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Thermal Modeling of the Surface Temperatures on the Liquid Lithium Divertor in NSTX

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Outline

Objectives for Thermal Model

- Predictive model for surface temperature versus heat load and shot time
- Extract information on porous layer of flame-sprayed Mo with infiltrated Li
  1. thermal conductance and
  2. emissivity of surface

Thermal Model and Results

- Initial work on LLD (heaters and gas cooling)
- Newer work (no pre-heat, Li evaporation)

Planned experiments at Purdue University

- Measure emissivity of Li surface and surface chemistry simultaneously using PRHISM

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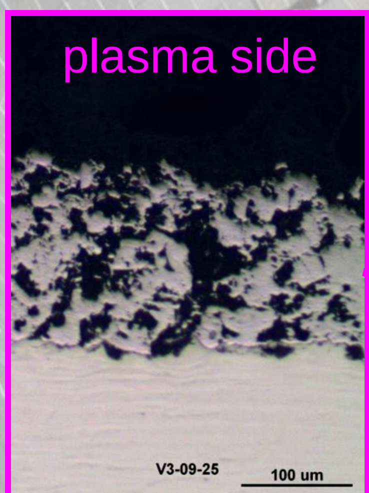
Objectives for Thermal Model

- **Predictive model for $T_{surface}$ vs heat load and shot time**
  (subsequent viewgraphs)

- **Information on porous layer of flame-sprayed Mo with Li**
  1. **thermal conductance and**
  2. **emissivity of surface**

Relate modeling results to IR and TC data during operation



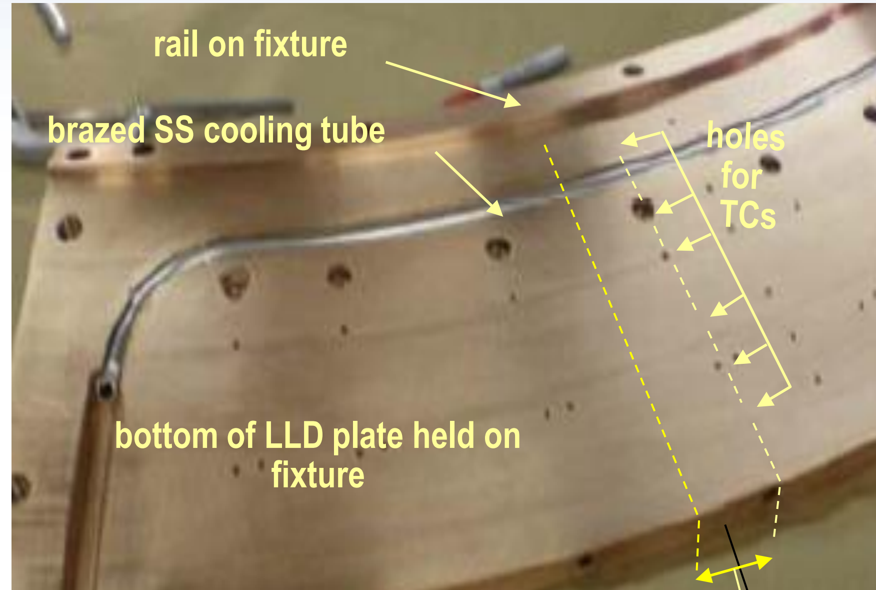
LLD surface cross section: plasma sprayed porous Mo

LLD plates (4) after installation

ABAQUS thermal model for LLD "half cell"

We use ABAQUS, a general purpose finite element code, for our 3-D model. We analyze a "half cell" of the LLD, and calculate temperatures over time.

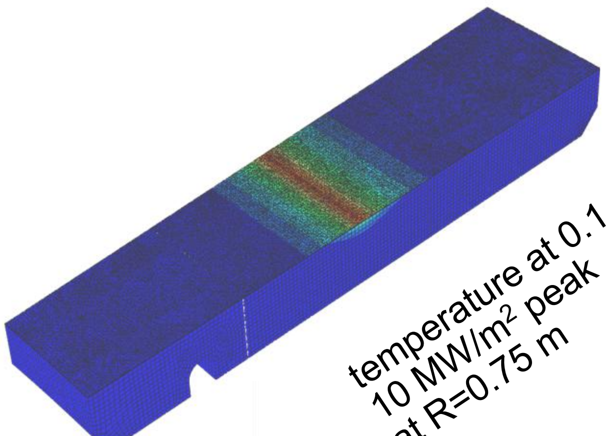
The shape comes directly from the CAD model for fabricating the plates



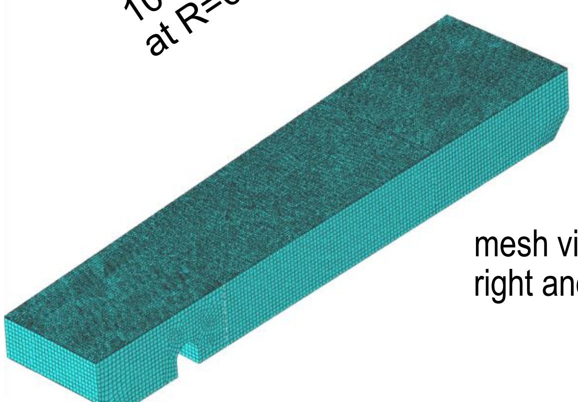
solid angle of the half unit cell

A "unit cell" contains one (of 8) electrical heaters in an LLD plate.

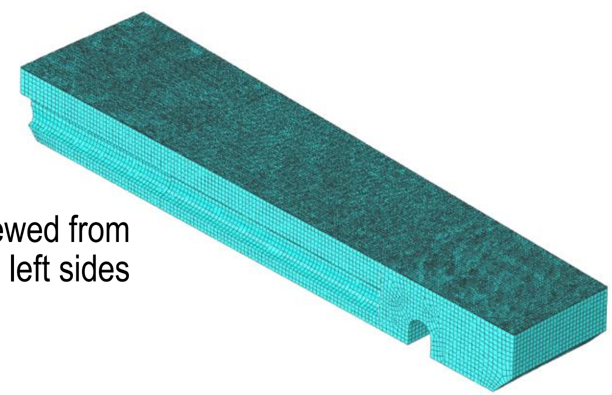
The half cell is divided on a mirror symmetry plane through the heater.



temperature at 0.1 s
10 MW/m^2 peak
at R=0.75 m



mesh viewed from right and left sides



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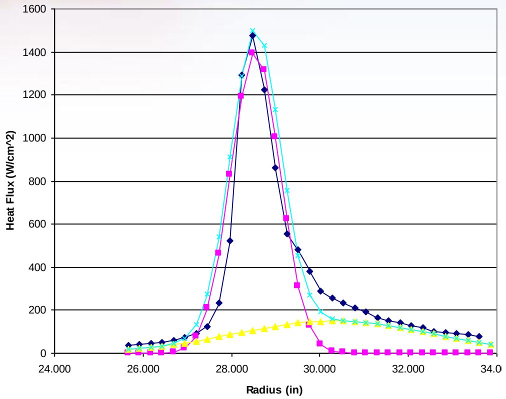
EARLY THERMAL MODEL & RESULTS



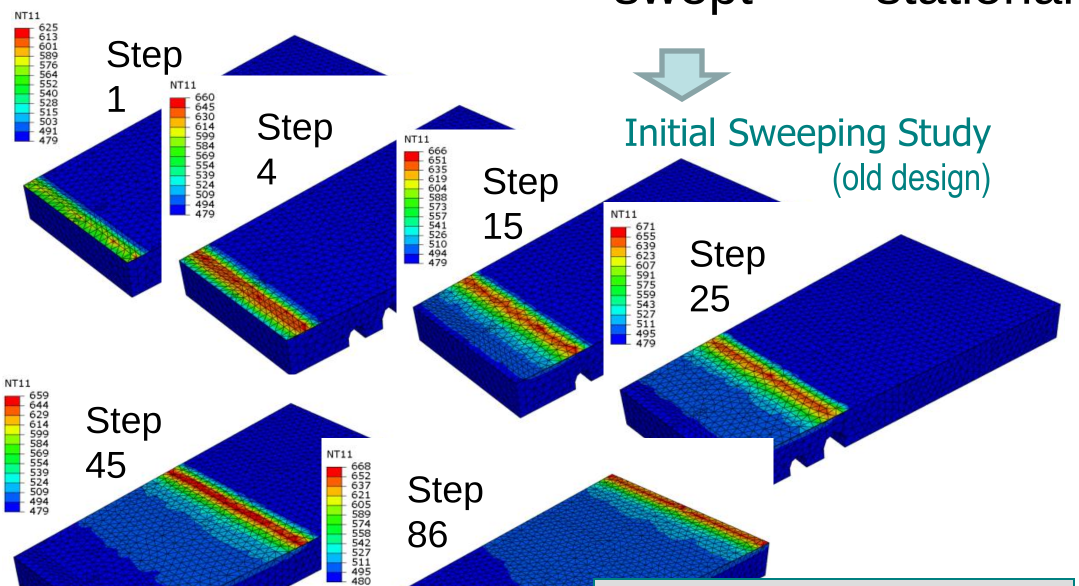
Strike point profile (outer div.).

"Wings" are important in sweeping.

Strike point on LLD

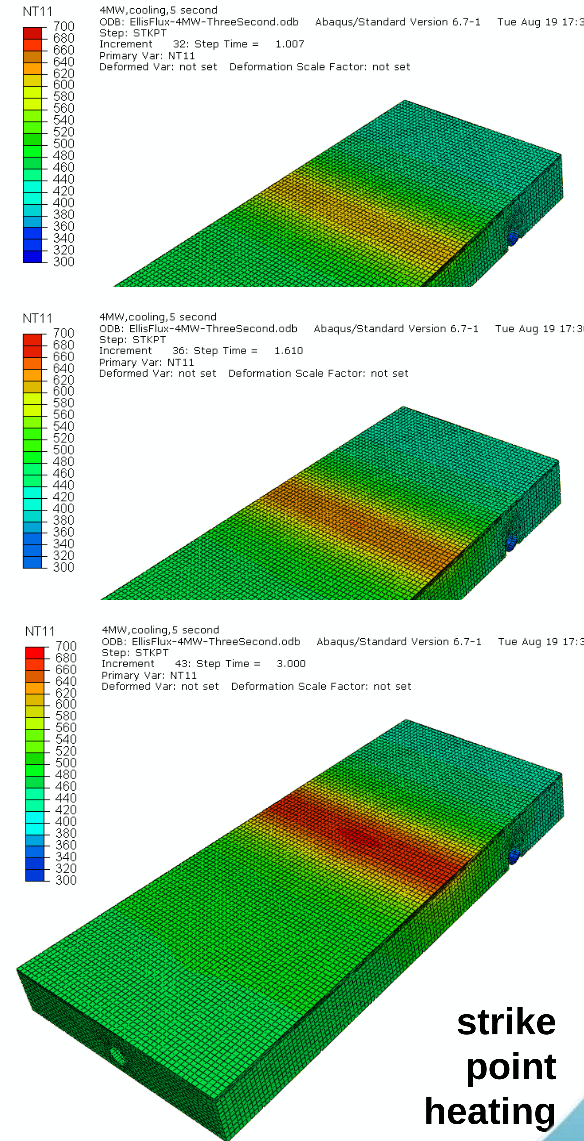
swept stationary

Initial Sweeping Study (old design)



SOL profile is important because "Tail" pre-heats Li ahead of strike point.

- 200W heater, 25 min.
- T-start 475 K.
- 500 mm/s "sweep"
- 5 ms heat, 2.5mm zones
- 43 s across entire area.



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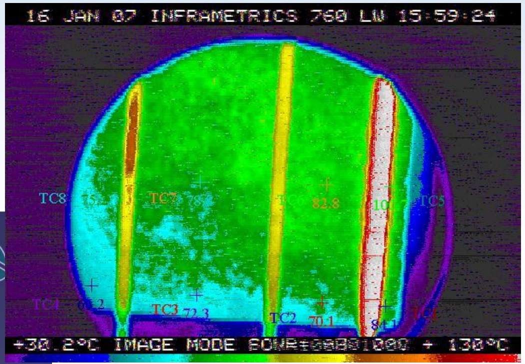
EARLY THERMAL MODEL & RESULTS

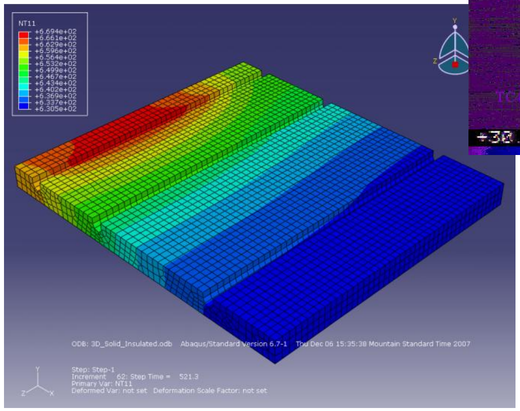


- Initial tests on Mo mesh
- heater failure

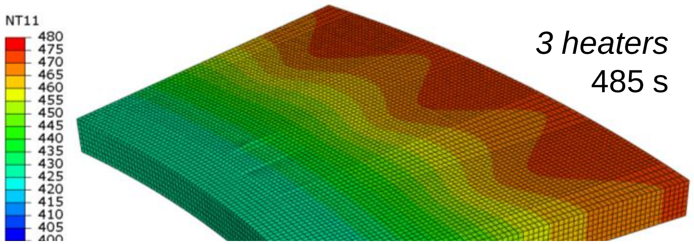
<u>*Cases not presented here*</u>

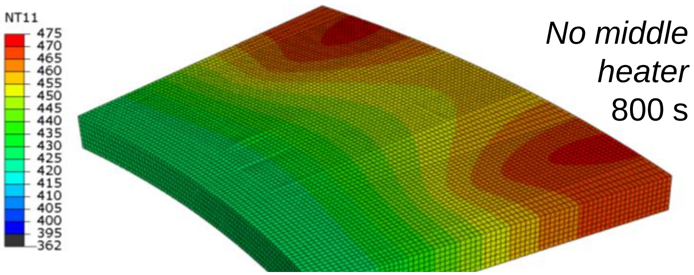
- inboard of LLD
  - *pumps the outer SOL**
- outboard of LLD
  - *pumps private flux region**

* *longer shot times with strike point off the LLD*

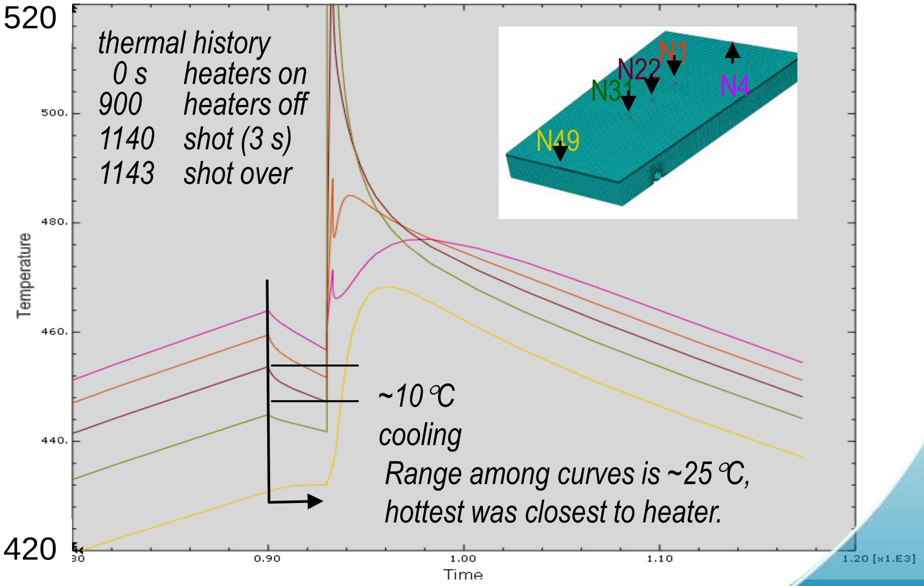


Sandia initially studied a CVD Mo-coated pyrolyzed C mesh as a Li reservoir for the LLD. The thermal conductivity of the mesh was unknown.





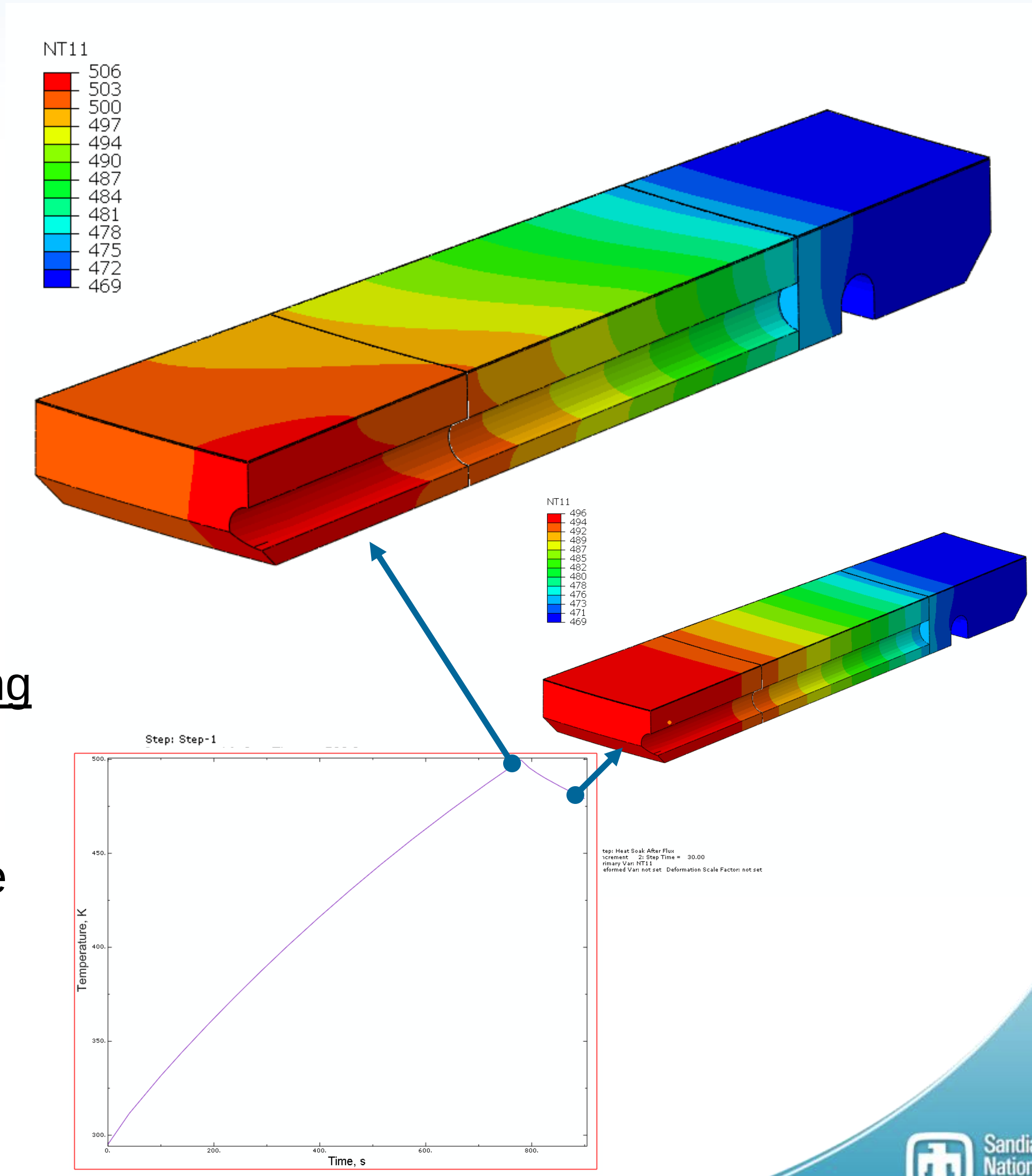
Heat to ~480K, electrical heaters operated at 400 W each



Example of ABAQUS plots of LLD "half cell"

Possible conditions in model:

- heating from the plasma
- heating
  - electrical heaters or hot gas
- continuous cooling
  - nitrogen flow in the tube
  (before, during and after shots)

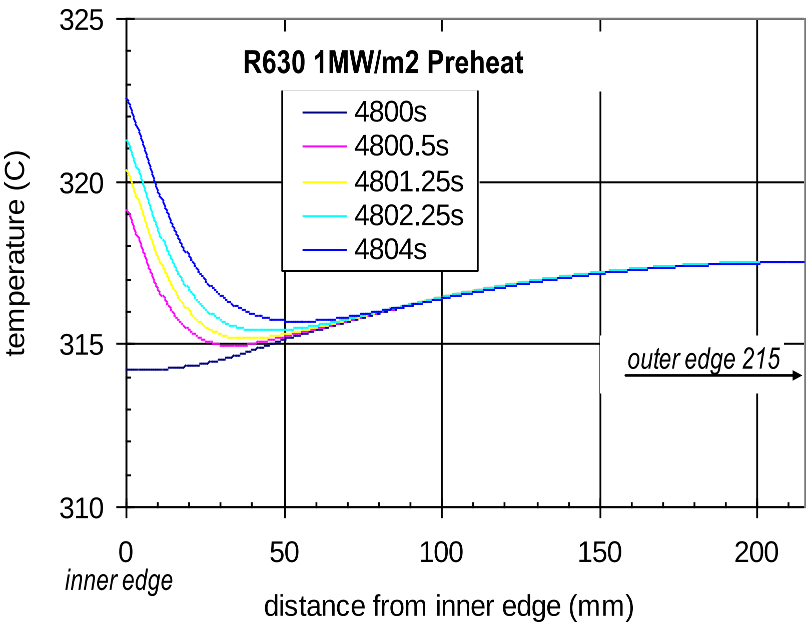


<u>Case: Heating of plate, N2 cooling</u>

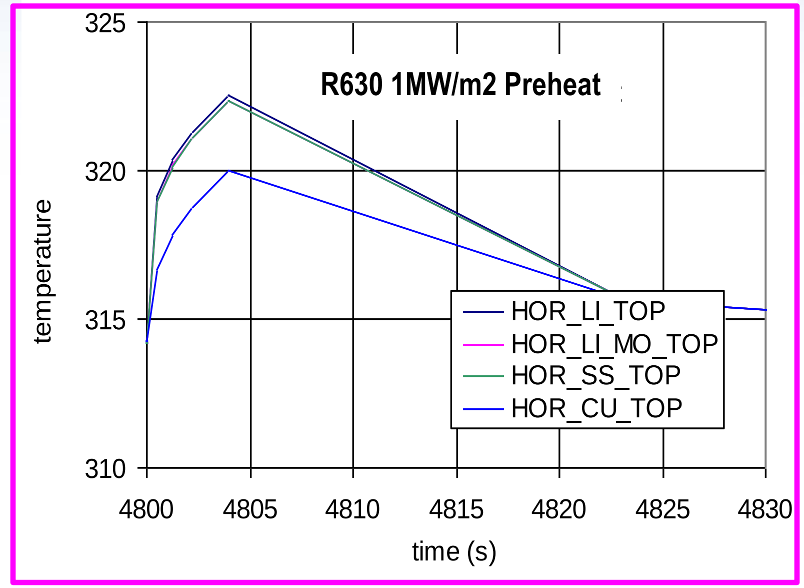
- Mo properties for Li/Moly layer
- Initial temperature 22^{o}C
- 400W applied to heater surface
- 0.029W/cm^{2}K film coefficient and 22^{o}C sink temperature for cooling tube.

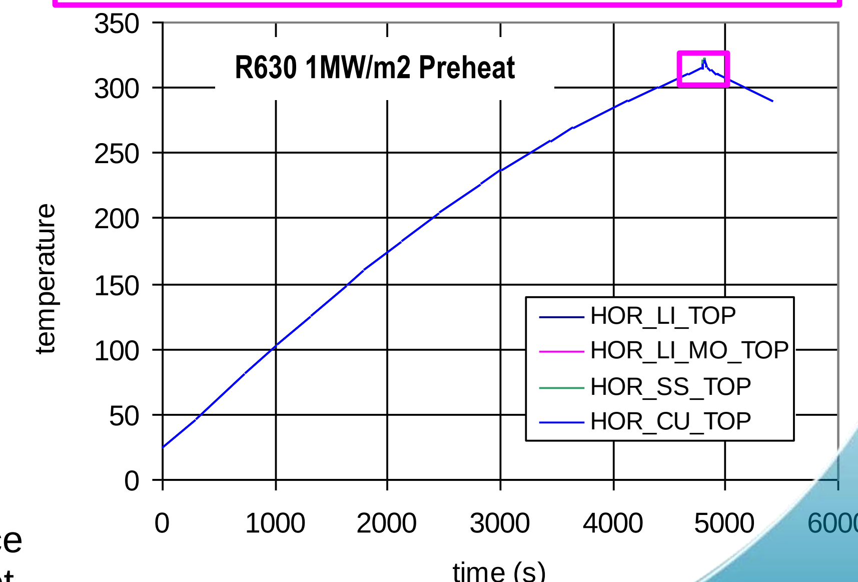
Sample of Results for R63cm 1MW/m^2

- strike point at 63 cm (near LLD's inner edge)
- preheating with electrical heaters
- no gas cooling (included in other analyses)
- heating from heater(s) set by trial and error based on TC measurements
- plasma heating from 4800 to 4804 s



Poloidal distribution of temperature on the surface of the LLD model at several times during the 4-s shot.





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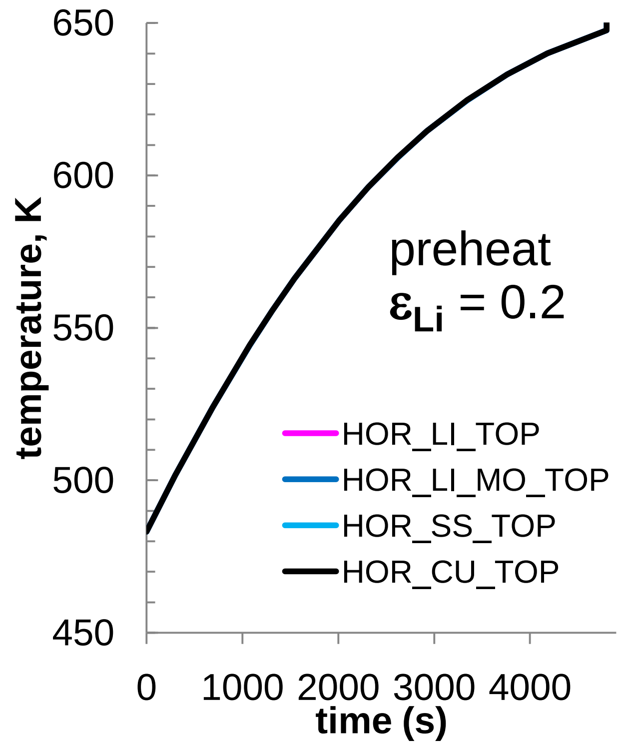
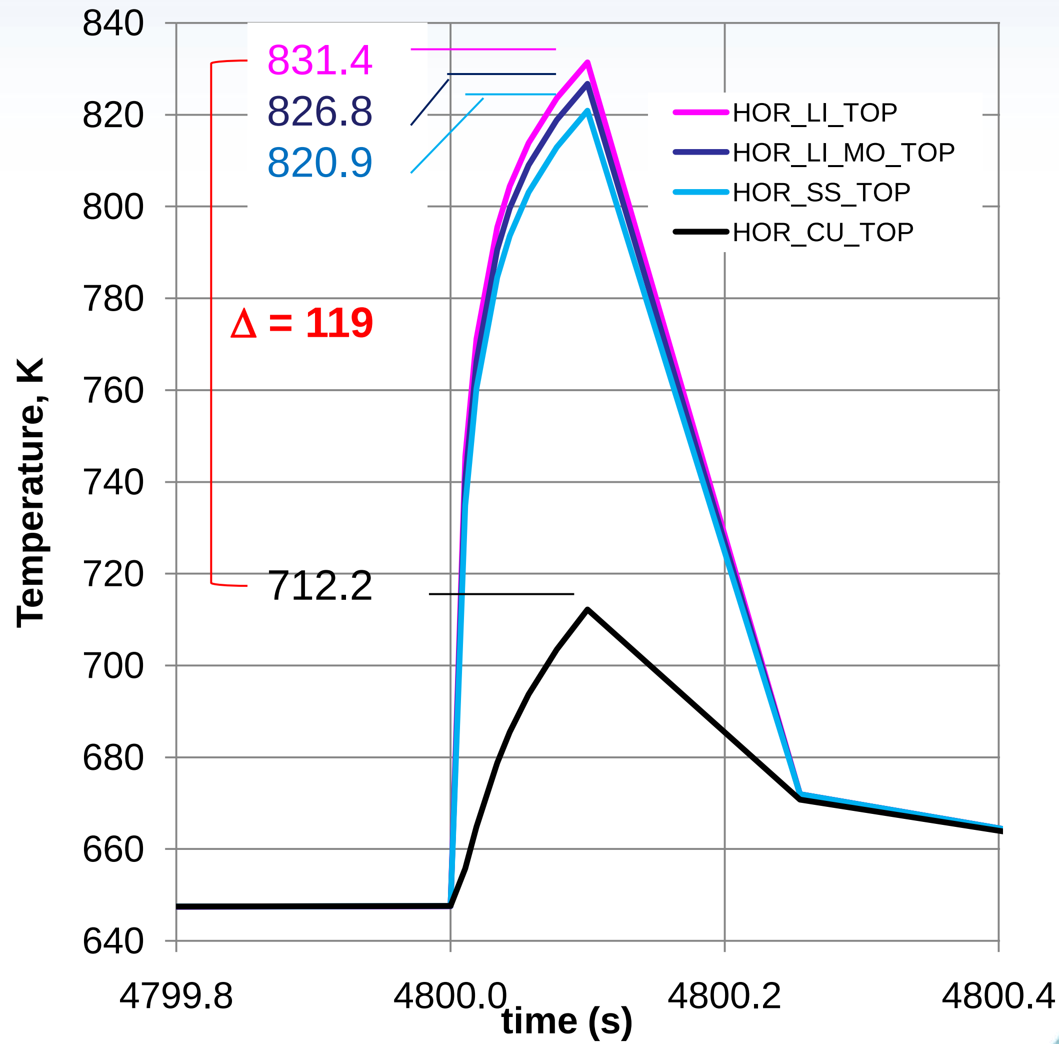
Sample of Results for R75cm 20MW/m²

- strike point at 75 cm (near middle of LLD)
- preheating with electrical heaters
- gas cooling
- plasma shot of 0.1s (4800 to 4800.1 s)





In 0.1s at 10MW/m² copper heats slightly, but Li surface is almost 120 higher.

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LLD plate heating during XP1041-A

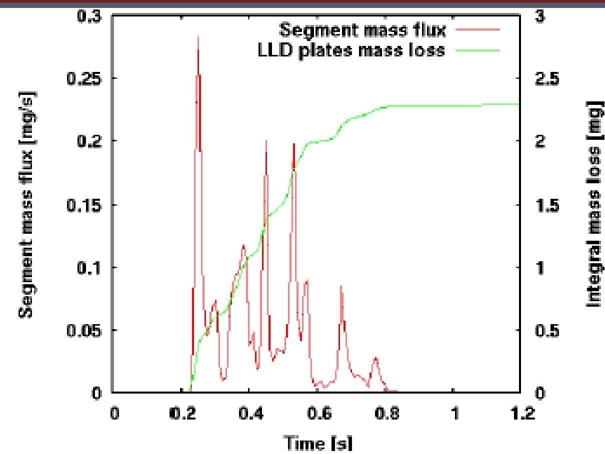
M.A. Jaworski (PPPL), et al.

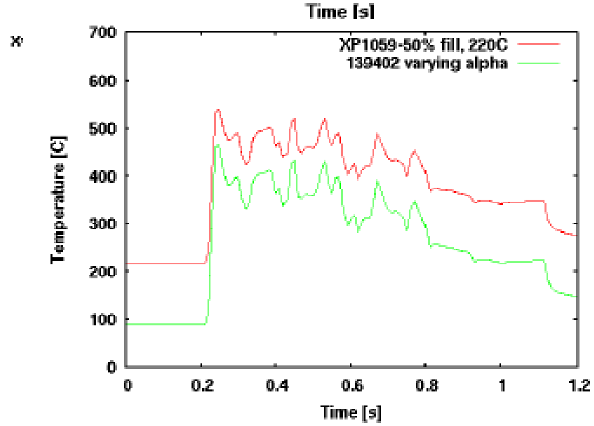
College W&M
Colorado Sch Mines
Columbia U

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

XP1059 prediction for 220C starting temperature

- Same parameters utilized for this simulation, except starting temperature
- Evaporative cooling significant
  - Prevents straight linear adjustment of previous temperature solution
  - Total mass loss from all four LLD plates is about 2.3mg
- May be pessimistic if a liquid lithium layer is present (alpha → 1)





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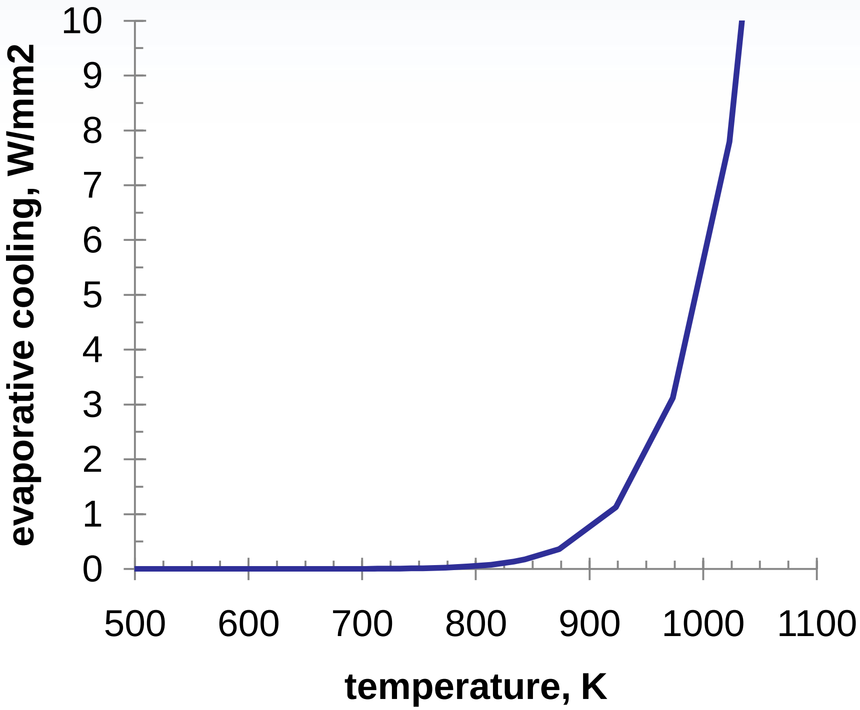
Evaporative cooling in our model

Evaporation of Li is a quantity of interest. We include the cooling effect of evaporation in the model.

We calculate the integrated amount of lithium evaporated separately in post-processing based on the evolution over time of the temperature across the face of the LLD.

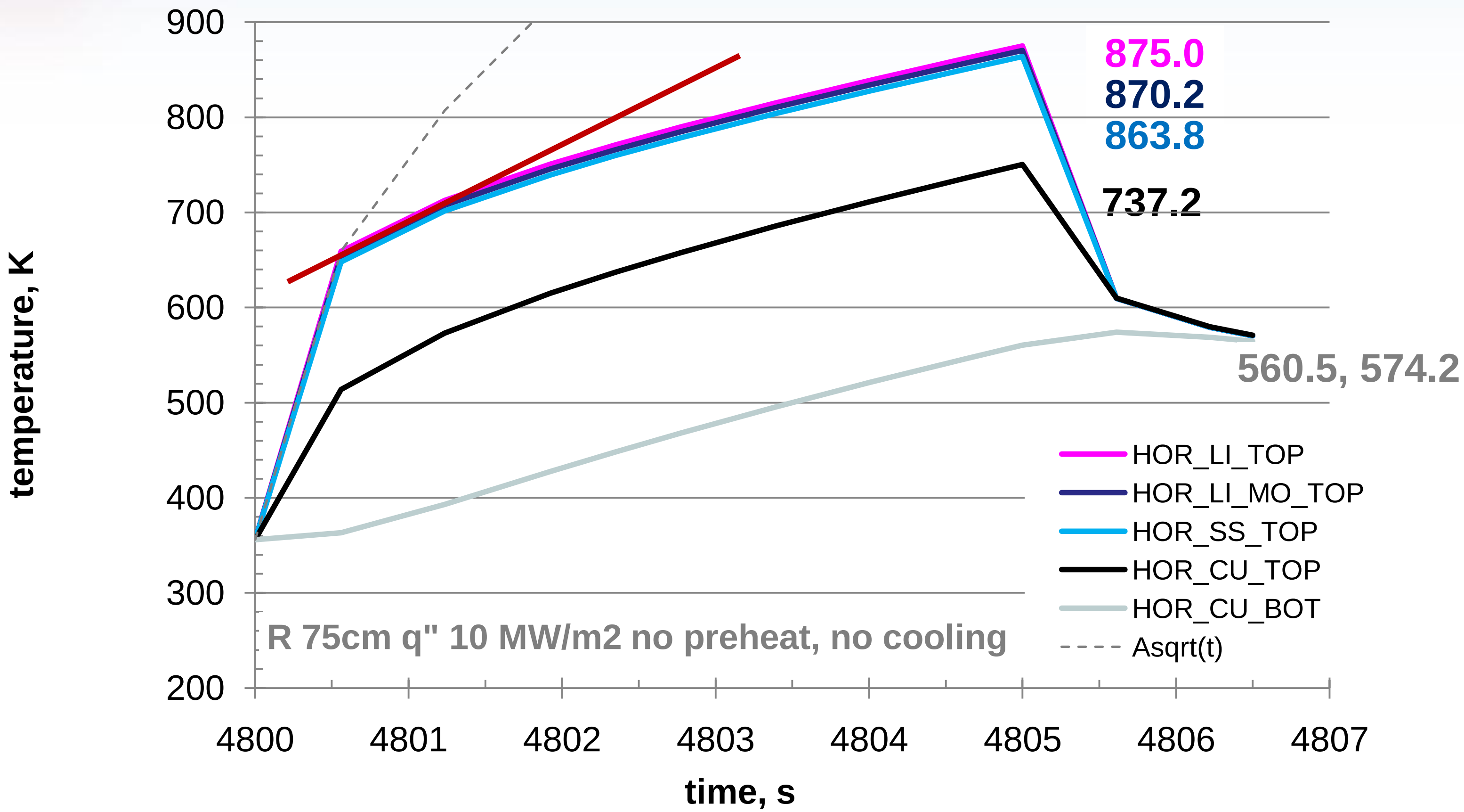


Cooling (W/mm^2) = 595.7 * [10^(8-8143/T] /SQRT(6.941*T)

Based on the expression for vapor pressure of 3.5E22 * [10^(8-8143/T]
from Jensson et al. (old HEDL Report) and the equation below.

$$\text{Evaporation } \Gamma_{evap}\,(\text{atoms/cm}^2\text{-s}) = 3.5\text{x}10^{22}\,\frac{P(Torr)}{\sqrt{mass(a.u.)T}}$$

Sample of Results for R75cm 10MW/m²

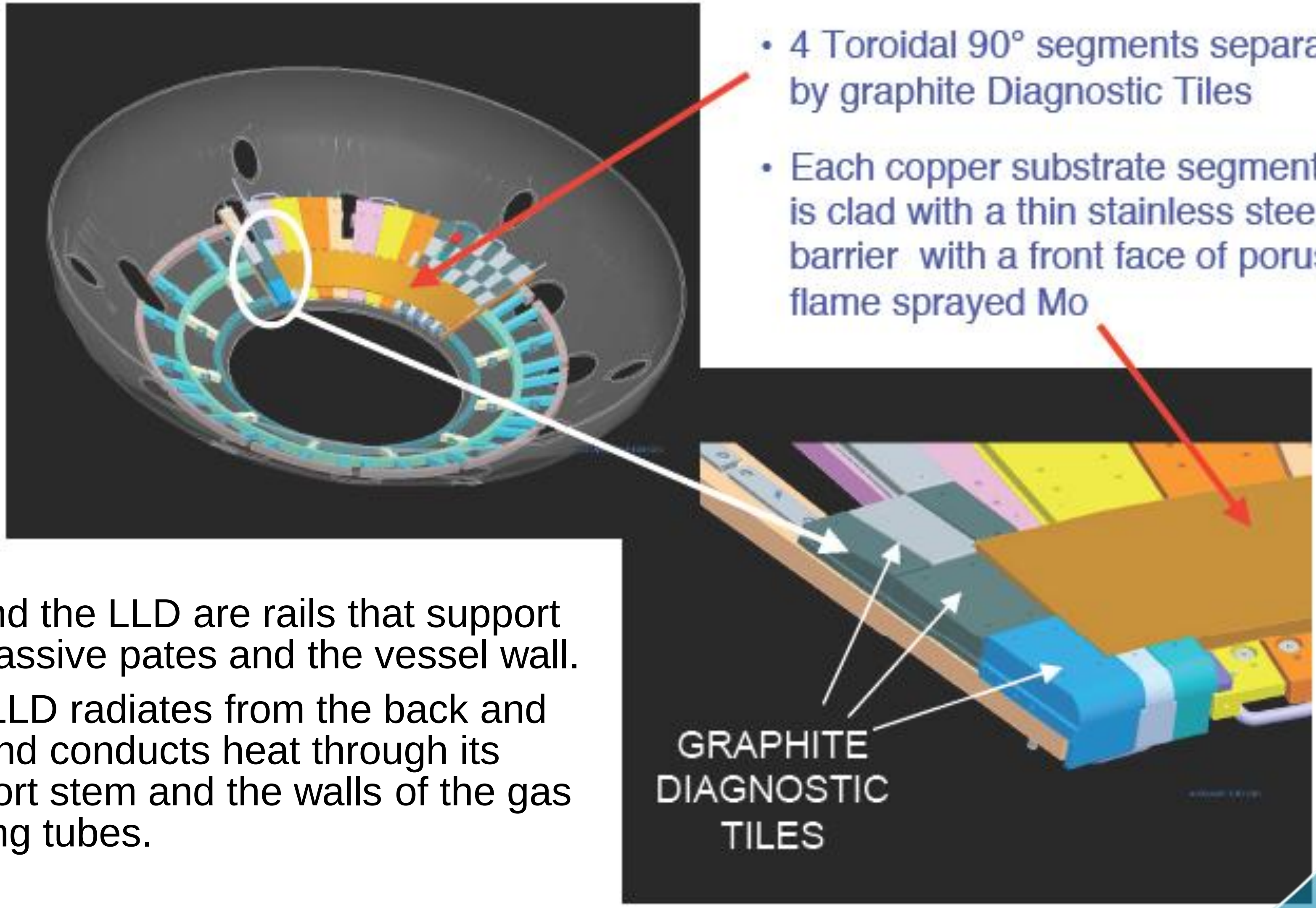


In 5s at 10 MW/m^2 heat penetrates rapidly into top of Cu plate, and after ~0.5s to the back of the plate. Li surface is over 140° higher than the Cu.

Heating does not follow C*SQRT(time) but is close to the linear pattern for heating of a solid plate after the heat reaches the back. However, the roll away from linear (red line) may indicate evaporation. We need further analysis of the model.

Can the cooling cycle provide information?

- 4 Toroidal 90° segments separated by graphite Diagnostic Tiles
- Each copper substrate segment is clad with a thin stainless steel barrier with a front face of porus flame sprayed Mo



Behind the LLD are rails that support the passive pates and the vessel wall.

The LLD radiates from the back and top and conducts heat through its support stem and the walls of the gas cooling tubes.

Radiation Exchange between two infinite plates where $T_1 > T_2$

Radiation, two infinite plates, solve as follows:

$q_1/A_1 = -q_2/A_2$ where q's are net radiant energy leaving, also received irradiation G_1 equals the radiosity J_2 of the other and vice versa.

Also, for a surface $J = E + \rho G$ and $\rho = 1-\alpha$ for an opaque surface, and for a gray diffuse surface $\alpha = \varepsilon$, and on gets for each surface:

$J_1 = \varepsilon_1 E_{b1} + (1-\varepsilon_1)G_1$ and $J_2 = \varepsilon_2 E_{b2} + (1-\varepsilon_2)G_2$; since $G_1 = J_2$, these may be solved for J_1 and G_1

$J_1 = [\varepsilon_1 E_{b1} + (1-\varepsilon_1)\varepsilon_2 E_{b2}]/[1-(1-\varepsilon_1)(1-\varepsilon_2)]$

$G_1 = [\varepsilon_2 E_{b2} + (1-\varepsilon_2)\varepsilon_1 E_{b1}]/[1-(1-\varepsilon_1)(1-\varepsilon_2)]$; then from the 1st equation, $q_1/A_1 = -q_2/A_2$, we get

$q/A = [E_{b1} - E_{b2}]/[1/\varepsilon_1 + 1/\varepsilon_2 -1] = \sigma (T_1^4 - T_2^4)/[1/\varepsilon_1 + 1/\varepsilon_2 -1]$

So, if we apply this separately to the front and back surfaces, but also assume that the tiles and the mounting structure behind the LLD are the same, then we have two the loss channels for both faces

$\text{r-loss}_{top} = A_{top}\, \sigma (T_{LLD}^4 - T_V^4)/[1/\varepsilon_{Li} + 1/\varepsilon_{Tiles} -1]$

$\text{r-loss}_{bott} = A_{bott}\, \sigma (T_{LLD}^4 - T_V^4)/[1/\varepsilon_{Cu} + 1/\varepsilon_{SS} -1]$

$$\textbf{r-total} = \sigma (T_{LLD}^4 - T_V^4) \{A_{top}/[1/\varepsilon_{Li} + 1/\varepsilon_{Tiles} -1] + A_{bott}/[1/\varepsilon_{Cu} + 1/\varepsilon_{SS} -1]\}$$

RE Nygren 26apr2010 note from Heat Transfer, Alan Chapman 4th Ed.

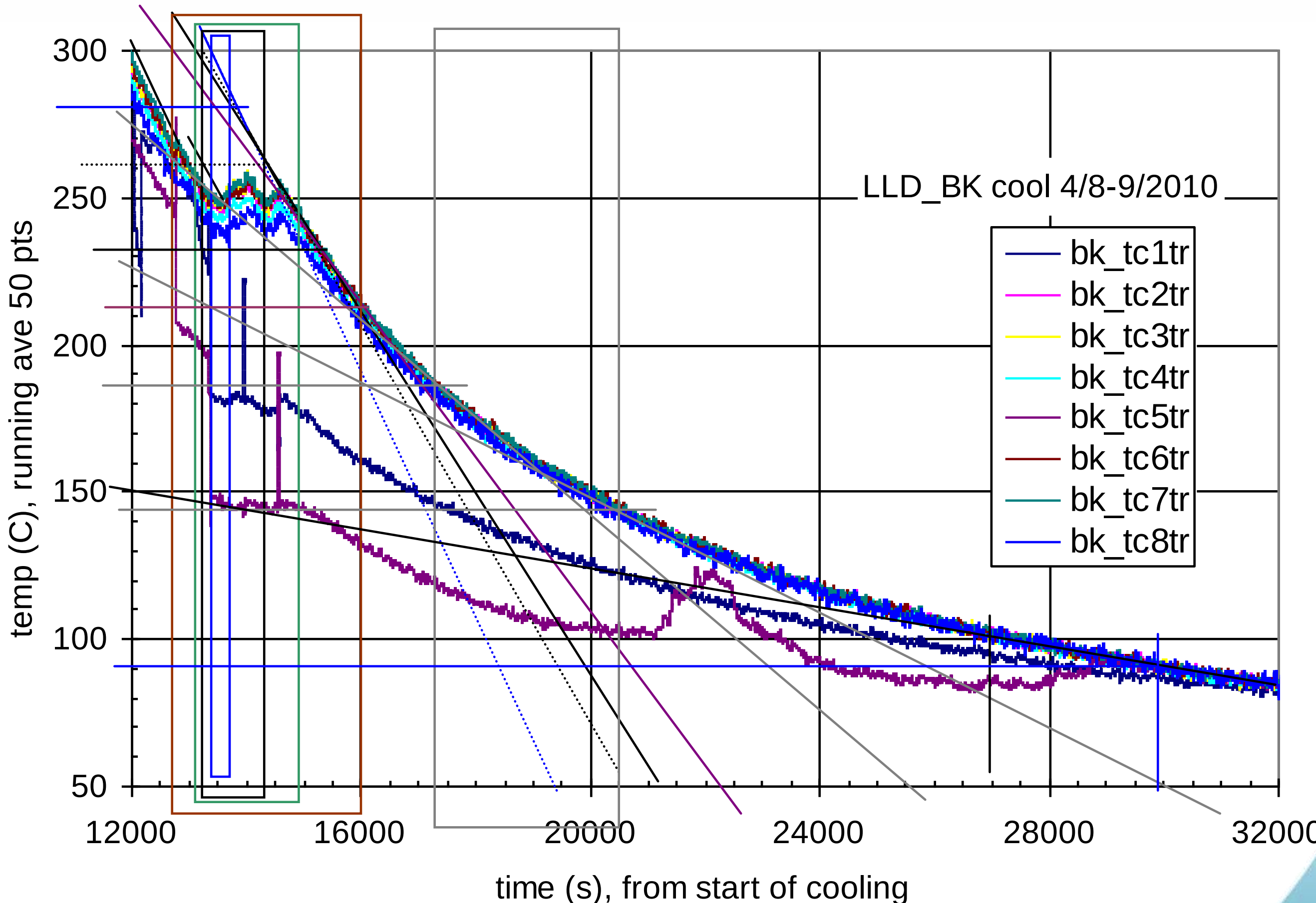
TCs during long cooling of LLD section BK

(1PM on April 8 until after midnight)

Idea: Estimate the emissivity of the Li surface if radiation dominates cooling.

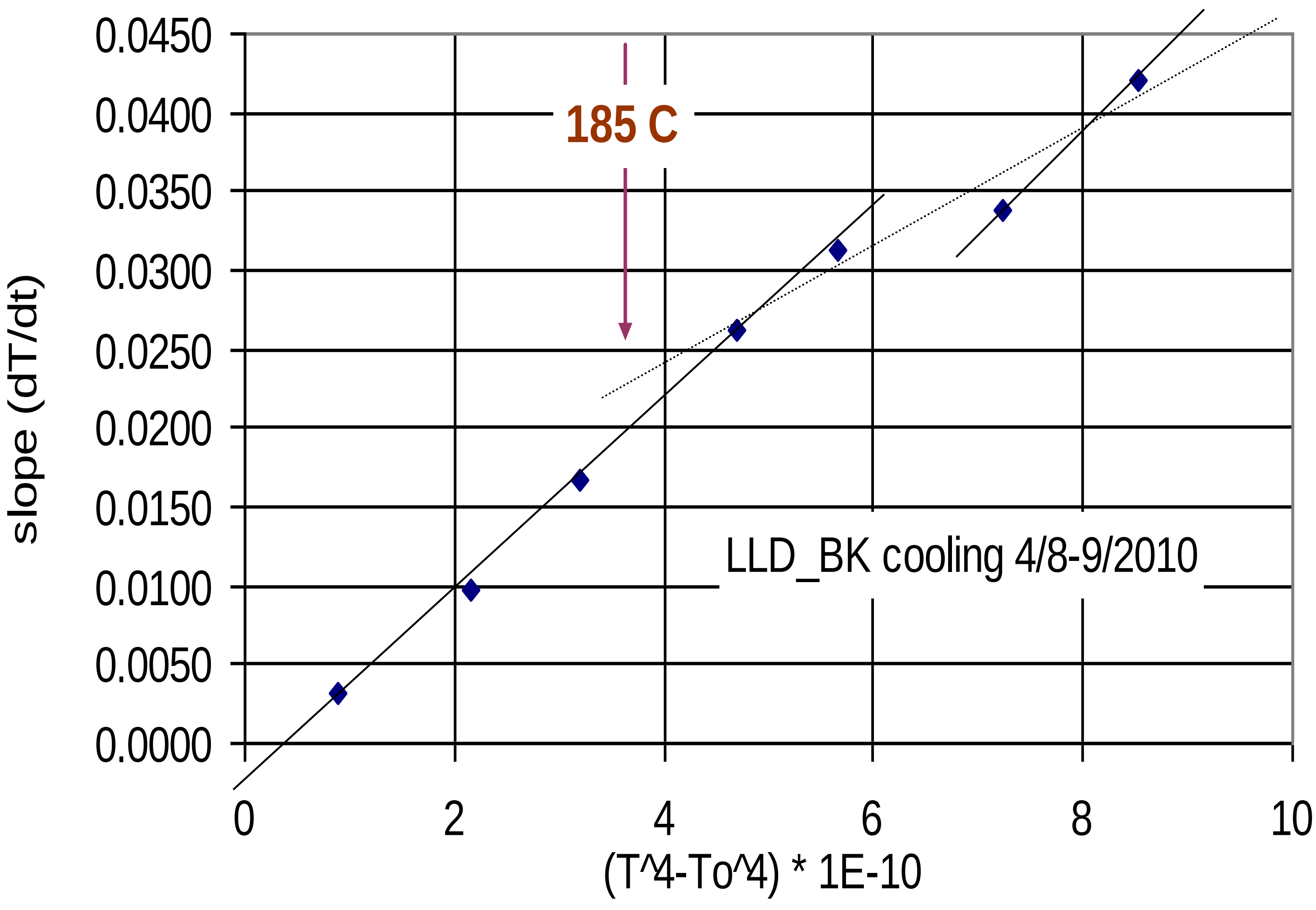
Plot has initial treatment of slopes.

TC signals are very noisy. Running average of 25 points is used here.



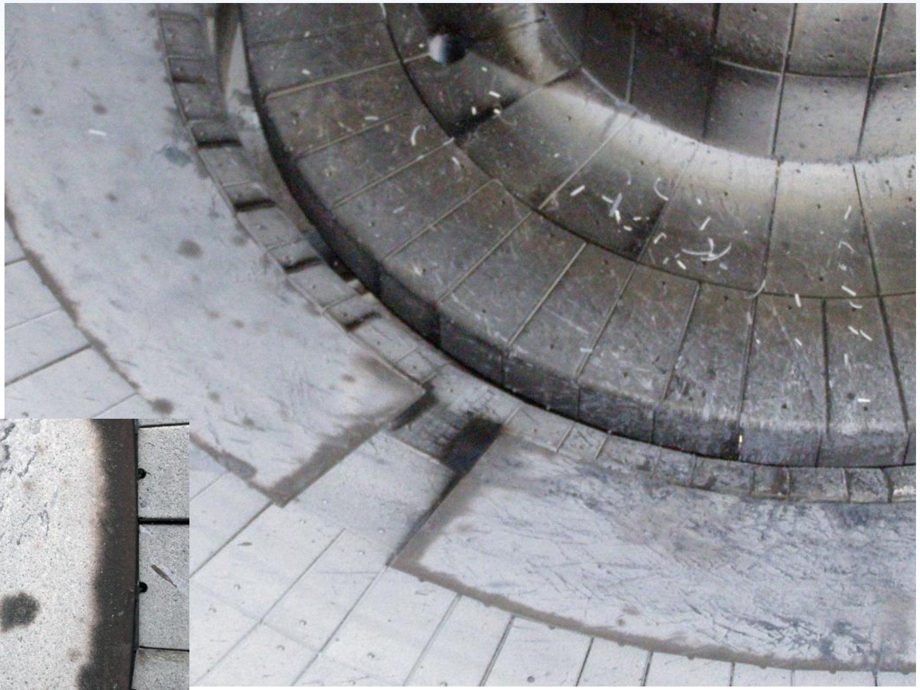
TCs during long cooling of LLD section BK

Initial treatment was encouraging with apparent strong dependence on T^4.



Emissivity from which lithiated surface?

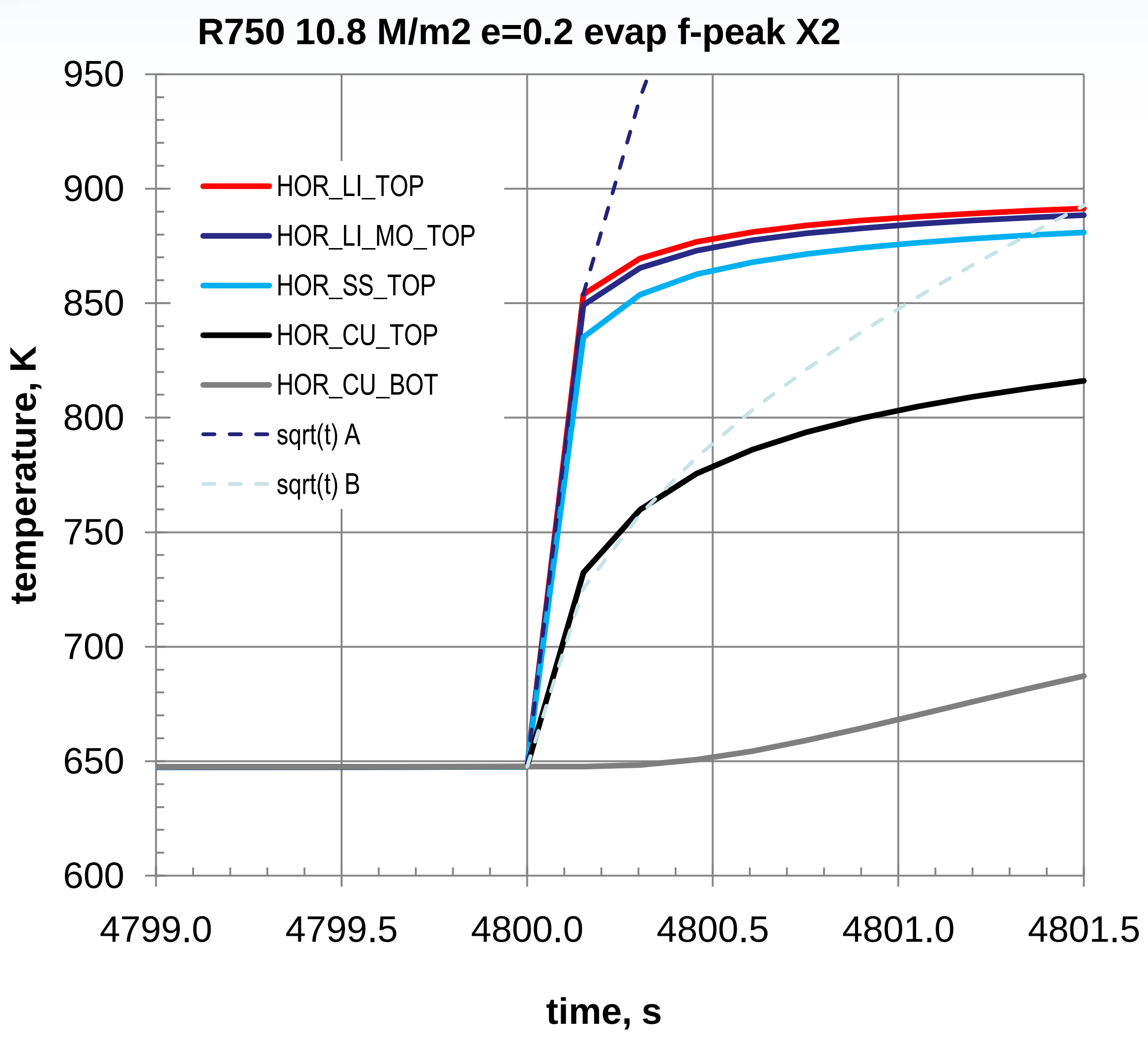
Evaporation of Li is a quantity of interest, but the work function depends on the surface chemistry. Often we do not have pure lithium.



Sandia will collaborate with Purdue University and add an IR camera and software to PRIHSM to monitor a heated lithium target while JP Allain and co-workers modify and monitor surface chemistry.

END

THANK YOU


R750 10.8 M/m2 e=0.2 evap f-peak X2
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900
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700
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HOR_SS_TOP
HOR_CU_TOP
HOR_CU_BOT
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