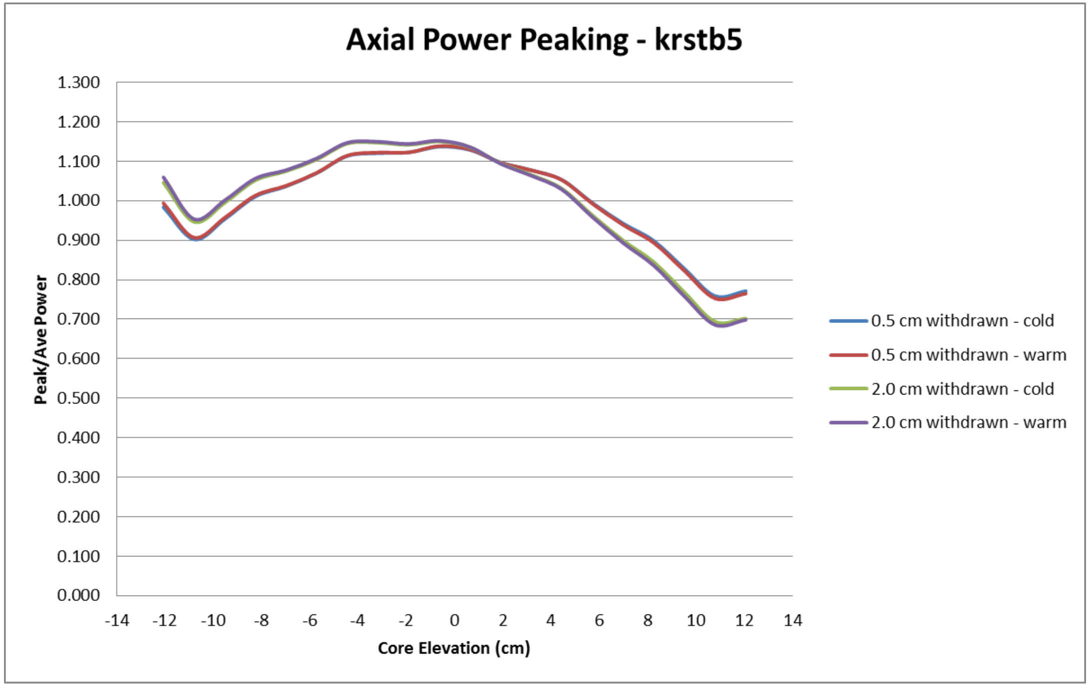
Bad news: this is significantly different than resistant heated, which puts 100% on the inside (which is more conservative than we'd like) – fortunately the core survived unscathed in resistance-heated tests!

The 4+ W/cc layer is so thin that localized heat-up would not be a noticeable, plus the outer layer radiates to the clamps and insulation.

This peaking would be an issue in burnup limited concepts, but is not an issue for KRUSTY and 1-kWe Kilopower because burnups are so low.

Higher power concepts are designed with much thinner reflectors, and have higher internal power densities, both which will reduce this effect.

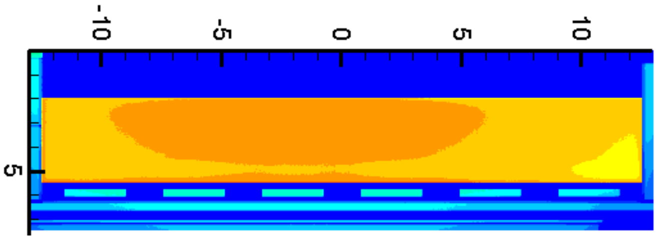
Axial Power Peaking



The axial peaking is small compared to most reactors, despite having an extremely large L/D. This is because the mean-free-path of neutron is 3 cm (very large relative to core size)

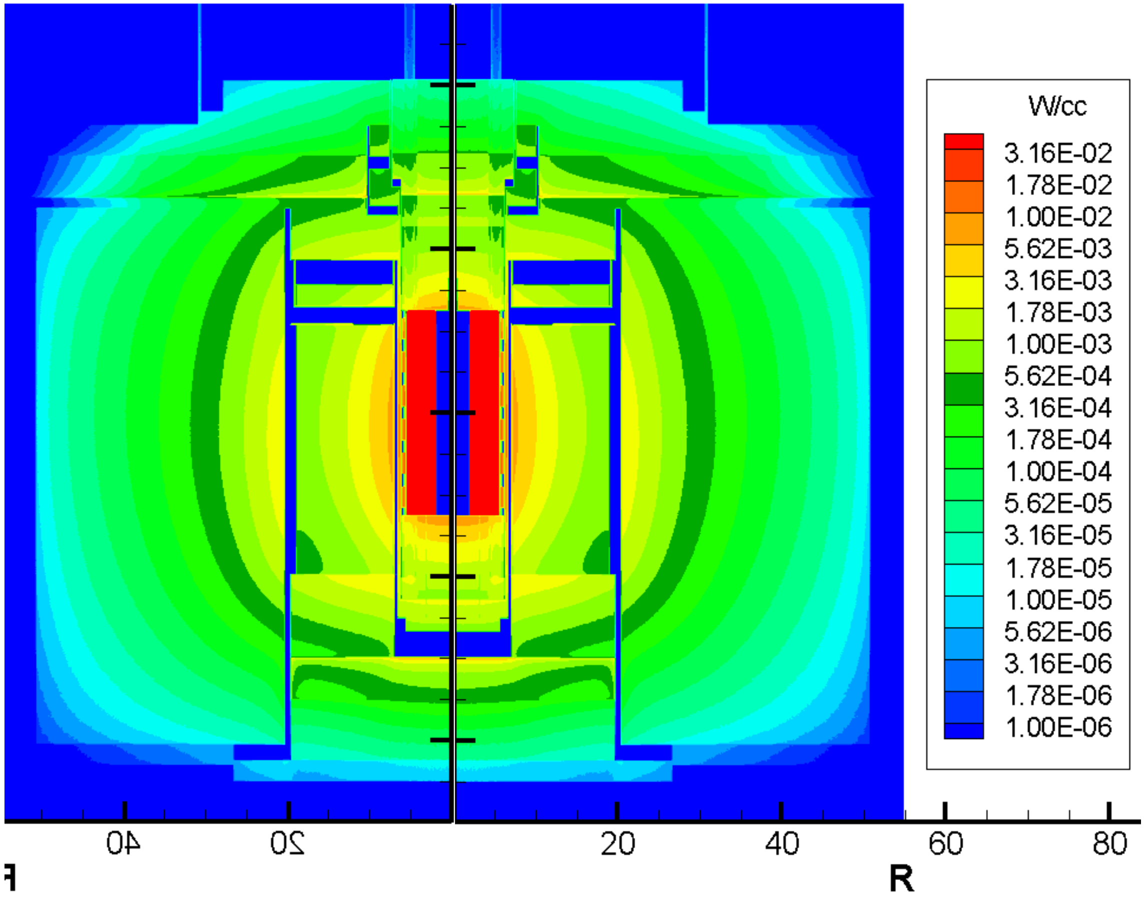
The effect of the core clamps is distinguishable – 5 relative peaks occur at the location between the clamps. However, the “peaks” are ~1% of power, so the net impact is minor.

The chart confirms that the more closed platen position results in less peaking.



← Power Deposition on log scale

System-wide Power Deposition



Power deposition in the shield means it is “doing its job”, reducing energy deposition (Rads) outside of the system.

The system model deposits power into each component to calculate temperatures and thermal balance.

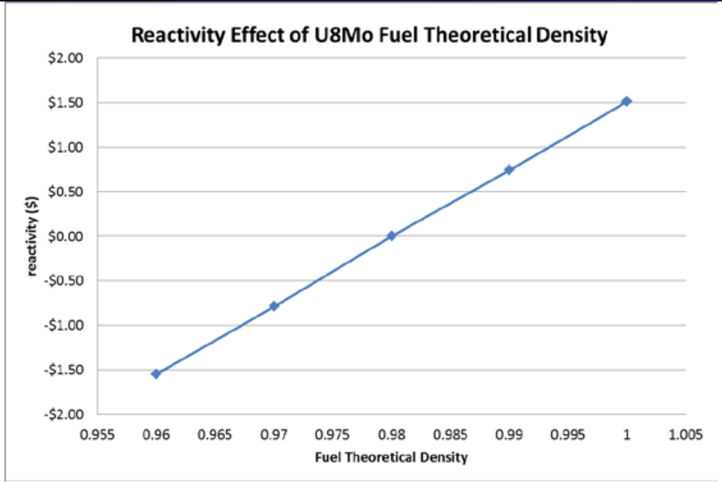
Component (not all listed)	Watts (3kW)
heat pipes	1.79
fuel	2816.15
clamps	3.20
multifoil	0.74
radial vessel	3.57
radref sleeve	0.90
radref	47.81
radial shield	86.33
upper axref	1.81
lower axref	2.98
upper external B4C shield	7.39
lower B4C shield	4.32

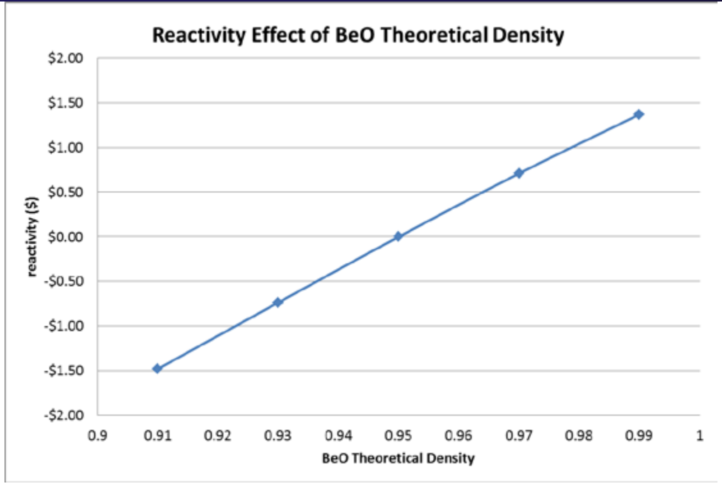
So much cool stuff going on that I added the reverse image!

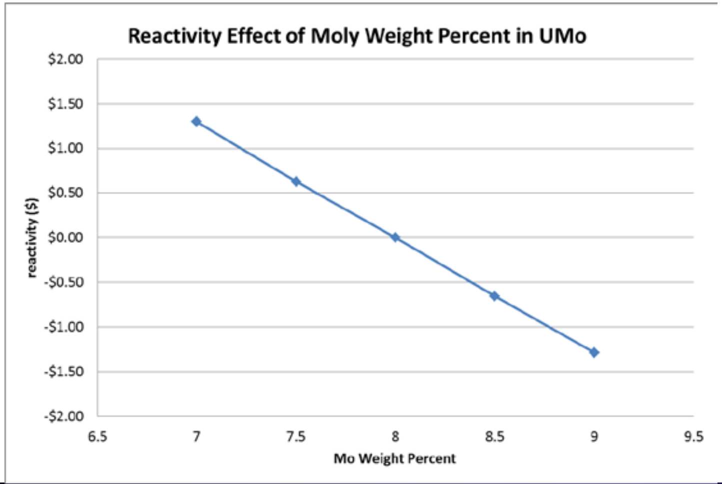
Model Bias – Need to be prepared for over/under prediction

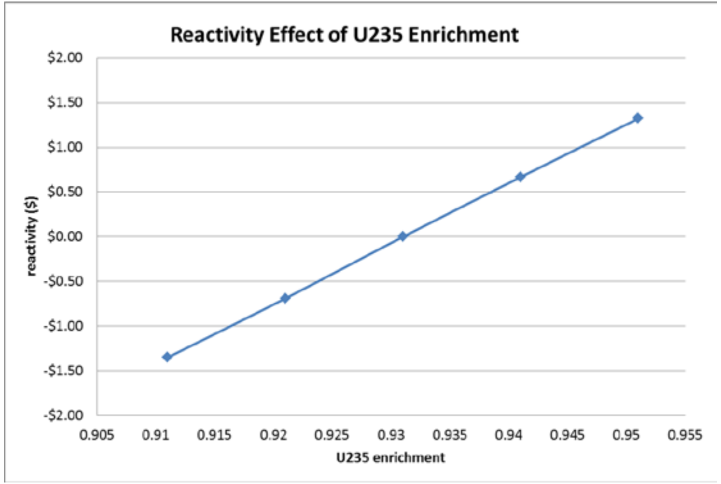
- **Numerous reasons why reactivity of the actual system could be over/under predicted.**
  - Model inaccuracies
    - Cross sections
    - MCNP modeling/computational techniques (not expected to be issue)
    - Statistical errors are not a problem with current computing power (MCNP statistical errors <0.1 cent)
  - Physical discrepancies
    - Fuel density, enrichment, Mo fraction, impurities
    - Haynes 230, BeO, SS316, B4C densities, composition and impurities
    - Dimension and tolerances of parts
    - Spacing and alignment of assembled parts
    - As-loaded Na level in heat pipes
    - Tolerances of Comet.
  - Environment
    - Ambient temperature (~0.2 cents/C)
    - Heat removal mechanisms/paths from components
- **Calculations were performed to evaluate the possible effects of (model bias)**
  - Grossly underpredicted (-\$2) – highly negative model bias
  - Underpredicted (-\$1) – negative model bias
  - Nailed it – no model bias
  - Overpredicted (+\$1) – positive model bias
  - Grossly overpredicted (+\$2) – highly positive model bias
- **The majority of bias is expected to come from potential inaccuracies in the Be cross sections**

Design Sensitivity to As-Delivered Fuel/BeO Properties


Reactivity Effect of U8Mo Fuel Theoretical Density


Reactivity Effect of BeO Theoretical Density


Reactivity Effect of Moly Weight Percent in UMo


Reactivity Effect of U235 Enrichment

We set our material specs to decrease difficulty/cost of fabrication, while minimizing the risk of not having enough reactivity.

Excess reactivity – Design Values

- **The MCNP model gives cold, fully-loaded BeO system keff=1.0229 ($3.32 excess).**
- **Operating reactivity defect – currently calculated at $1.70**
  - 1a) Temperature defect – currently calculated as $1.63
    - Nominal temp = heat pipe vapor temp ~773 C , average fuel temp 800 C.
    - The main component of temperature defect is fuel expansion,
  - 1b) Power defect – currently calculated as $0.07
    - The power defect in KRUSTY is caused by the sodium level fluctuating in the heat pipes
    - At zero-power, all of the Na will be in the pool at bottom of the HP
  - 1c) Drift defect – depends on length of operation: =$0.00 at 4 hours
    - ~1 cent drop in reactivity every 4 hours as reflector/shield heat up slowly.
- **The leaves a margin of $1.62 for model bias**
    - Hopefully enough to reach full temperature, but there is some risk of operating at reduced temp.
    - Note the majority of expected bias (Be cross sections) will be well quantified by the zero-power criticals (ZPCs), so when the time comes to load Comet for full temperature operation we will have eliminated most of our need for margin.
    - In the full-power testing, we will load $0.50 of margin on to the machine.

Neutron Kinetics Parameters, Reactivity Worth, Feedback

- **Beta-effective**
  - MCNP kopts card give .00687 +/- .00002
  - MCNP Kcode totnu gives .00689 +/- .00002
- **Prompt neutron generation time**
  - Average neutron generation time of system = 3.5e-5 sec
  - Fast neutron generation time (fuel and nearby reflector) = 5.5e-8 sec
- **Geometrically delayed-neutrons**
  - The difference between the fast and average generations times is the effect of neutrons taking longer to return from further out in system.
  - Geometrically delayed neutron groups are like traditional delayed neutron groups - they bin neutrons based on the average time it takes to cause fission (as determined by geometry).
    - This includes the delayed effect of n2n (significant for KRUSTY) and photoneutrons (insignificant for KRUSTY)

- **Reactivity Coefficients/Worths**
  - Physical Inputs
    - Platen Position
    - BeO Radial Reflector Stack-Height
    - B4C Central Rod Height
  - Temperature Feedback (density, geometry, cross sections)
    - Fuel Temperature (as a function of core region)
    - Axial Reflector Temperature
    - Heat Pipe Temperature
    - Core Bracket Temperature
    - Multi-Layer Insulation Temperature
    - Vessel (Core Can) Temperature
    - Radial Reflector Temperature
    - Shield Temperature
  - Power Feedback
    - Na pool height
- **Each of the above is calculated and input into FRINK in polynomial form.**

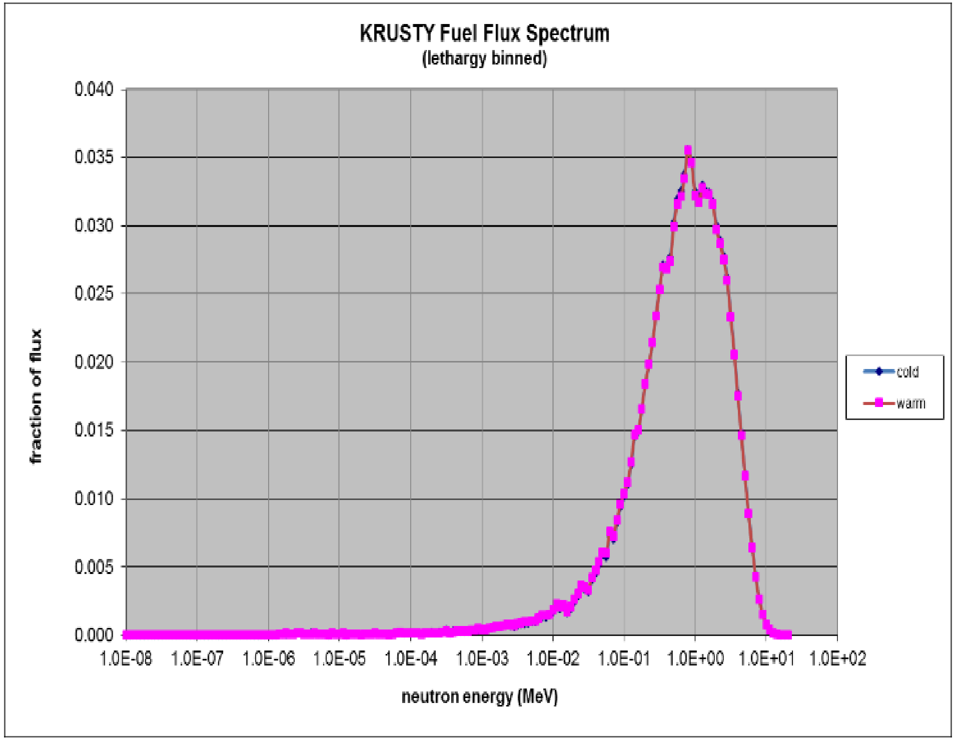
Cross Sections

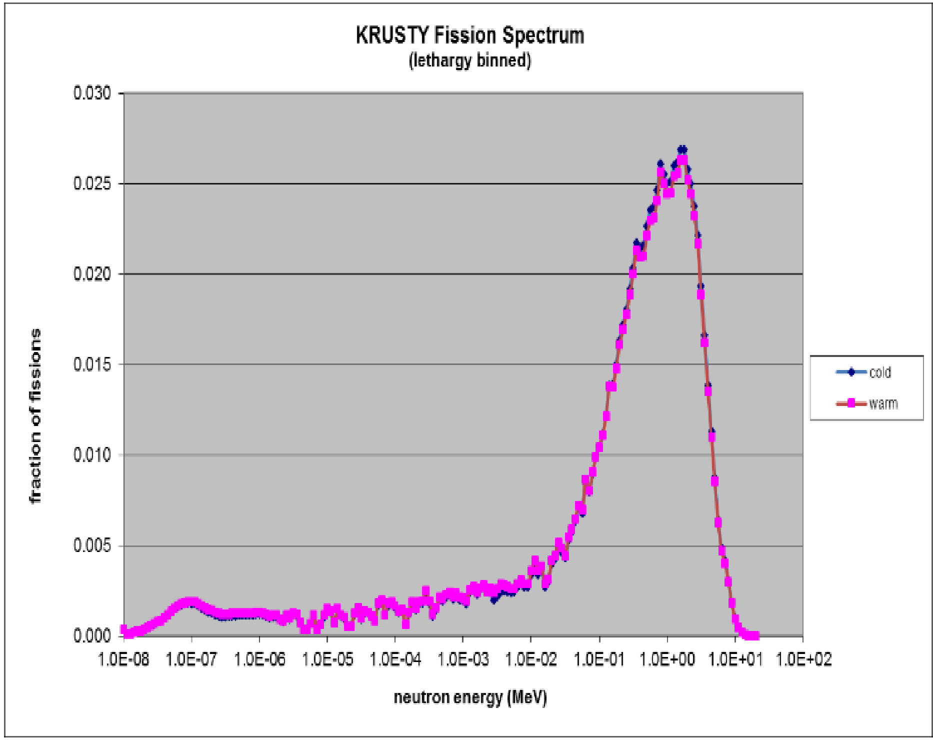
- **Continuous energy MCNP cross sections generated by NJOY/ACER**
- **Cross section set called SPACE07**
- **~360 isotopes**
  - ENDF/B-VII
  - If xs not available in ENDF/B-VII then use
    - JEF2.2, 3.0
    - JENDL3.2, 3.3
- **25 temperatures**
  - 300K through 3000K
    - Every 50 degrees <1000 K (for thermal systems we sometimes use 10 K intervals in regions of interest)
    - Every 100 degrees >1000 K
  - S(a,b), generated at 100 K intervals.
- **Difference between ENDF7.0 and ENDF7.1 is a net 18 cent increase – chart on right.**

Reactivity change moving from ENDF7.0 to END7.1

Be	29.9 ¢	± 0.4 ¢
Ni58	7.1 ¢	± 0.4 ¢
Cr53	2.2 ¢	± 0.4 ¢
Mo	1.0 ¢	± 0.4 ¢
Ni60	0.9 ¢	± 0.4 ¢
U235	0.6 ¢	± 0.5 ¢
C	0.6 ¢	± 0.6 ¢
Cr50	0.4 ¢	± 0.4 ¢
Fe56	0.1 ¢	± 0.5 ¢
Na23	0.0 ¢	± 0.4 ¢
B	-0.3 ¢	± 0.5 ¢
balance of fuel	-0.4 ¢	± 0.6 ¢
rest of Fe (other than 56)	-0.4 ¢	± 0.5 ¢
everything else to70	-0.4 ¢	± 0.4 ¢
rest of Ni (other than 58, 60)	-0.6 ¢	± 0.4 ¢
rest of Cr	-0.6 ¢	± 0.4 ¢
W in Haynes 230	-1.0 ¢	± 0.5 ¢
balance of BeO	-1.0 ¢	± 0.5 ¢
Mn	-3.2 ¢	± 0.4 ¢
Cr52	-16.4 ¢	± 0.4 ¢

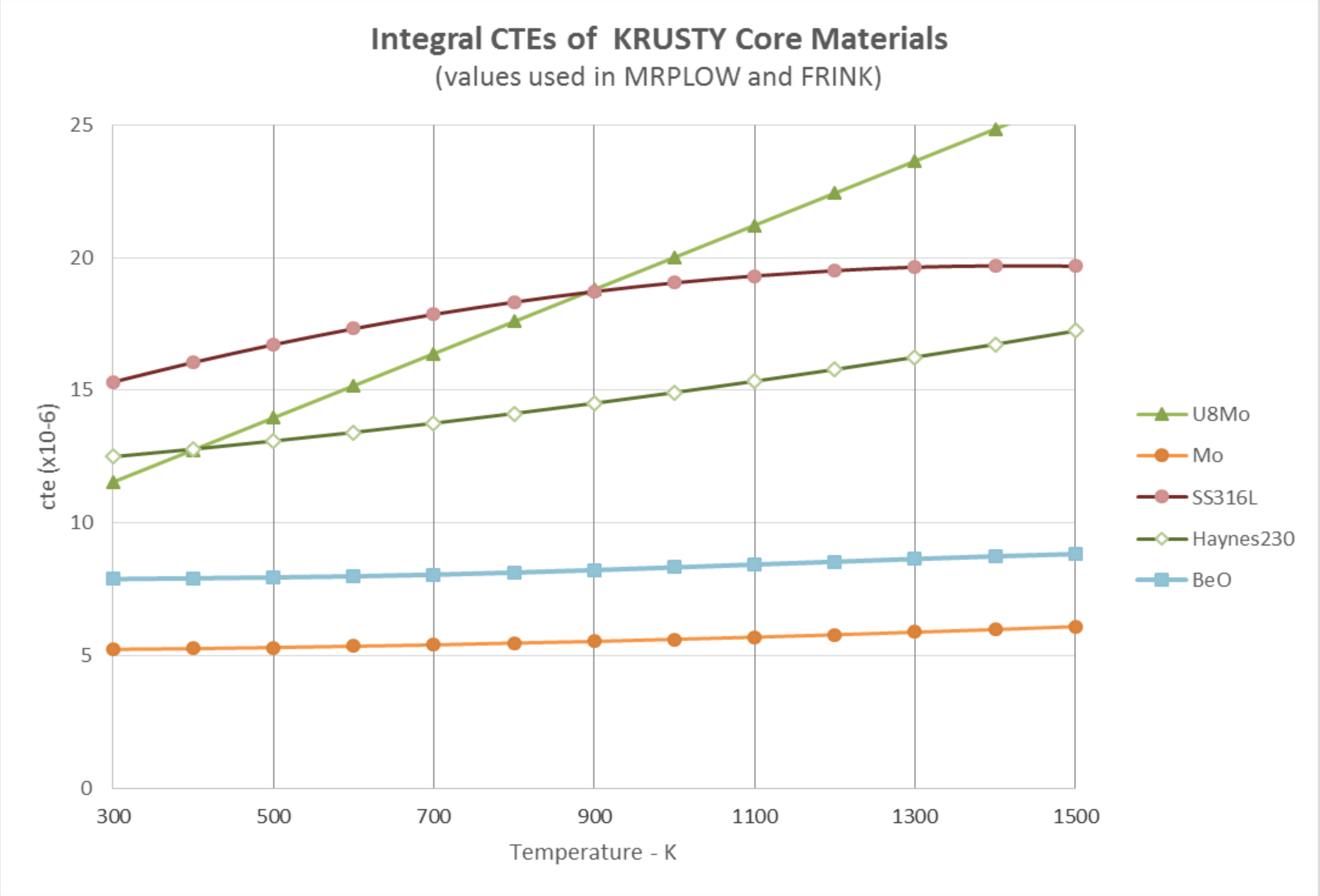
KRUSTY Flux and Fission Spectra





Spectrum is very fast, such that changes in cross sections with temperature are largely insignificant, >90% of feedback is dimensional changes due to thermal expansion.

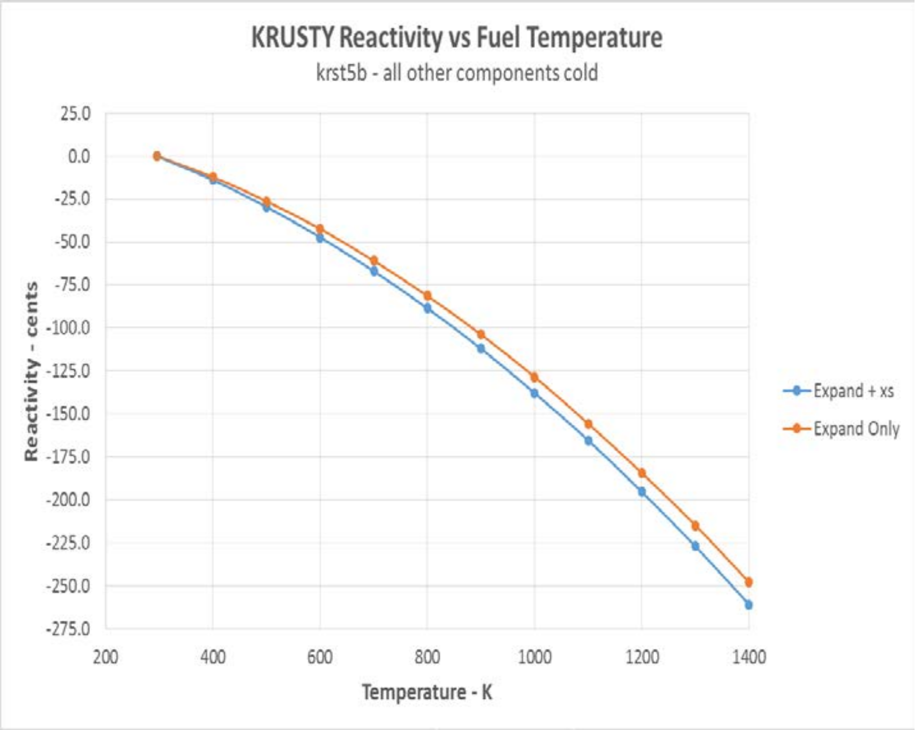
Linear Thermal Expansion Coefficients



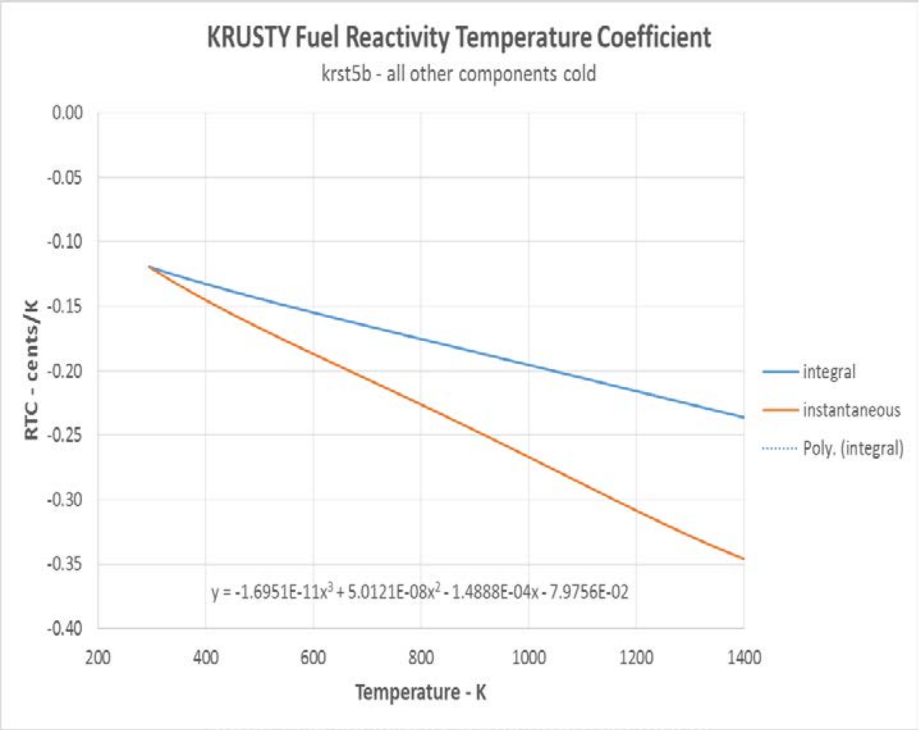
Mo and BeO are small, while U8Mo, Haynes 230, and SS316 are all in the same ballpark.

U8Mo CTE is very large at higher temperature, which is great in terms of providing stronger negative feedback at high temperatures. The lower CTE at low temperatures is also ideal so that less excess reactivity is required to bring the reactor to high temp. U8Mo is gamma phase.

Fuel Temperature Worth and RTC (Reactivity Temp Coef)


KRUSTY Reactivity vs Fuel Temperature

krst5b - all other components cold

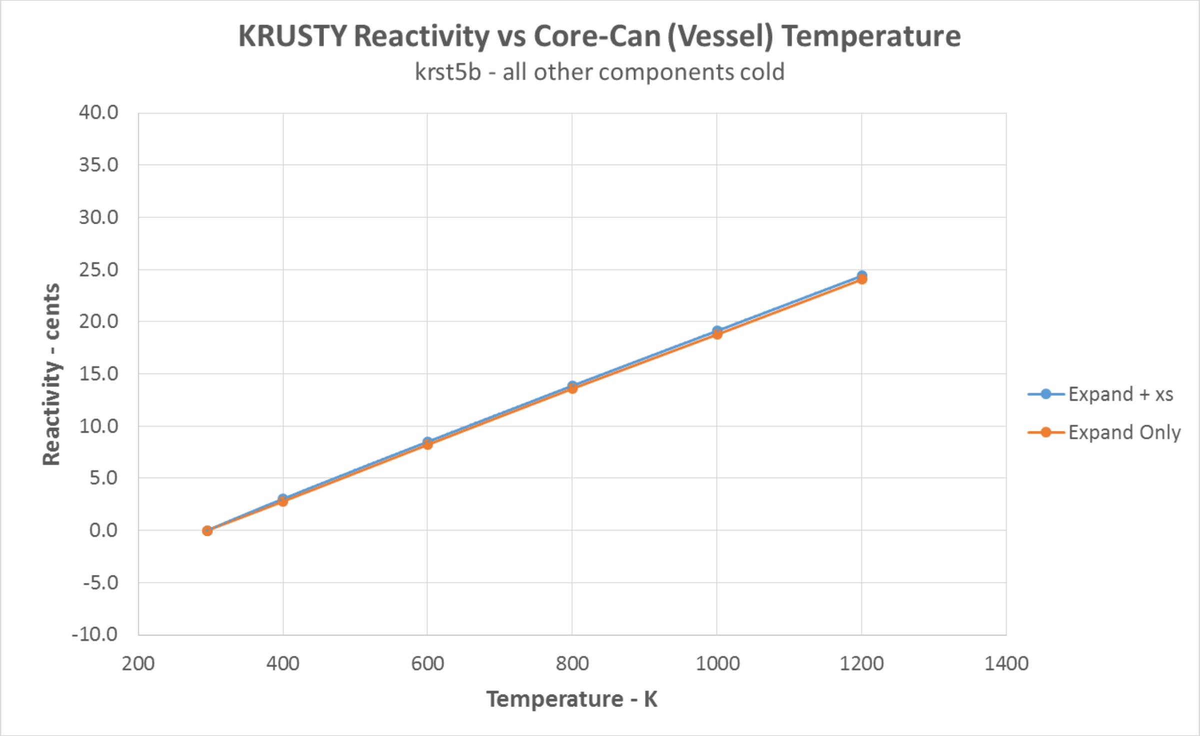

KRUSTY Fuel Reactivity Temperature Coefficient

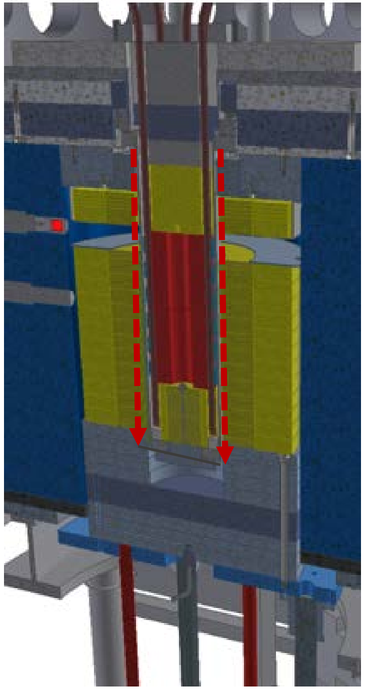
krst5b - all other components cold

Worth is dominated by expansion coefficient of U8Mo. Warmer cross sections add additional negative feedback because Doppler broadening of U235+U238+Mo capture has more effect than Doppler broadening of U235+U238 fission.

These curves were generated for 9 reactor components, and input as polynomials into the system dynamic model.

Core-Can (Vacuum Vessel) Temperature Worth





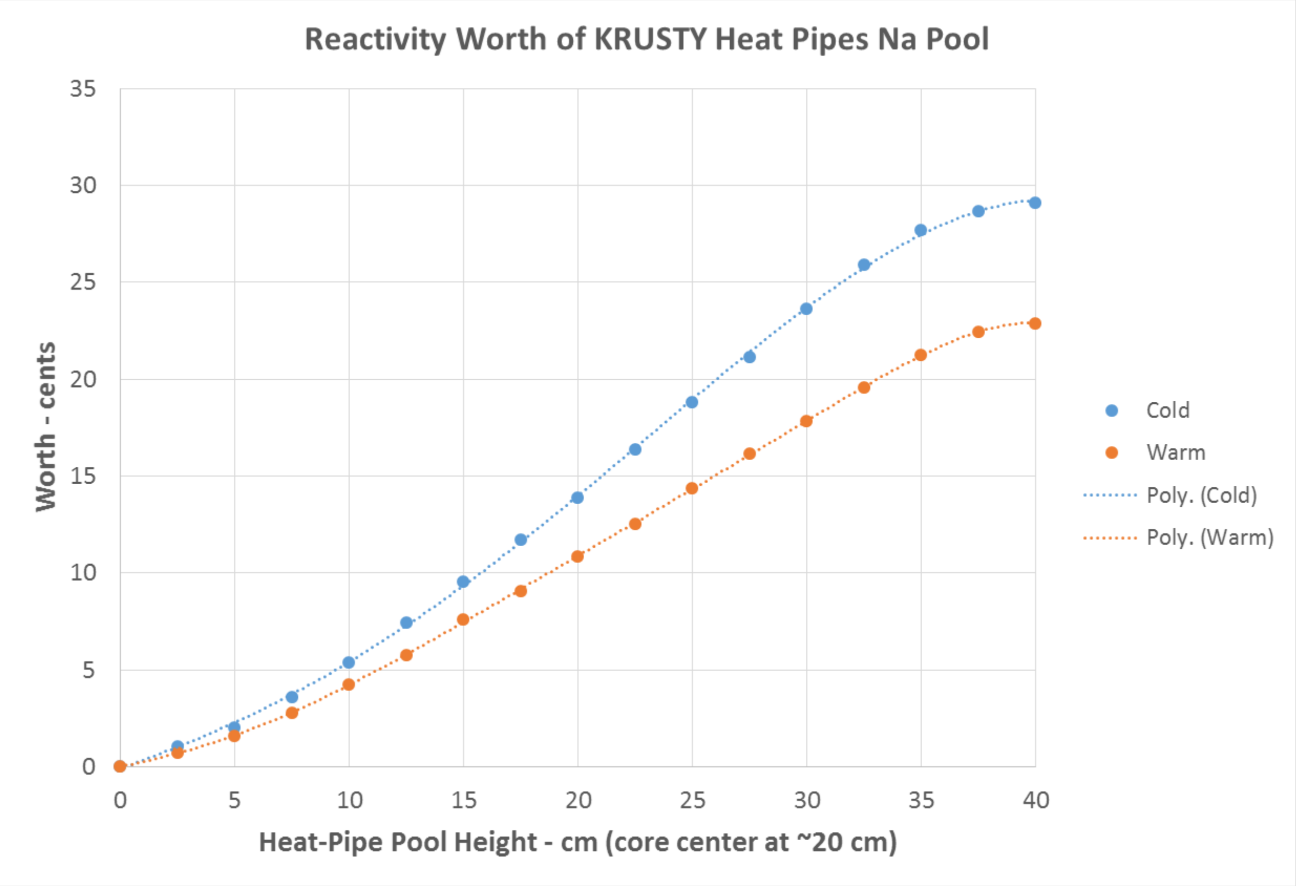
Nominally, the change in temperature of the core-can vessel is negligible – a balance between the increased leakage, decreased macroscopic capture XS (density), with a small increase in microscopic capture XS (Doppler); HOWEVER, expansion of the core-can lowers the fuel within the reflector assembly (dashed red arrows), which has the same effect as raising the platen, thus an increase in reactivity. Fortunately, the vessel should not heat much, predicted max rise of ~100 K.

Summary of KRUSTY RTCs

Each of the RTCs is in polynomial form via a curve fit, which are used in FRINK, except for radial mli, for which a constant value was used based on the defect.

	Operating Temp	Reactivity Defect	Integral RTC at Operating Temp	RTC at Room Temp	Instantaneous RTC at Operating Temp
	(K)	(cents)	(cents/K)	(cents/K)	(cents/K)
Fuel	1075	-157.9	-0.2029	-0.1195	-0.2825
Axial Reflector	413	-0.2	-0.0020	-0.0017	-0.0023
Heat Pipes	1051	-3.1	-0.0041	-0.0041	-0.0041
Core-Clamps	1045	-2.9	-0.0039	-0.0055	-0.0030
Radial MFI	806	-0.7	-0.0014	-0.0014	-0.0014
Vacuum Vessel	374	2.1	0.0274	0.0277	0.0270
Radial Reflector	311	0.2	0.0155	0.0161	0.0149
Platen Shielding	309	0.3	0.0239	0.0239	0.0239
Radial Shielding	297.2	0.0	-0.0663	-0.0663	-0.0663

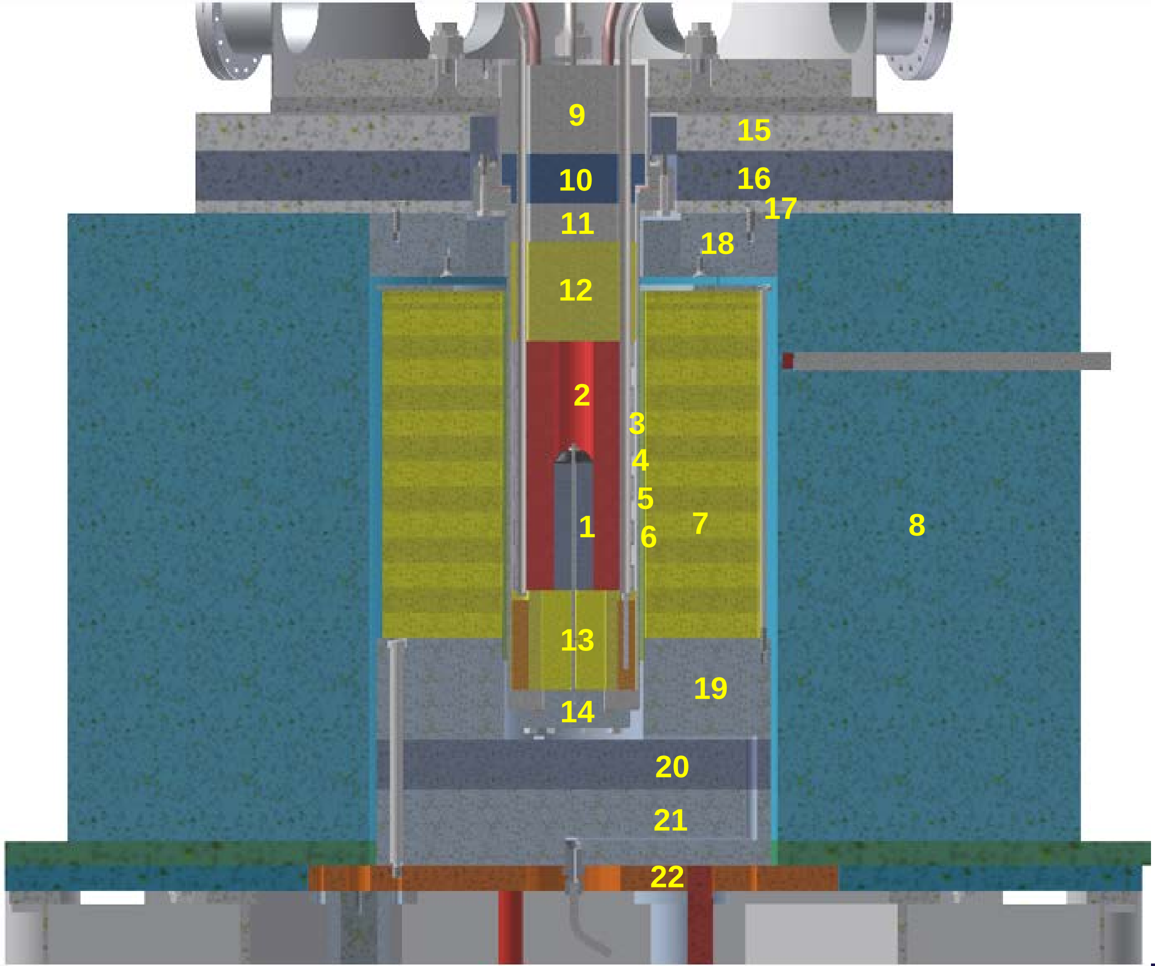
Sodium Pool Level



The baseline HP design has a cold pool height of 17.5 cm, or 2.5 cm below core axial center. In this case the change in pool height with operation will at most be ~12 cents (i.e. if the entire pool is evaporated), or ~1.5 cents per individual HP.

The pool height is a function of temperature (density), but even more-so a function of heat pipe power throughput, such that a good fraction of the pool is gone (flowing elsewhere in the HP) at full power (perhaps ~50% gone at 3 kWt core power)

FRINK Transient Point-Kinetics System Model



FRINK implicitly solves a matrix of differential equations (point-kinetics and thermal).

Non-linear terms, like radiation, temperature dependent properties, Na pool feedback, etc. are solved explicitly between iterations.

FRINK input defines the geometry, material, reactivity coefficient, and power deposition for each component. For the most part, the entire system is laid out on a r,theta,z mesh

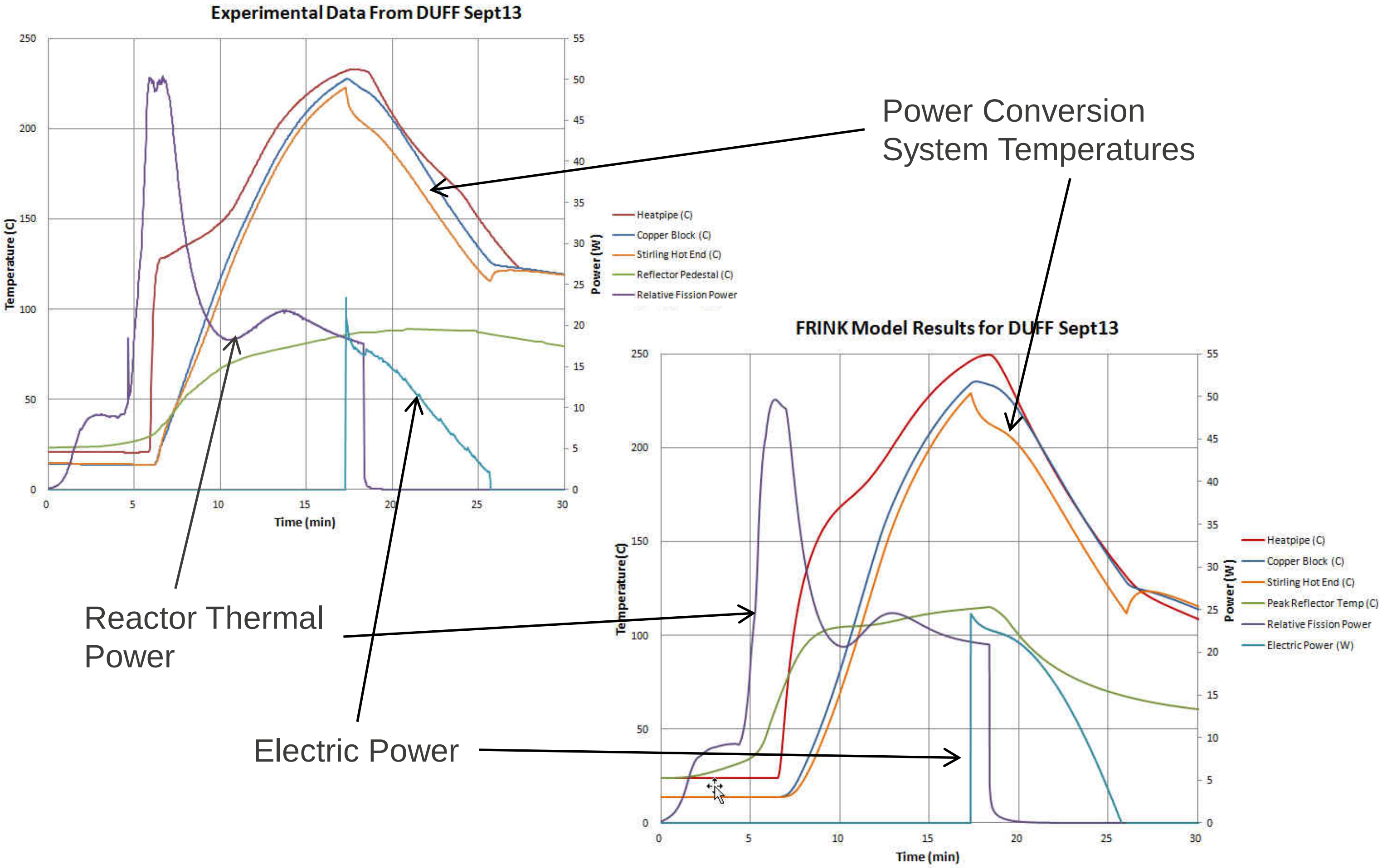
FRINK input also defines the transient initiators/events, decay power profile, delayed beutron structure, computational, nodalization parameters, etc,

FRINK input defines coupling of nodes as either.

- Conduction – full or impeded
- Air-gap
- Vacuum-gap
- Ambient air.

Heat pipe model is based on testing at NASA GrC. Stirling heat removal is also determined by correlations from NASA.

DUFF Sept 13th Results Compared with FRINK Model

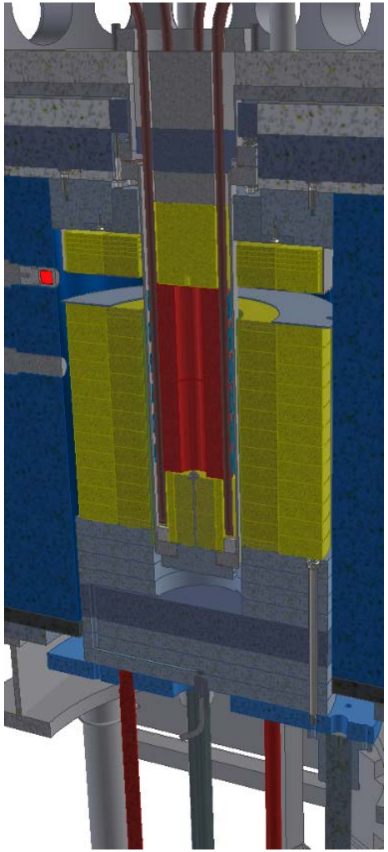


Power Conversion System Temperatures

Reactor Thermal Power

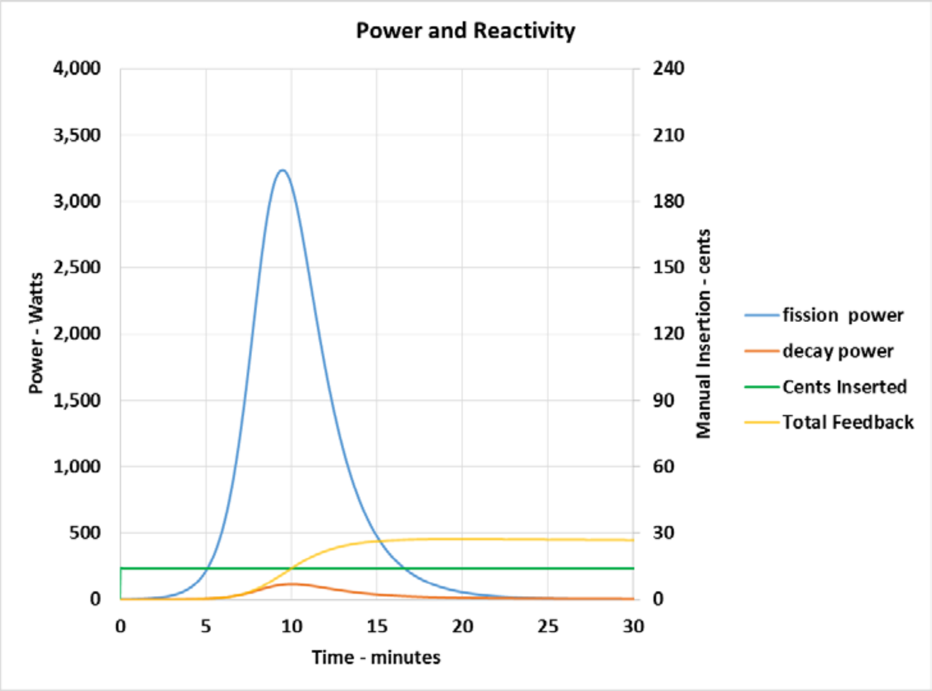
Electric Power

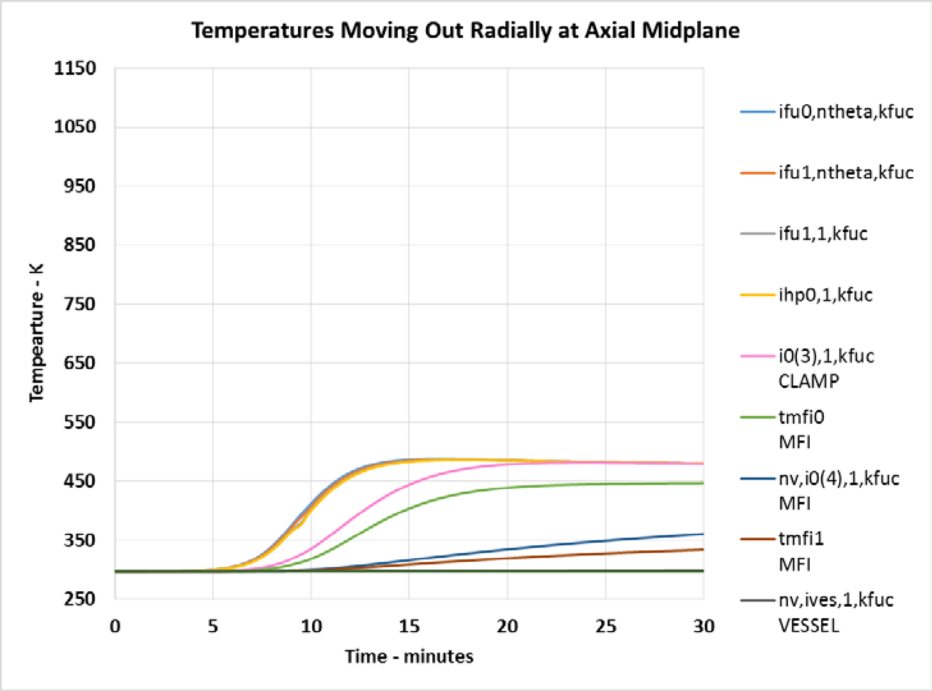
KRUSTY: Summary of Experiment Plan



- **Cold Component Approach to, and Zero-Power Criticals**
  - Prior to KRUSTY final assembly, use fuel, reflector and other components to gain “cleaner” neutronics data.
- **Cold Assembly Approach to Critical**
  - Start at low k-eff. Increment BeO rings to determine the stack height for the first critical.
- **Cold Assembly First Zero-Power Critical**
  - Set BeO height based on “approach” and determine k-eff based on power slope
- **Cold Assembly Seesaw Zero-Power Criticals (up to 20 critical configurations, depending on time available)**
  - Alternate reactivity increases (via adding BeO thickness) with reactivity decreases (via adding B4C rod thickness)
- **Warm, Powered, Assembly Criticals**
  - Three separate tests which insert 15, 30 and 60 cents of reactivity, monitor power, temperature, reactivity feedback. Verify ok to proceed – procedural “Hold Point”
- **Full-Power Run**
  - Start the same way as warm criticals, but continue to add reactivity until an average fuel temperature of 800 C is reached, demonstrate Stirling engine operation, system dynamics, etc.

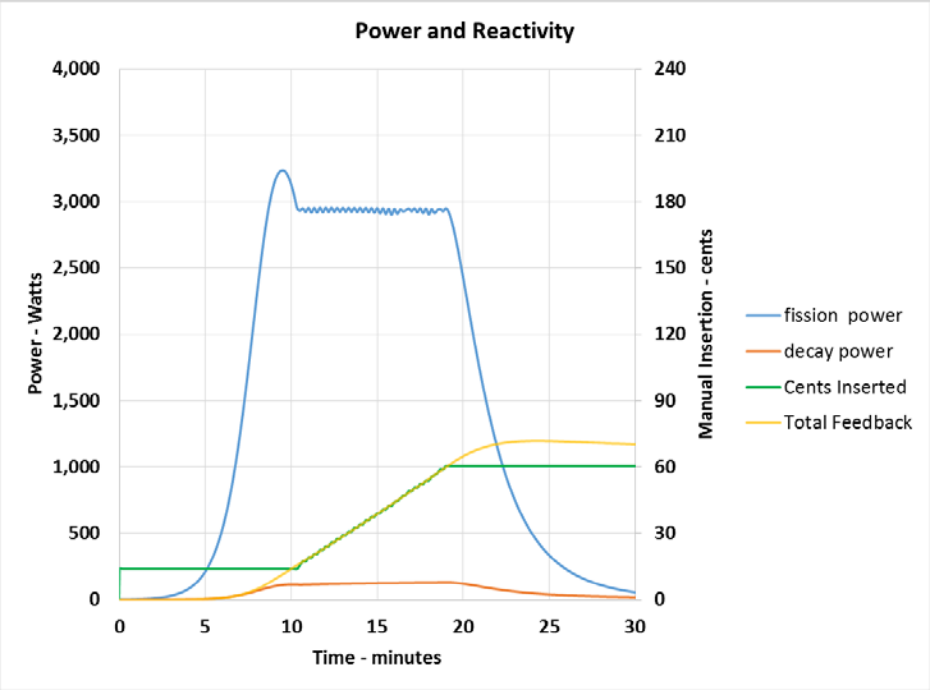
Simulation of KRUSTY 15 cent free run – 1st 30 min.

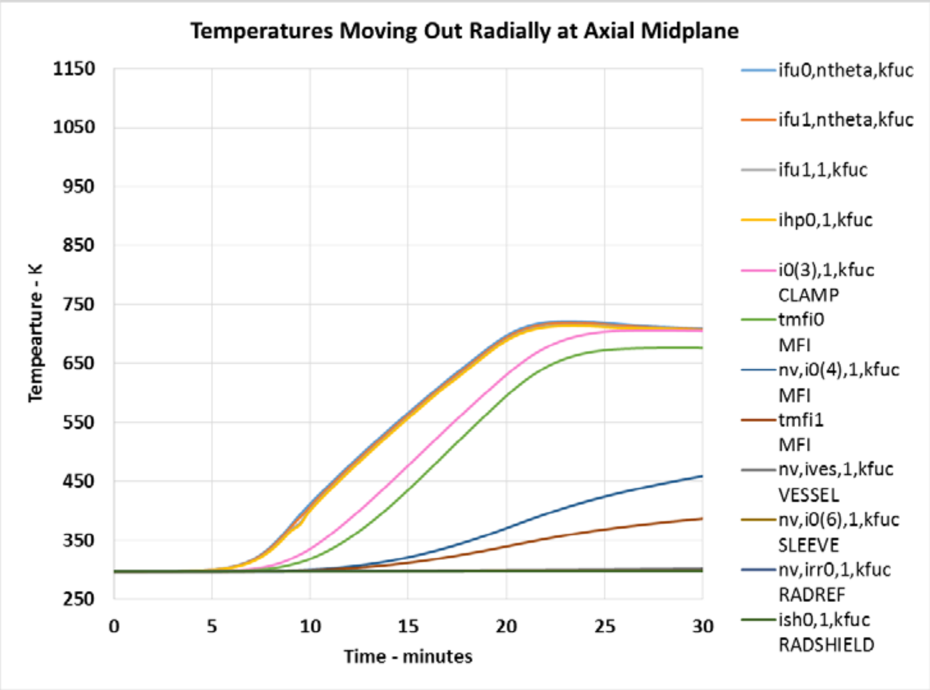




This response should be very similar to Flattop Free Runs routinely run at NCERC, except that KRUSTY has more thermal inertia. The free run is the best tool to benchmark codes and isolate reactivity feedback, given us confidence to proceed with higher temperature runs. This test will also calibrate power with neutron detectors.

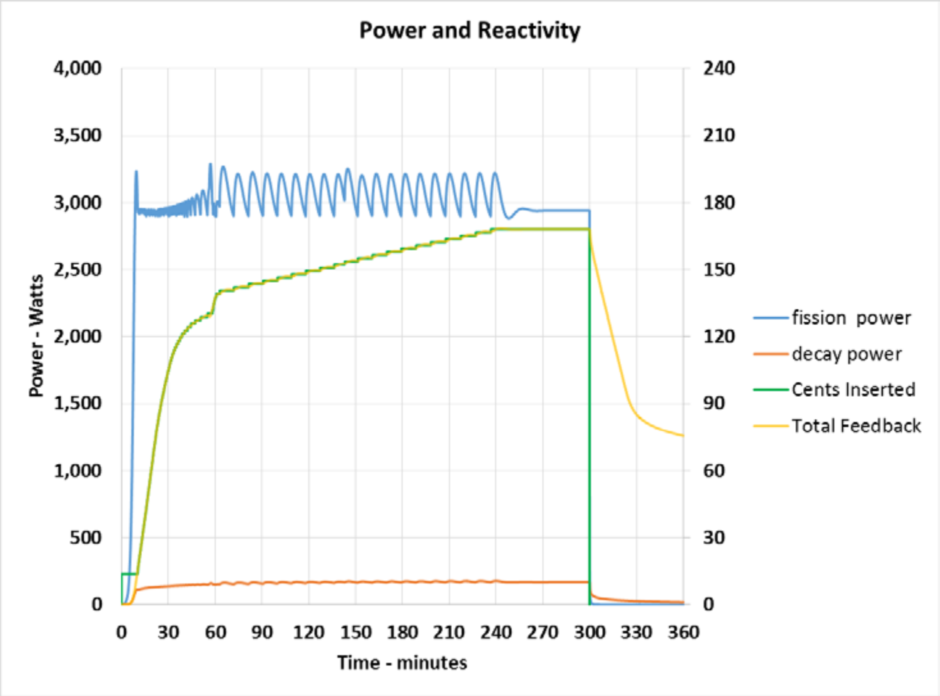
Simulation of KRUSTY 60 cent run – 1st 30 min.

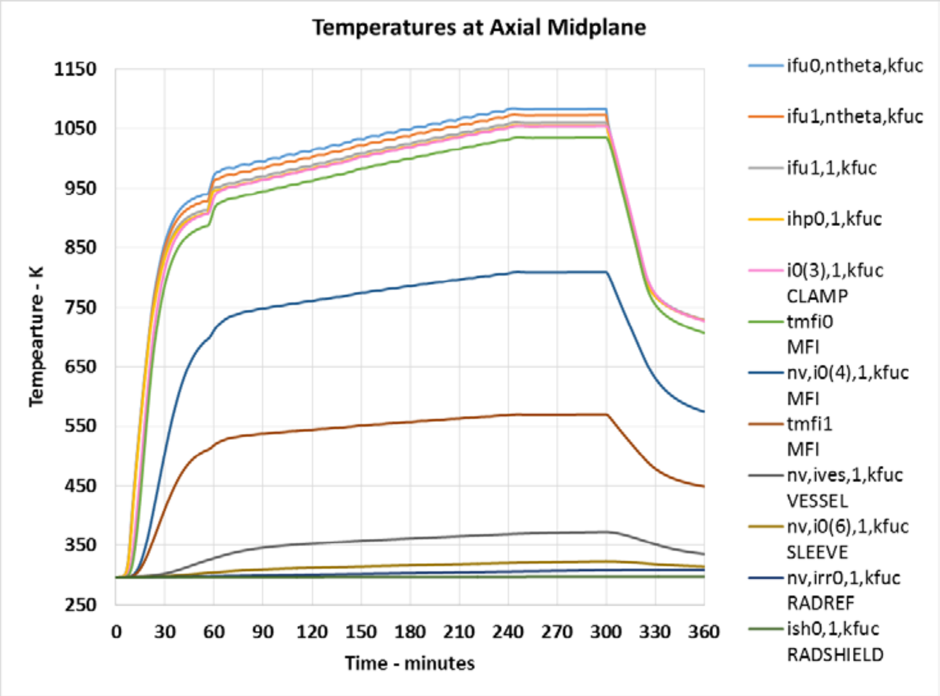




Follow on runs will begin exactly the same as the15 cent free run. Then, provided that performance matches the previous test, reactivity will be further added to increase temperature. The operator will attempt to keep power constant by inserting the platen every so often to add 1 or 2 cents of reactivity

Full Run Simulation – Steady-State Reached at ~4 Hours

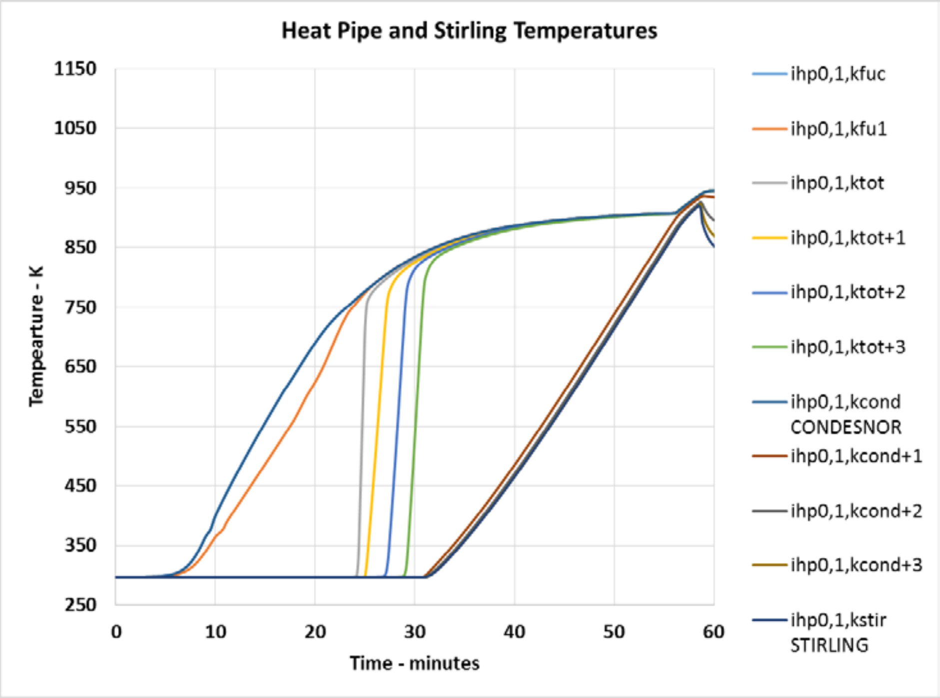




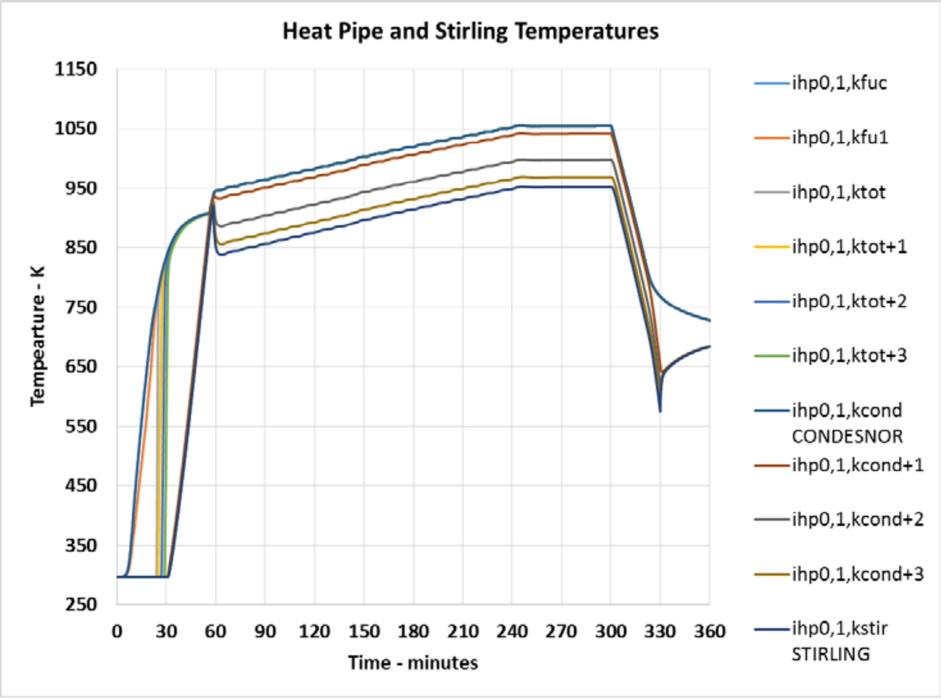
Note, the case shown shows the response of a scram at 5 hours – as opposed to the planned full run which will go ~28 hours (with several load-following transients performed in that time).

Full power/temp run – heat-pipe and Stirling startup

1st hour

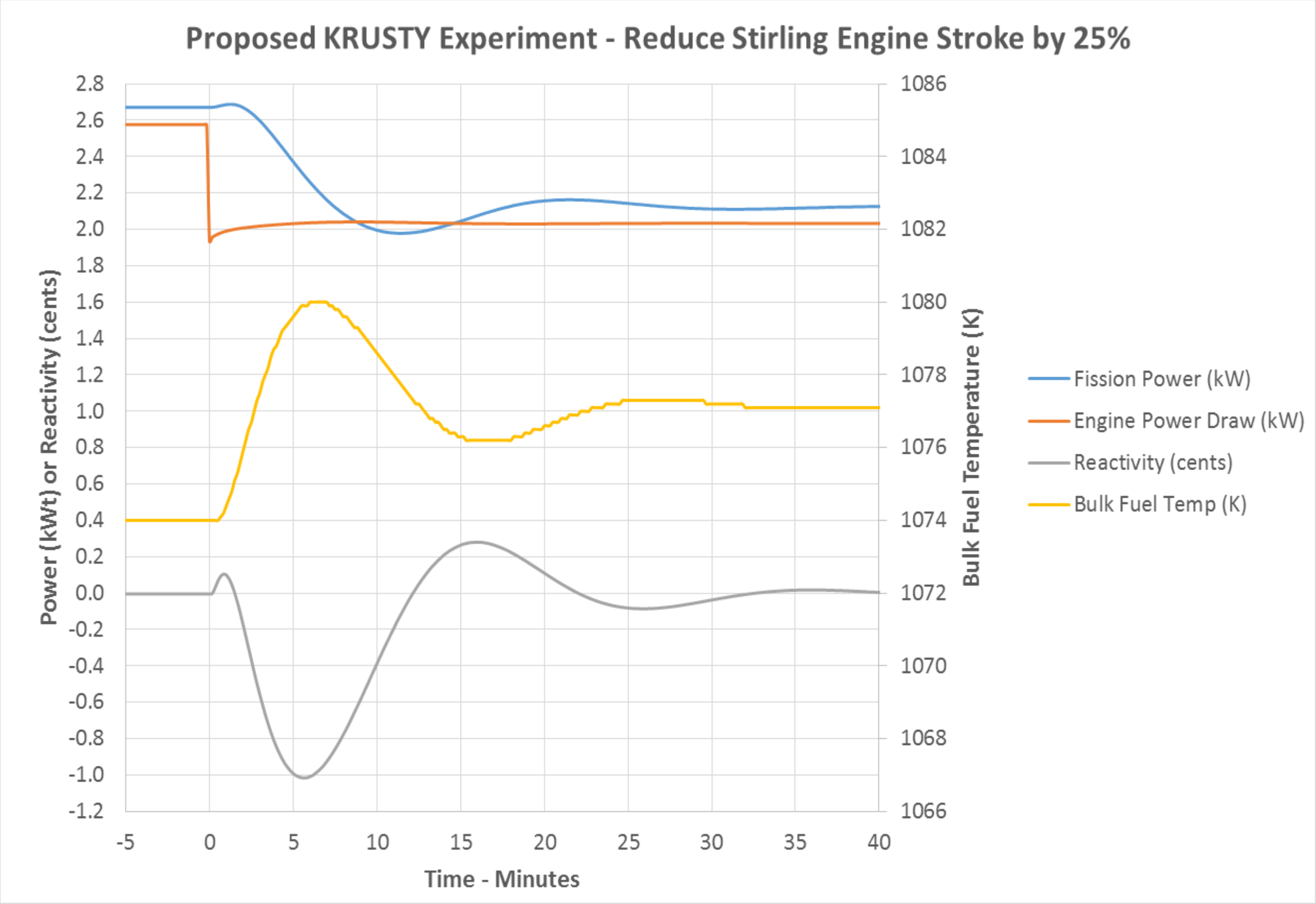


4 hours to reach steady-state



The left chart show axial locations along the heat pipe, and nodes of the Stirling converters. The vertical lines between 20 and 30 minutes are typical of heat-pipe startup. At ~57 minutes the Stirling engine is started and the hot end reaches the appropriate temperature, and a gradient begins to form from the HP condenser to the hot gas. The temperature continues to rise as more reactivity is inserted, then steady-state at 4 hours, and in this scenario a scram at 5 hours.

KRUSTY Load-Following Experiments



Several load-following experiments will be conducted during the KRUSTY full run. The example shows drop of Stirling engine strike by 25%.

The fission power is slightly higher than the power draw because of thermal leakage.

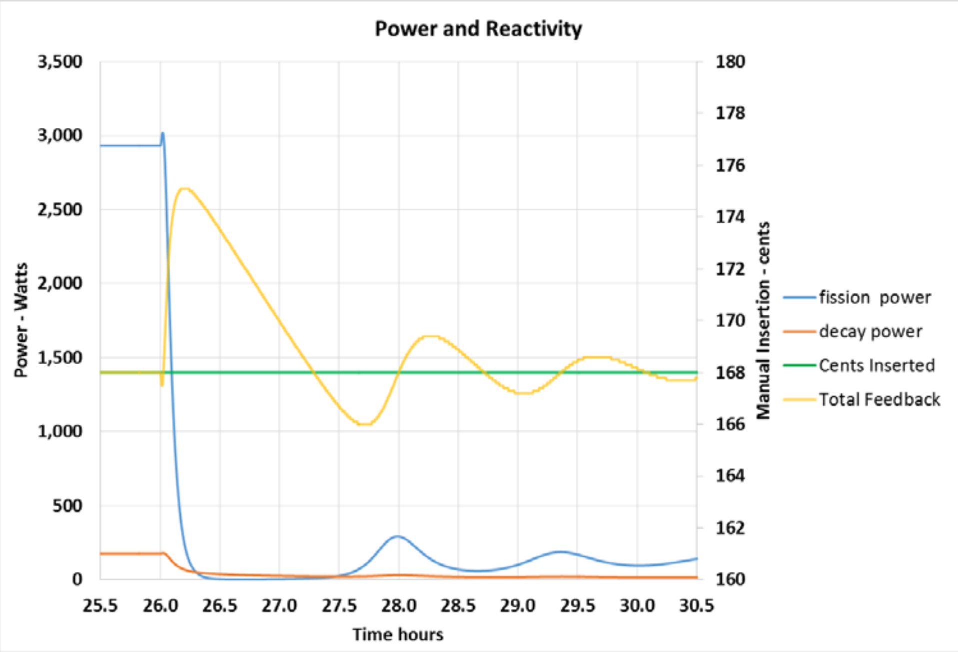
The actual power removal drops by less than 25% because the temperature of the engine hot-end increases.

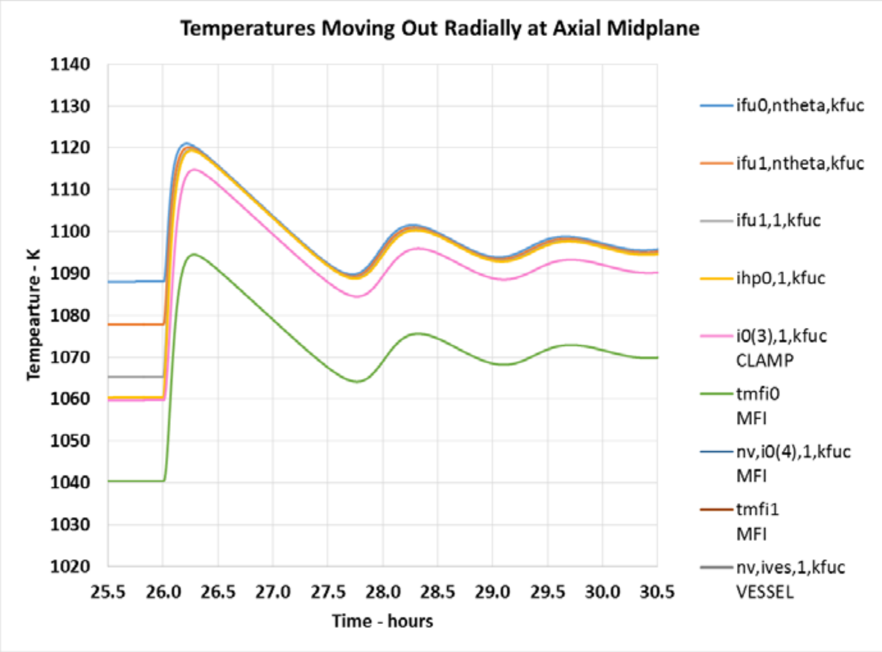
Initial small bump in reactivity and power is caused by increased Na inventory in the HP pools (lower power).

Bulk fuel settles at a higher temperature to counteract the reactivity increase caused by growth of the Na HP pools.

Full Run, Steady-State then Stop Power Removal @ 26 hours

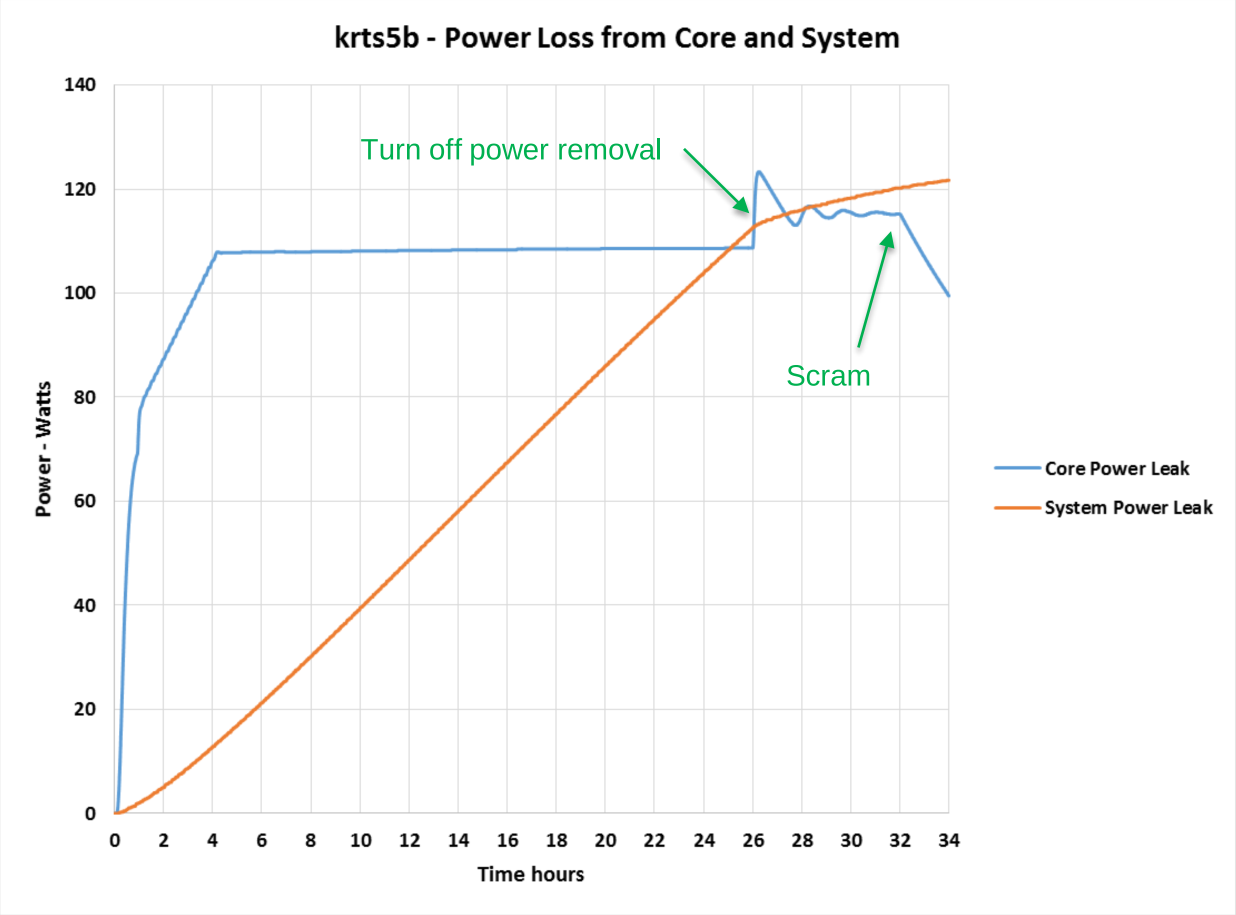
This is the conclusion and hallmark of the KRUSTY testing – hopefully showing that we can lose all active heat removal and the core will not be damaged (actually sitting-in-wait ready to provide power again if the Stirlings can be turned back on).





Upon loss of heat sink, the peak fuel temperature rises ~30 K and then the entire core settles an equilibrium temperature just below 1100 K. Fission quickly shuts down due to negative feedback, and decay power quickly falls below heat leakage from core.

Full Run – Power Loss from Core and System
(no intermediate transients)


krts5b - Power Loss from Core and System

Turn off power removal

Scram

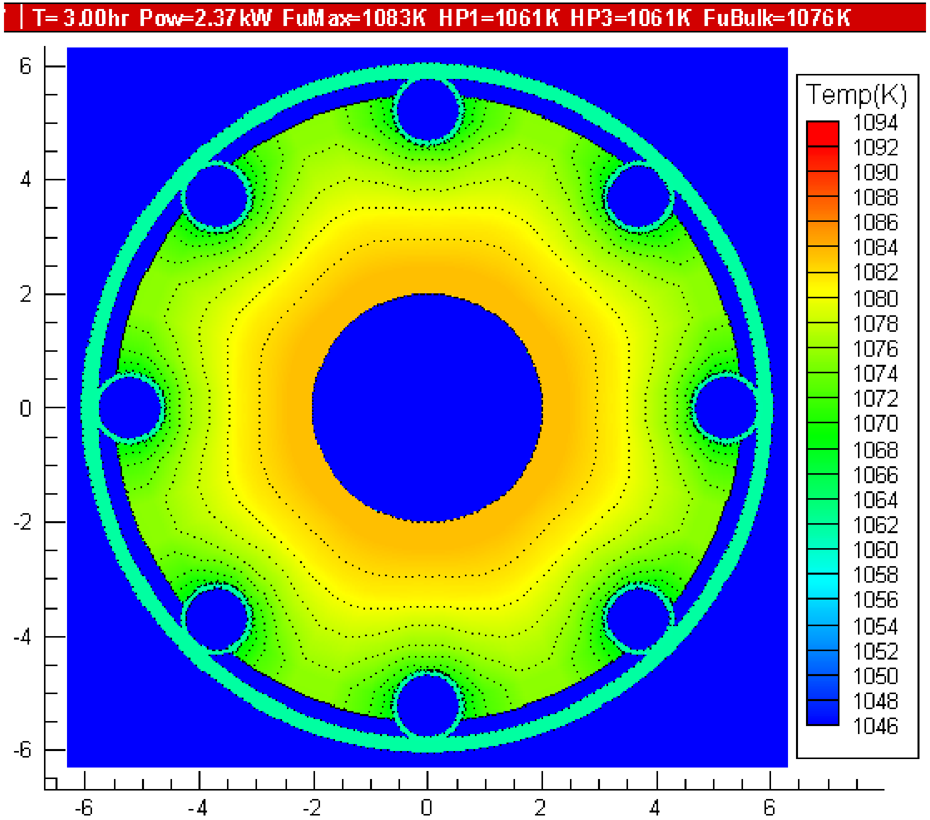
This chart shows the power "leakage" from core through the radial/axial mli (which reaches steady-state at ~110 W),

Heat rejection from the system to the room is not yet to steady-state, which would be expected to top out at ~280 W (110 leak from core and 170 W of ex-core power deposition) – this would likely occur after 2 or 3 days.

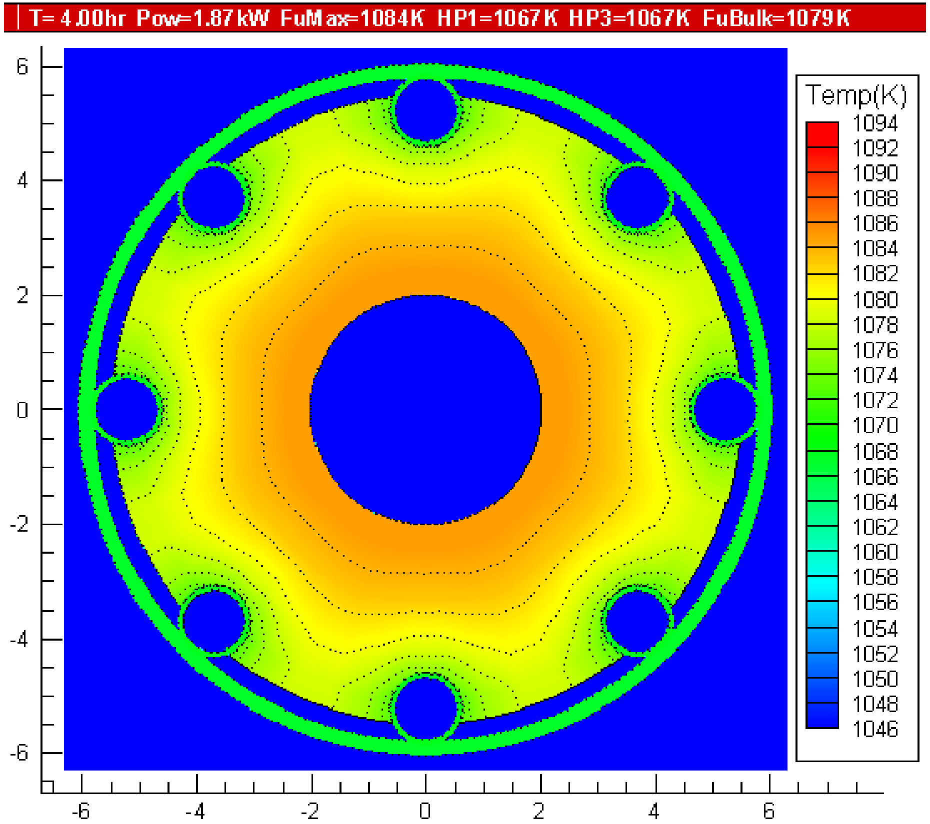
This power leakage is high enough to easily handle decay power even if the system had operated 15 years.

Even the 10-kWe systems have passive decay heat removal, by using a little less insulation.

KRUSTY: Nominal Operation and Reduced Power



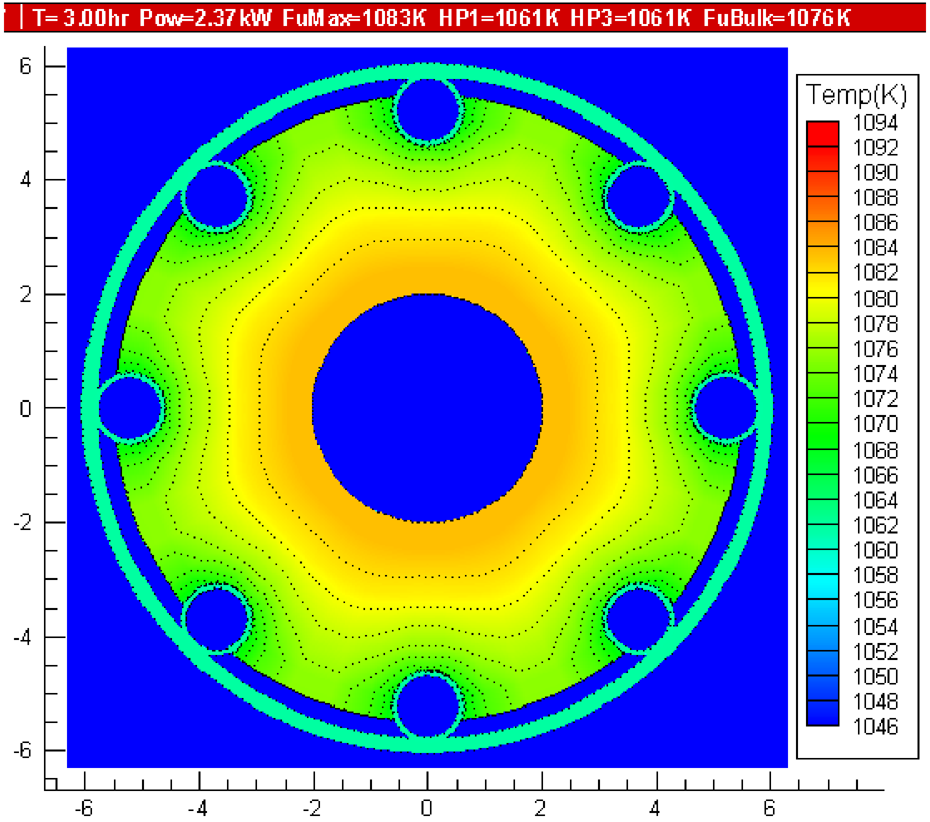
Inserted = $1.679, Temp FB = -$1.639, Pool FB = -$.040



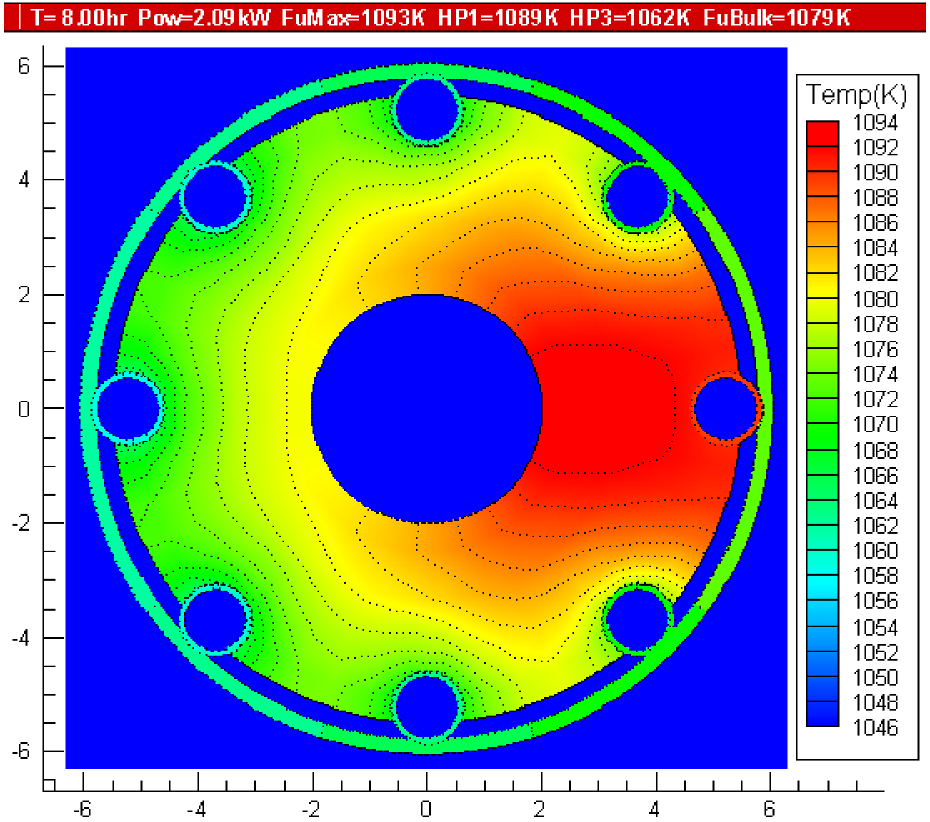
Inserted = $1.679, Temp FB = -$1.647, Pool FB = -$.032

Temperature plots are at ~peak axial elevation – goal is to stay below 1200 K, where uranium gets very soft (melt point 1405 K)

KRUSTY: Nominal Operation and Failed Heat Pipe



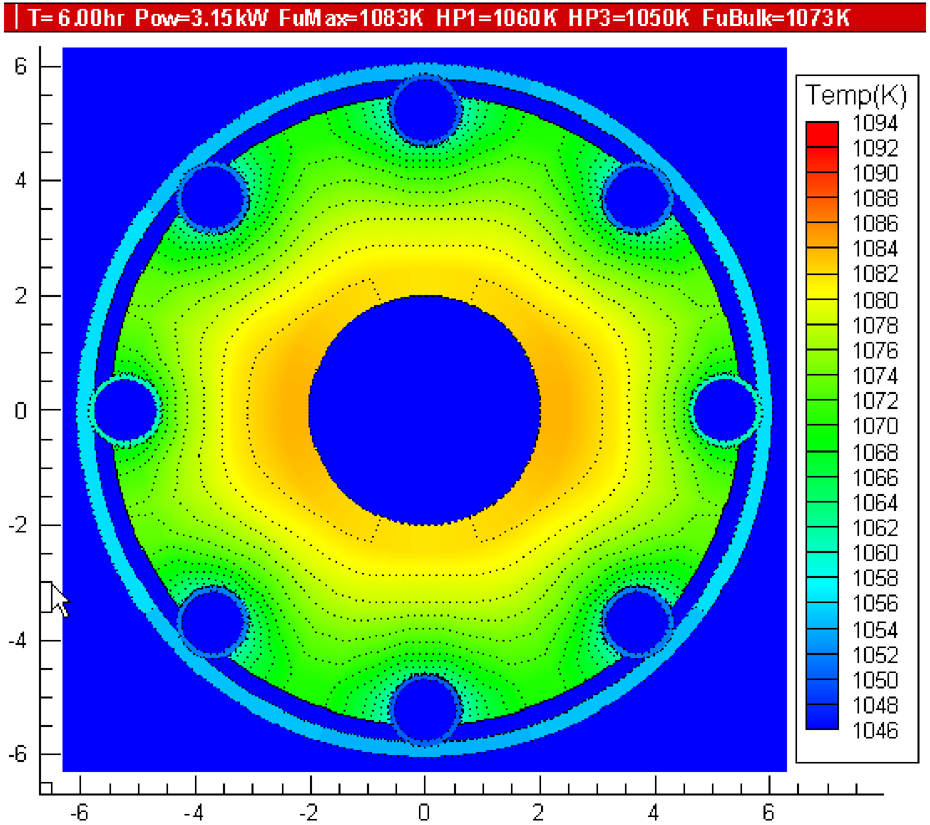
Inserted = $1.679, Temp FB = -$1.639, Pool FB = -$.040



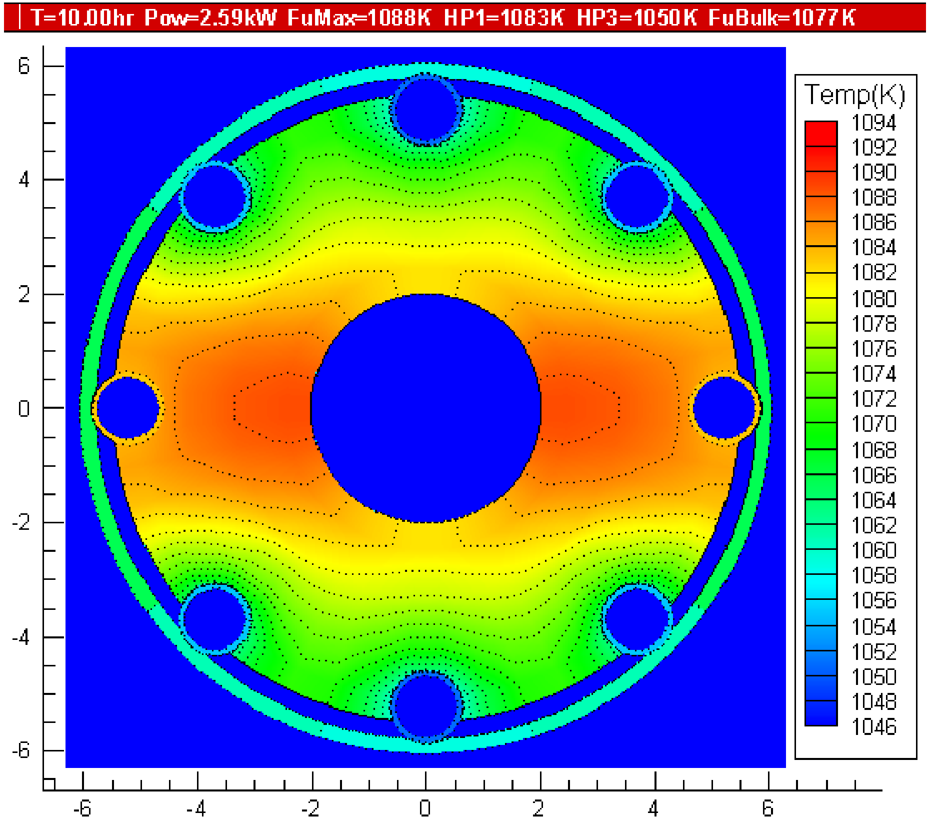
Inserted = $1.679, Temp FB = -$1.644, Pool FB = -$.035

Temperature plots are at ~peak axial elevation – goal is to stay below 1200 K, where uranium gets very soft (melt point 1405 K)

KRUSTY: “Full” Power and “Full” with 2 Failed HPs



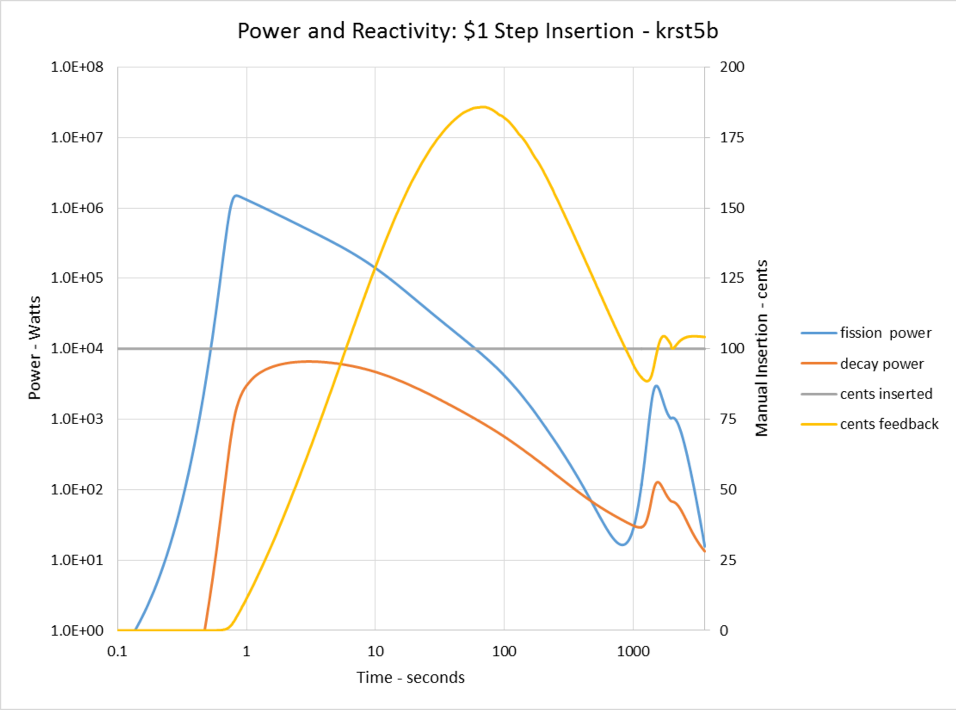
Inserted = $1.679, Temp FB = -$1.629, Pool FB = -$.050

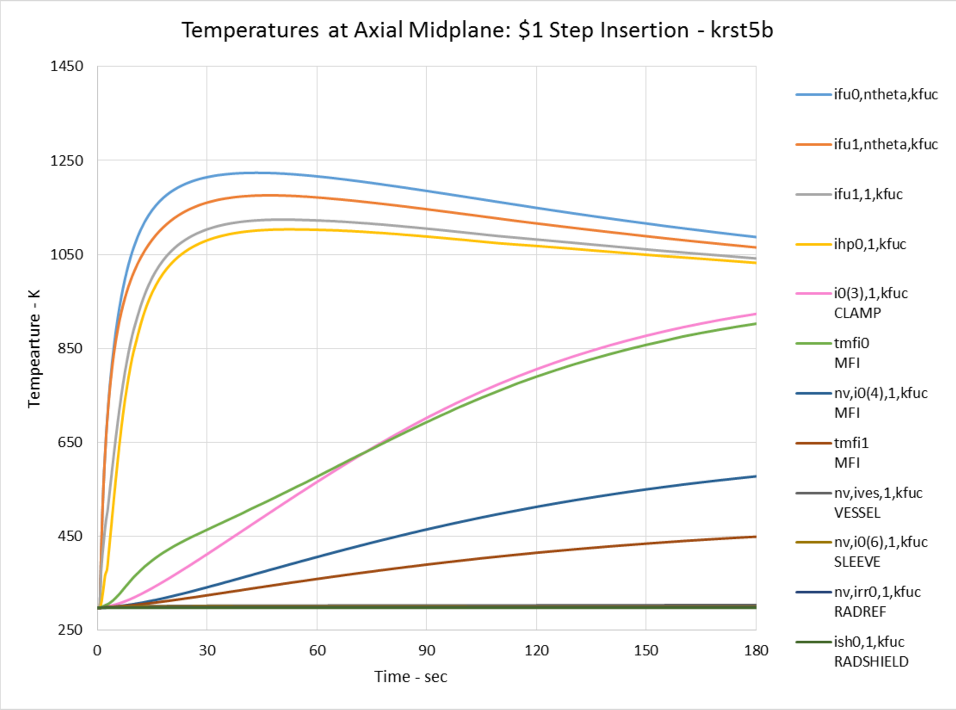


Inserted = $1.679, Temp FB = -$1.641, Pool FB = -$.038

Temperature plots are at ~peak axial elevation – goal is to stay below 1200 K, where uranium gets very soft (melt point 1405 K)

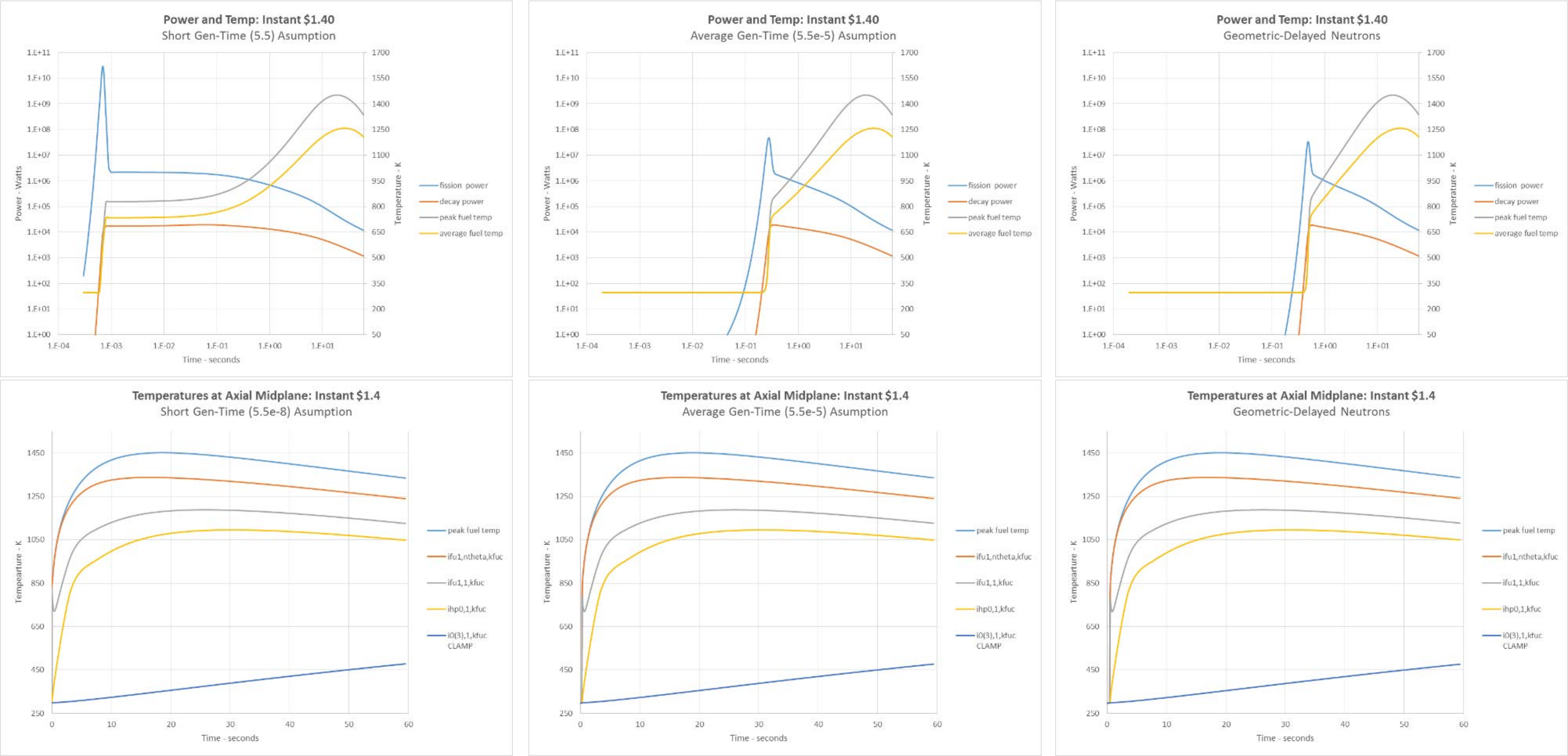
Safety Analysis Example: $1 Instantaneous Insertion


Power and Reactivity: $1 Step Insertion - krst5b


Temperatures at Axial Midplane: $1 Step Insertion - krst5b

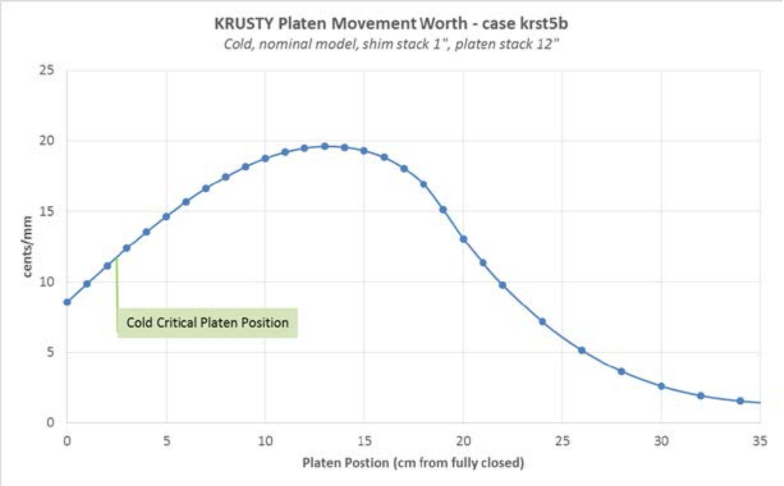
A step insertion is precluded by both operational procedures, slow platen speed, and a strong neutron source (which initiates transient before $1 could be accidentally inserted). Regardless, in this $1 step insertion example, the model shows no melting or damage regardless, except for maybe some stress-induced issues at the core clamp interface due to rapid heat up.

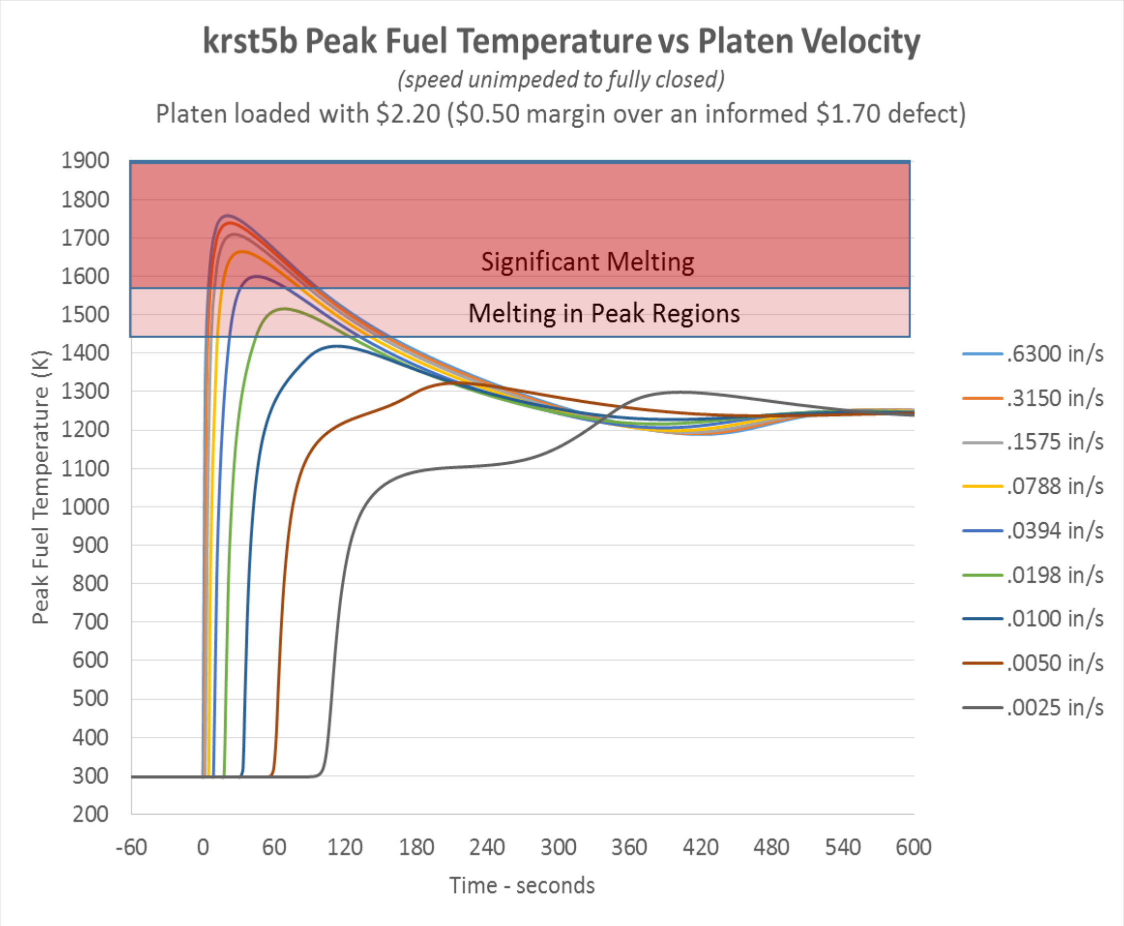
Impact of Neutron Generation Time, $1.40 Step Insertion (case krst1f)



Significant difference in power spike, but no difference in temperatures

Safety Analysis Example: $2.20 Uninterrupted Full Insertion

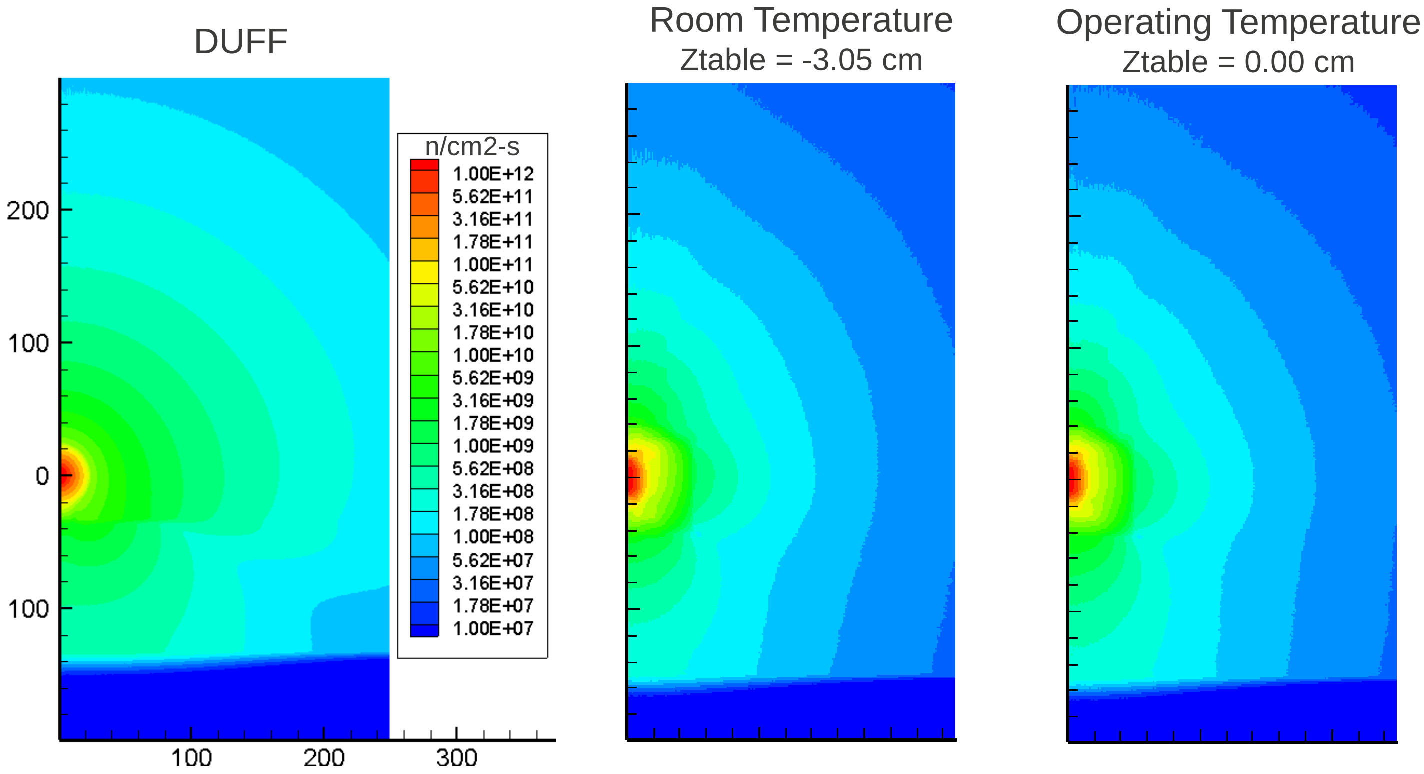




Uninterrupted full insertion represents worst-case scenario and is precluded via operational procures.

For KRUSTY, COMET speed limited = .008 in/s when first critical, = .002 in/s when warm critical (when platen is within 0.5” of closing).

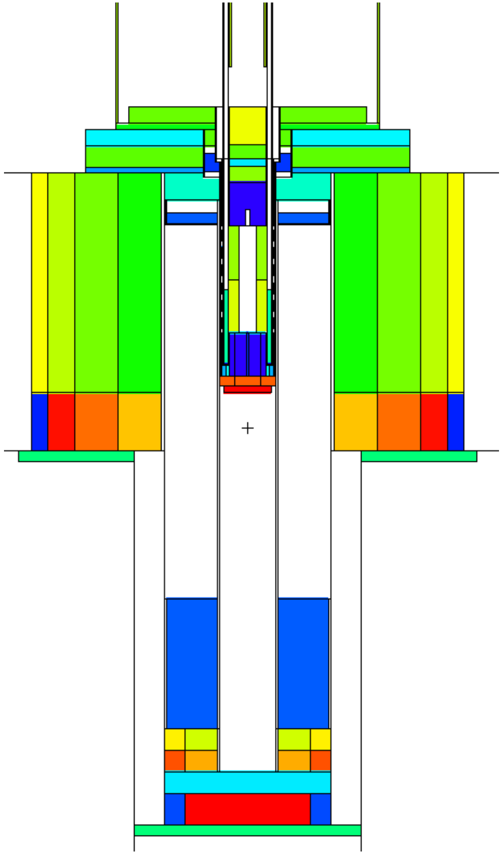
DUFF vs KRUSTY: Room Neutron Flux >100 keV During Operation



At 4 kWt, the room fast neutron flux from KRUSTY is ~4x lower than DUFF; slightly more then 4x radially, and slightly less than 4x above and below. The flux above the reactor is ~10% higher when the system is operating cold, because the BeO stack is not filling the gap in the upper corners. KRUSTY shielded to lower flux because it is expected to generate ~10 times the Kw-hr (fissions) as DUFF.

Activation and Dose After Operation – MCNP model

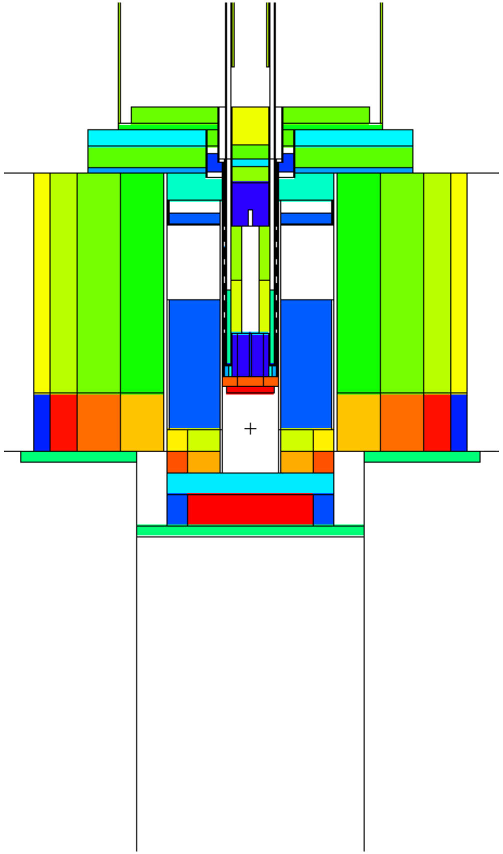
Fully withdrawn/Loading



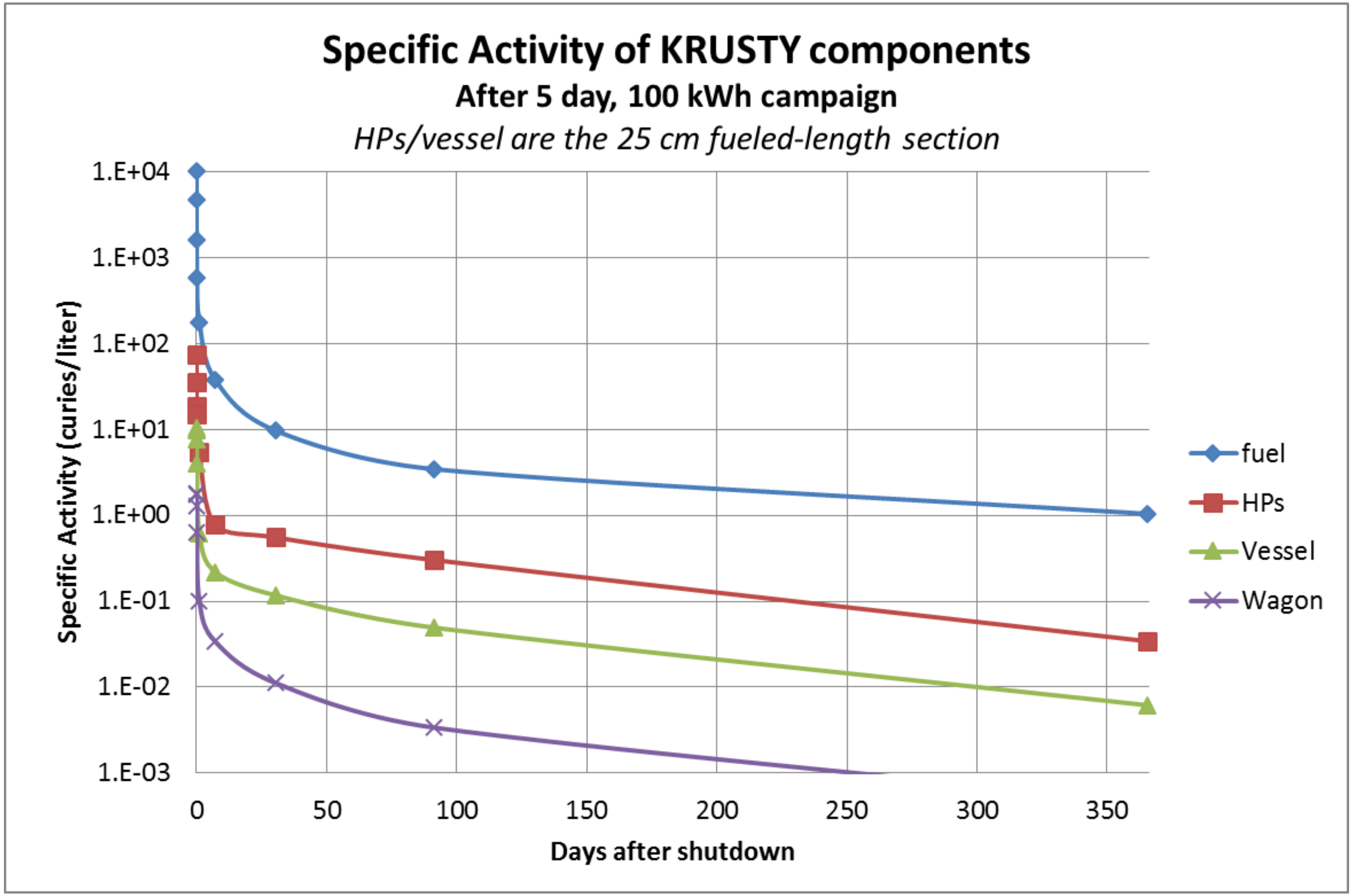
Each color represents a unique MCNP region for which activation was calculated via MONTEBURNS and a gamma source was calculated by MAGGIE. The transported dose from each individual component (and the sum of the components) is shown on the following slides.

The fully withdrawn platen leaves a large gap for core radiation to escape. This will be the position of the platen for loading and all zero-power criticals and low-temperature testing. For the final-run, the platen will be hand-cranked to the “stowed” position on the right, which substantially reduces the dose in the room until KRUSTY has cooled enough for removal from Comet.

Hand-cranked/Stowed



KRUSTY Activation

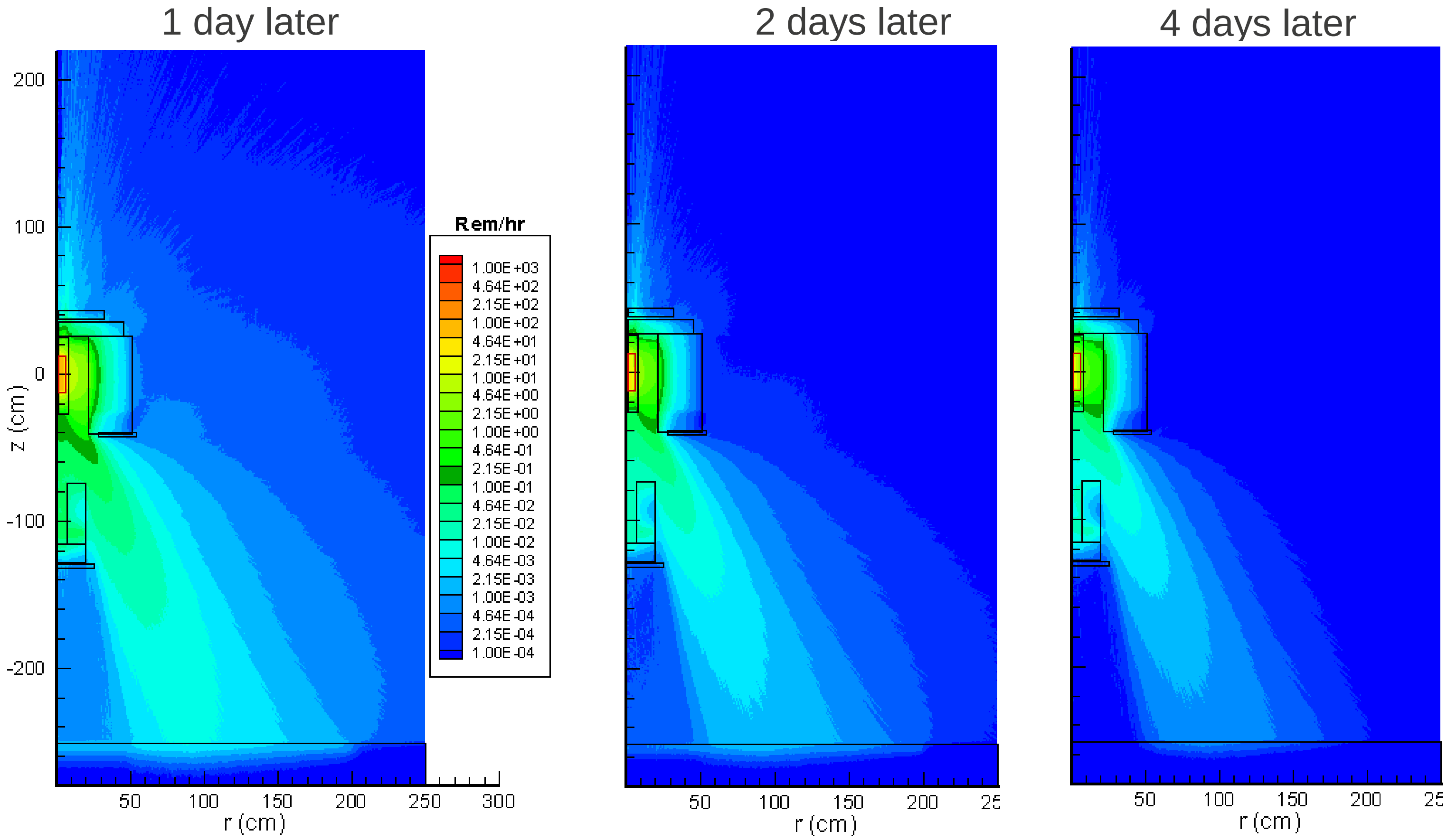


Dose calculations were performed using the activated fuel.

Calcs indicate that 9 months would be required until the fuel could be shipped and received under current DOE regulations (~1mr/hr per kg at 30 cm)

Most of the dose after 30 days is from gammas of energy <1 MeV, which are effectively shielding by thin layer of high-Z material.

Gamma dose from KRUSTY after 20 cent free run
(note revised plan is for 15 cent free run)



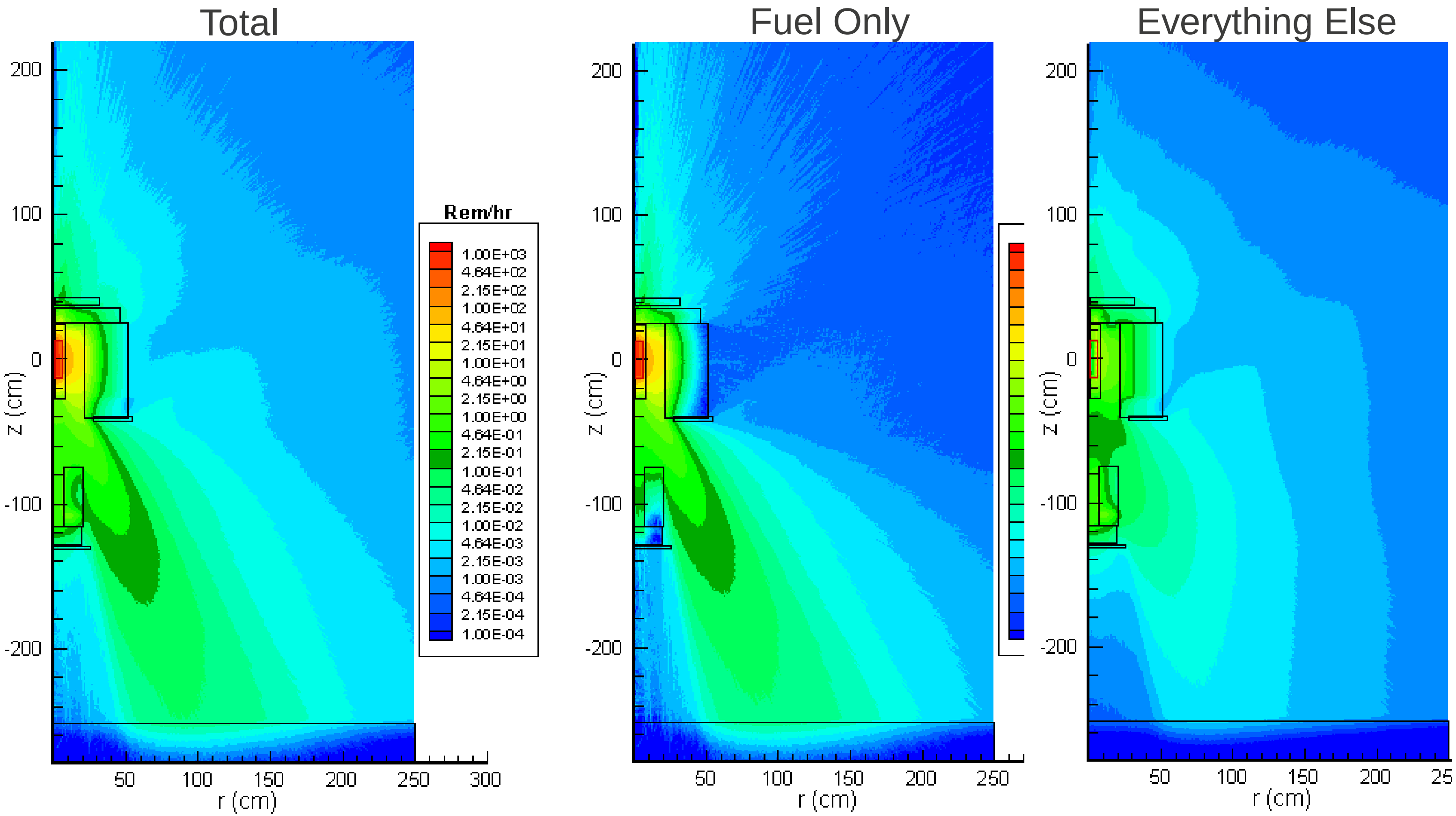
1 day later

2 days later

4 days later

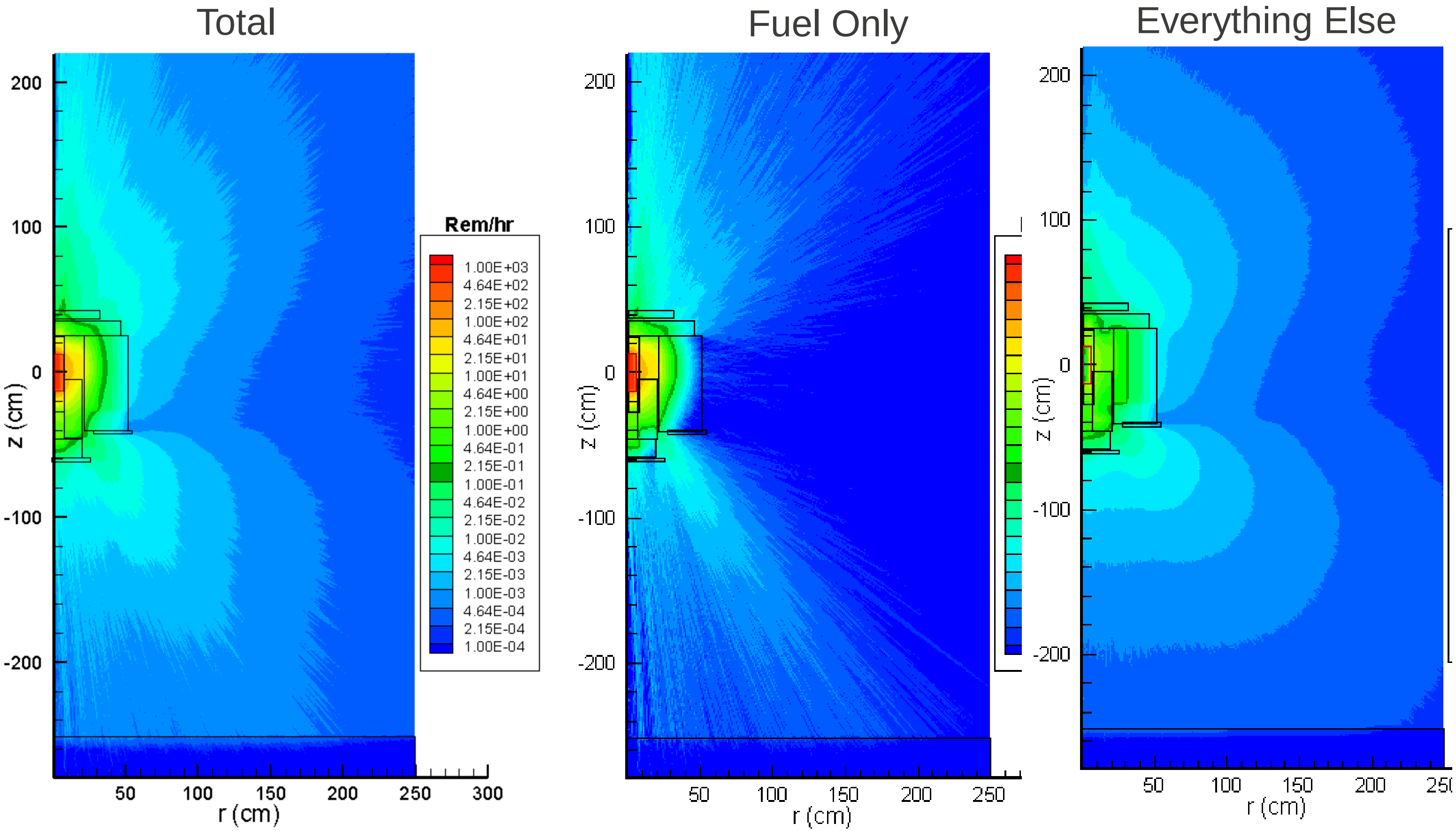
After 2 days, doses are low enough to perform hour-long operations directly on KRUSTY

Final Run: 16 day decay withdrawn



After 16 days, with platen withdrawn. doses are high in room, preventing extended work on other experiments.

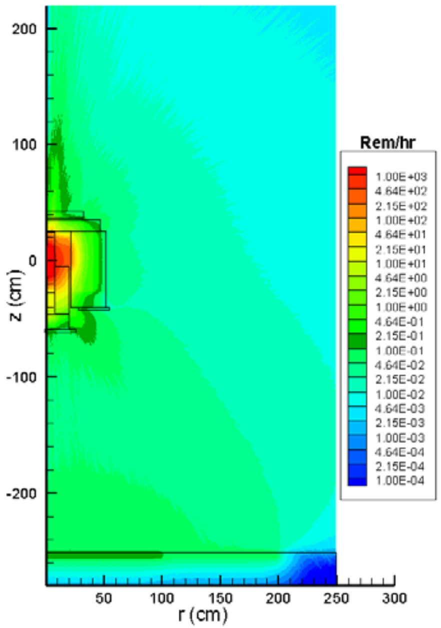
Final Run: 16 day decay stowed



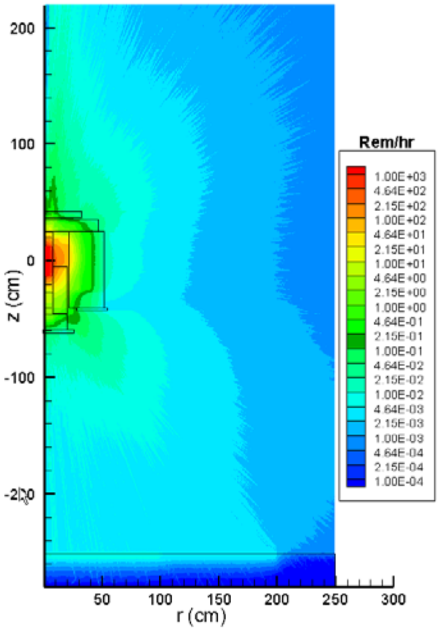
The “stowed” platen substantially shield the dose from fuel, allowing extended work on other experiments.

After Final Run, Platen Stowed

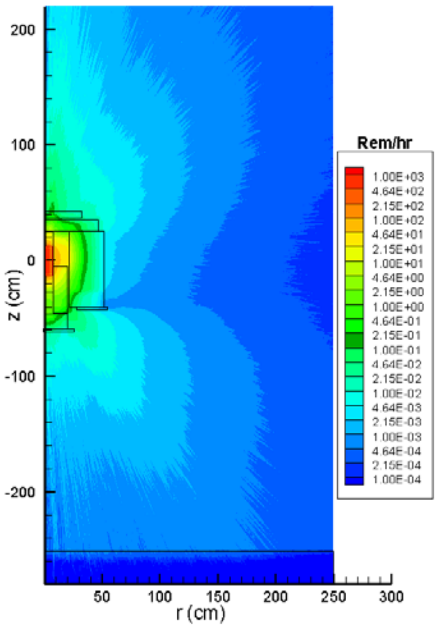
1 day decay



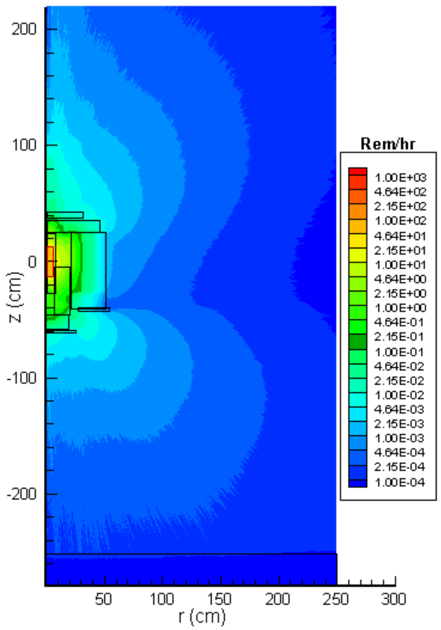
4 days decay



16 days decay



64 days decay



Somewhere between 16 and 64 days, the Rad-Techs will approve the operation to remove KRUSTY from Comet, place it on a transfer cart, and stow it “in a corner” until dose is low enough for complete disassembly.

First Order Value of Experiments

	Inform subsequent KRUSTY operations	**Inform Kilopower system design and operation**	**Provide overarching physics and reactor data.**
Component Approach to Critical	How much BeO to load for component crits		Are beryllium cross sections reasonable or way off?
Cold Component Criticals	Initial data for worth of KRUSTY BeO as functions of stack/platen height.	Physics likely closer to flight system than KRUSTY (i.e. no core clamps and vessel)	Clean data for evaluation of highly reflected Be reactor. Relative worth of various materials.
Assembly Approach to Critical	How much BeO to load for KRUSTY first critical		
Cold Assembly First Critical	First hard data point to inform execution of experiment plan.	Benchmark with Preliminary Crits to translate KRUSTY physics data to flight system	Worth of materials in the Hayn230 and SS316, and how they effect reflected neutrons.
Cold Assembly See-Saw Criticals	Detailed worth of BeO as a function of stack and platen height, worth of B4C height.	Worth of flight-like central rod as function of height; of great value to operational and safety design of flight system.	Large volume of data to for cross sections and transport physics, and ability to significantly reduce uncertainties.
Warm Assembly Criticals	Reactivity feedback data to predict temperature defect (how much BeO margin to load). Data to calibrate room log-N neutron counters with power. Provide "all-is-well" poinr for subsequent tests.		Free run provides best data for benchmarking transient codes, because reactivity input is well-known. All warm crits provide great feedback data.

First Order Value of Experiments (cont.)

	Inform subsequent KRUSTY operations	**Inform Kilopower system design and operation**	**Provide broader scale physics and reactor data.**
Full Power Test Startup	Is system performance consistent with the plan to move to full temperature?	Inform the startup sequence and timing for flight reactor. Doesn't matter much if reactivity is inserted via moving radref or central rod.	First ever start-up and operation of heat-pipe-cooled reactor
Full Power Test Steady State	Are temperatures and characteristics reasonable, such the transient testing can proceed?	Do Kilopower systems perform as advertised? Stable? Thermal efficiency? Materials performance/compatibility? Comparisons to electrical testing.	Solid steady-state data very important for benchmarking codes, and provides insight into elevated temperature cross sections.
Full Power Test Transients	Is system performing as expected so that loss of heat sink still looks benign?	Demonstrate dynamic response and load following ability of system	Transient data is invaluable for benchmarking nuclear engineering codes - there is extremely little that exists for compact-fast reactors.
Full Power Test Loss of Heat Sink		Demonstrate that Kilopower-type systems have the potential to fully survive total loss of heat-sink.	Clean data for passive response of system (heat transfer and neutronics), also some decay power data. Helps define thermal fudge-factors to close the solution.
Full Power Test Shutdown			Continued benchmark data of decay power, passive heat loss, activation and dose.