

# 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

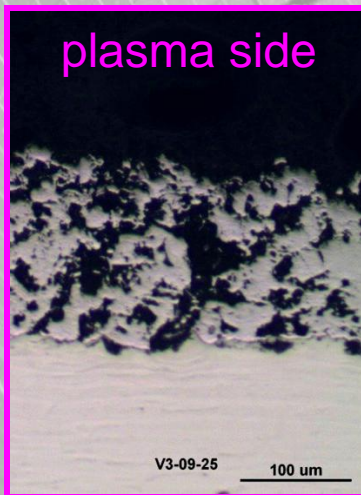
- Measure emissivity of Li surface and surface chemistry simultaneously using PRHISM



# Objectives for Thermal Model

- Predictive model for  $T_{\text{surface}}$  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*

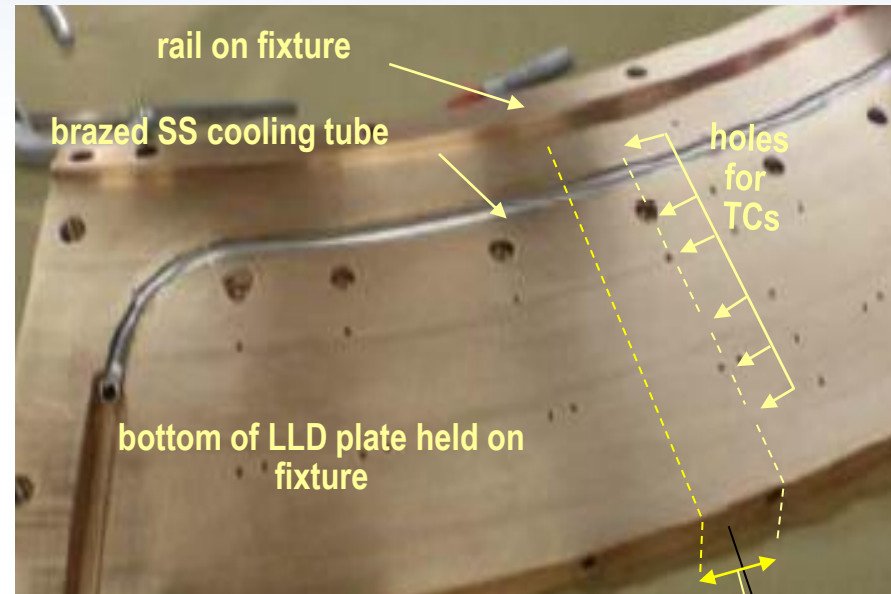
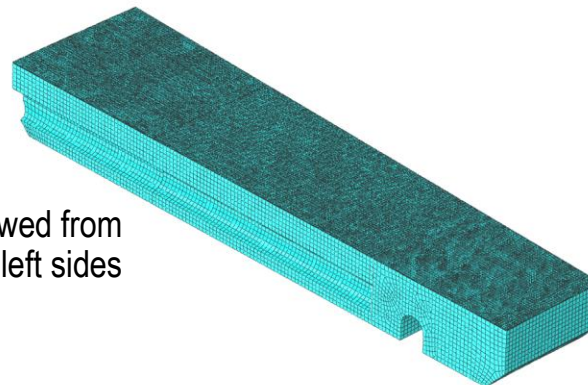
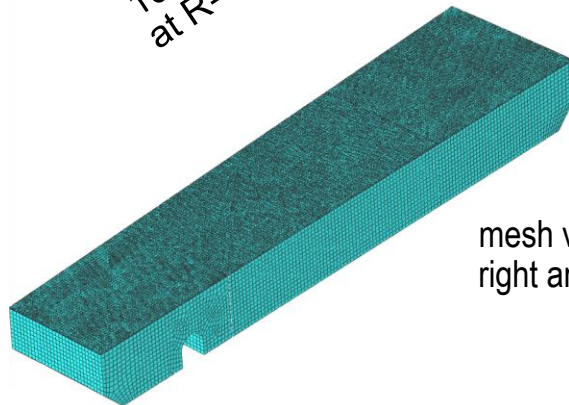
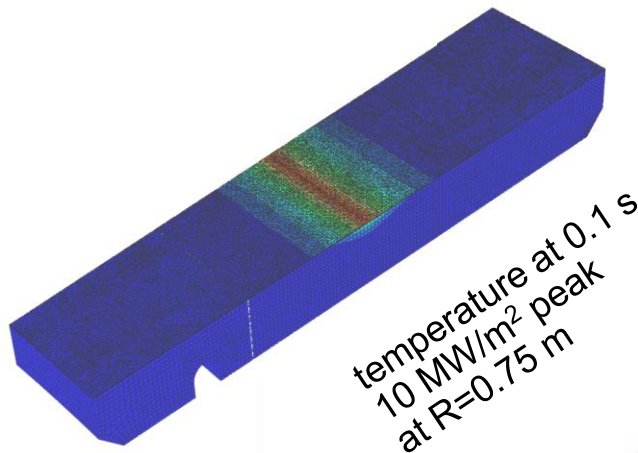


LLD surface cross section: plasma sprayed porous Mo

*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



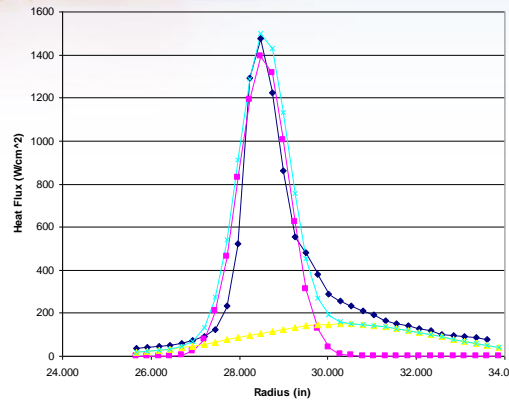
A “unit cell” contains one (of 8) electrical heaters in an LLD plate.

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

solid angle  
of the half  
unit cell



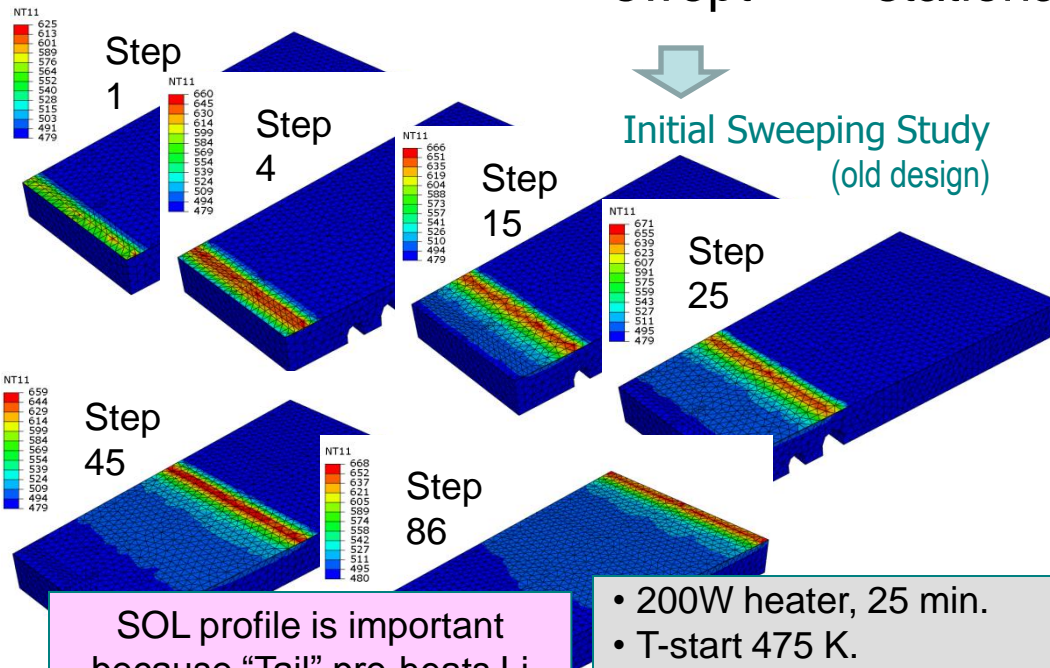
# EARLY THERMAL MODEL & RESULTS



Strike point profile  
(outer div.).  
“Wings” are important  
in sweeping.

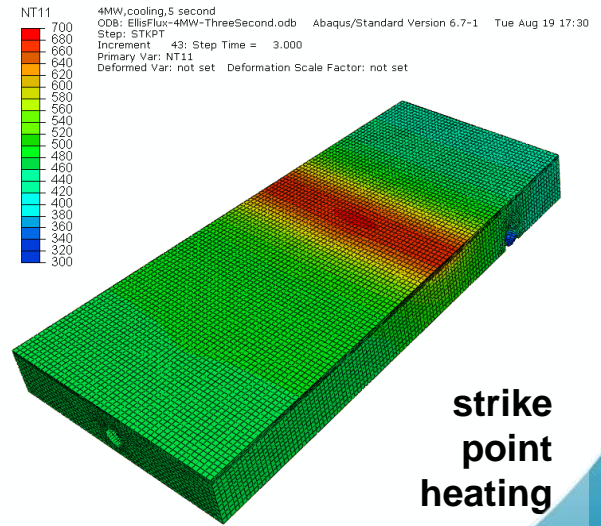
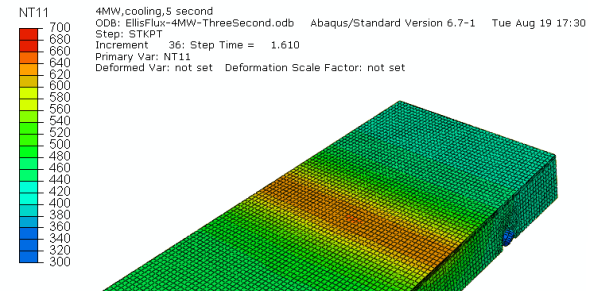
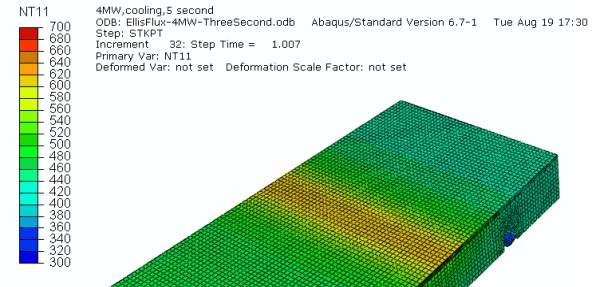
**Strike point on LLD**  
swept stationary

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.



strike  
point  
heating

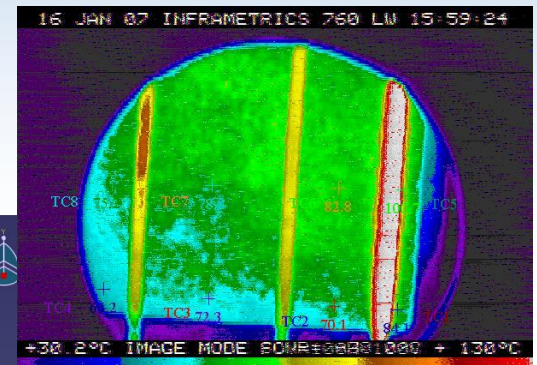
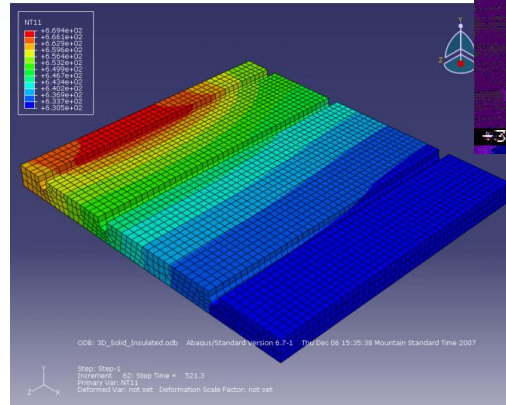
# EARLY THERMAL MODEL & RESULTS

- Initial tests on Mo mesh
- heater failure

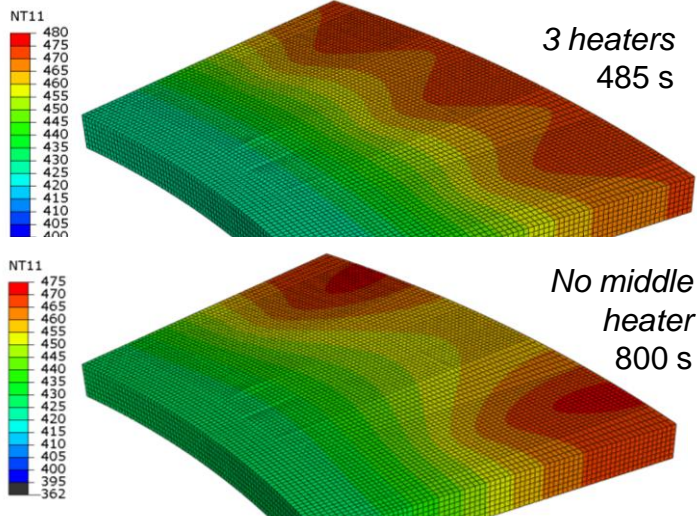
Cases not presented here

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

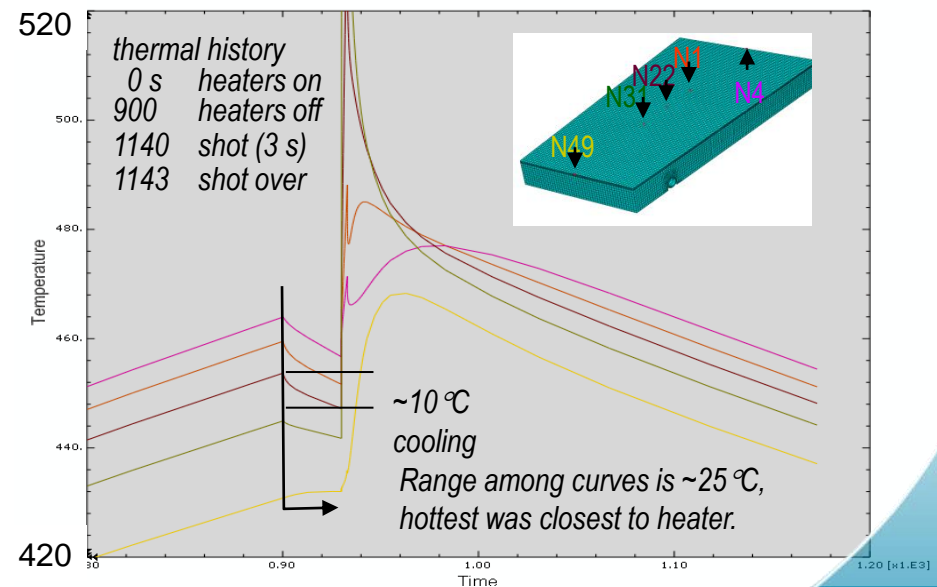
\* longer shot times with strike point off the LLD



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  $\sim 480\text{K}$ , electrical heaters operated at 400 W each



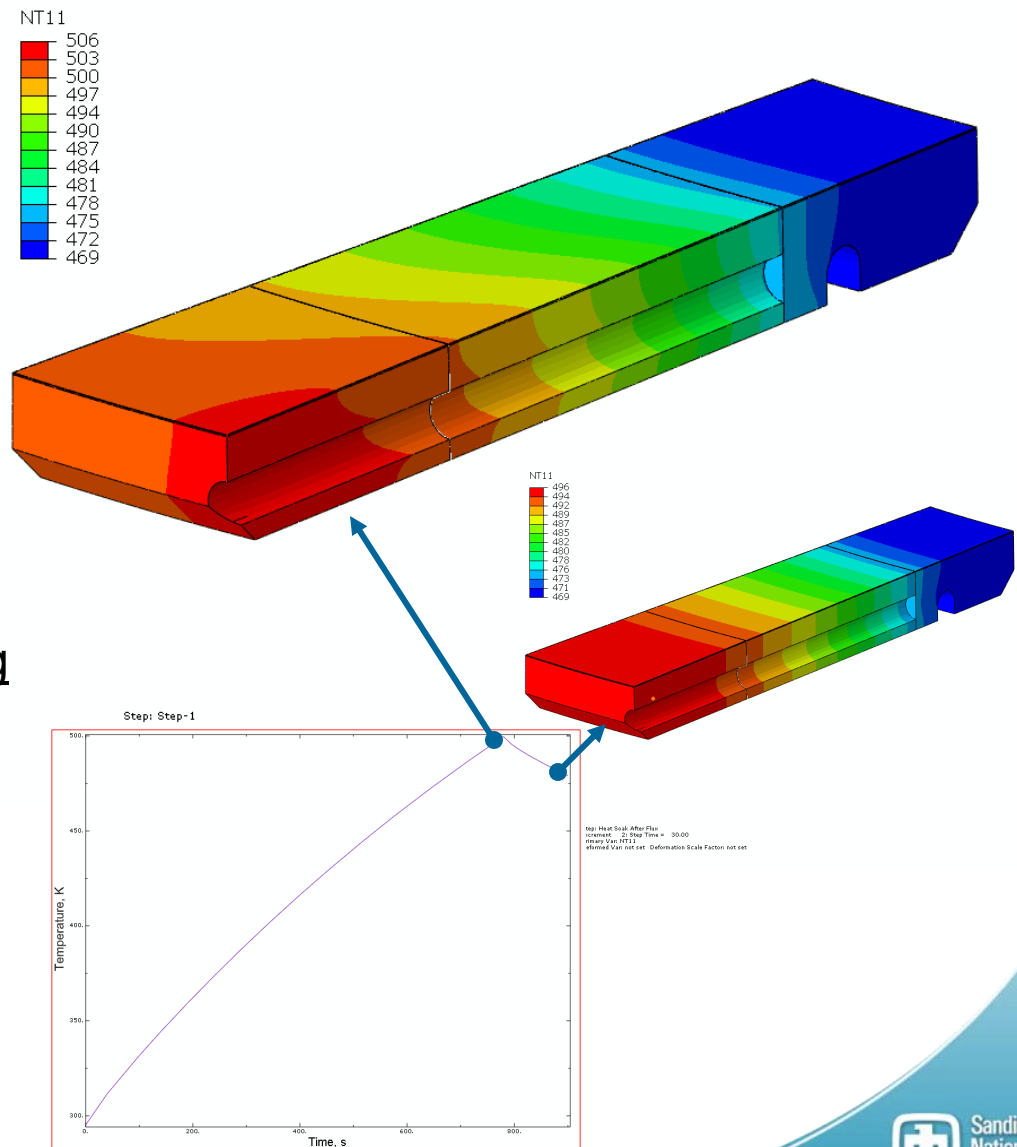
# Example of ABAQUS plots of LLD “half cell”

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)

Case: Heating of plate, N2 cooling

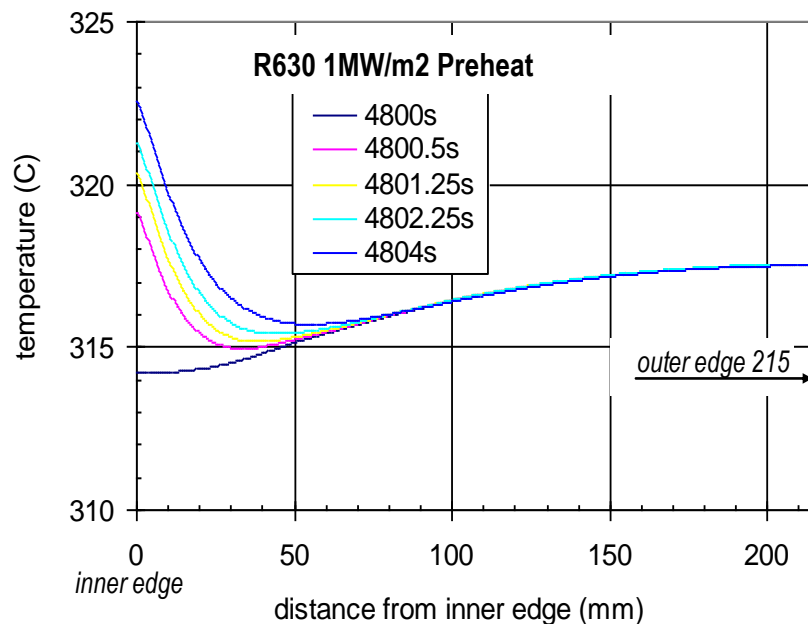
- No properties for Li/Moly layer
- Initial temperature 22°C
- 400W applied to heater surface
- 0.029W/cm<sup>2</sup>K film coefficient and 22°C sink temperature for cooling tube.



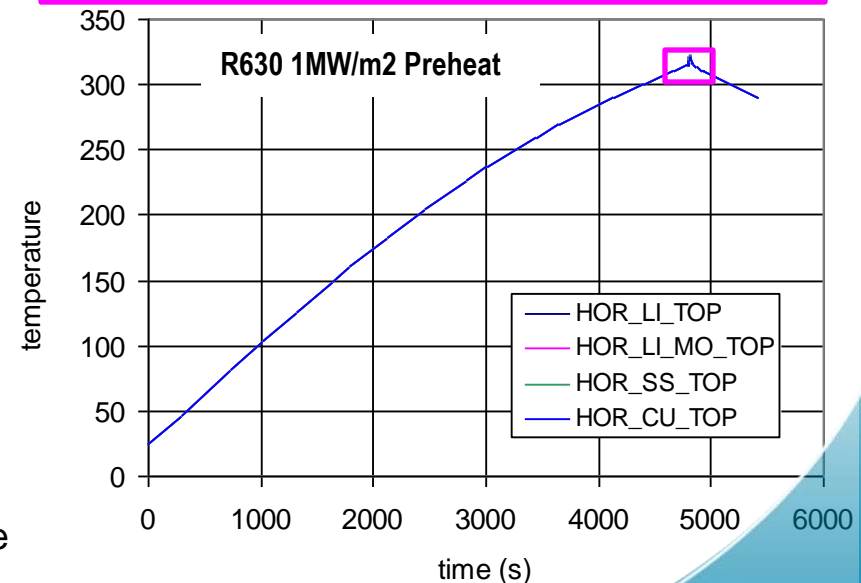
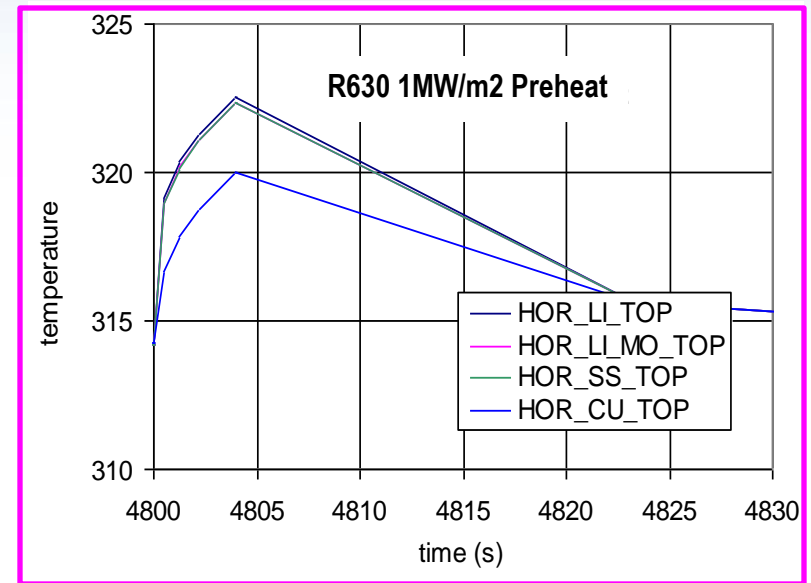


# Sample of Results for R63cm 1MW/m<sup>2</sup>

- 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



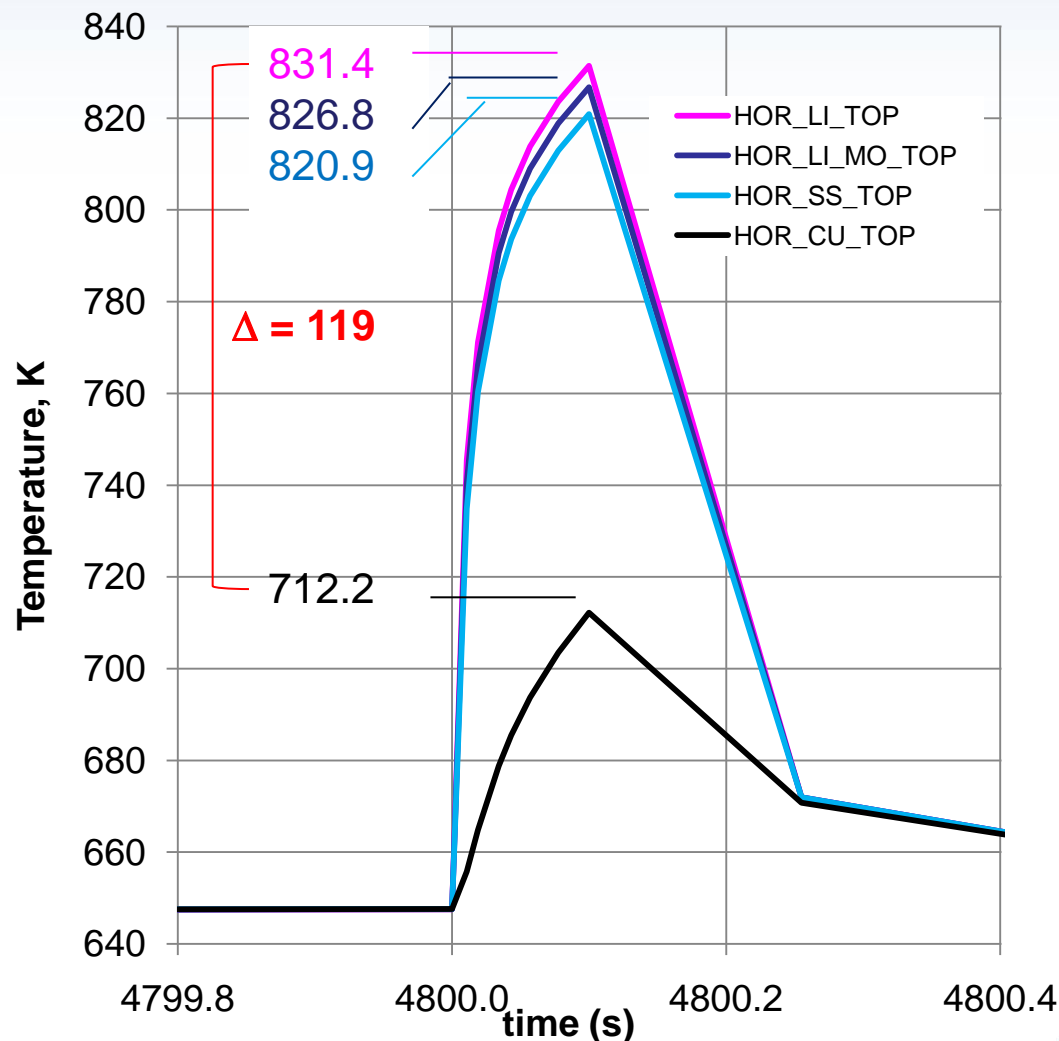
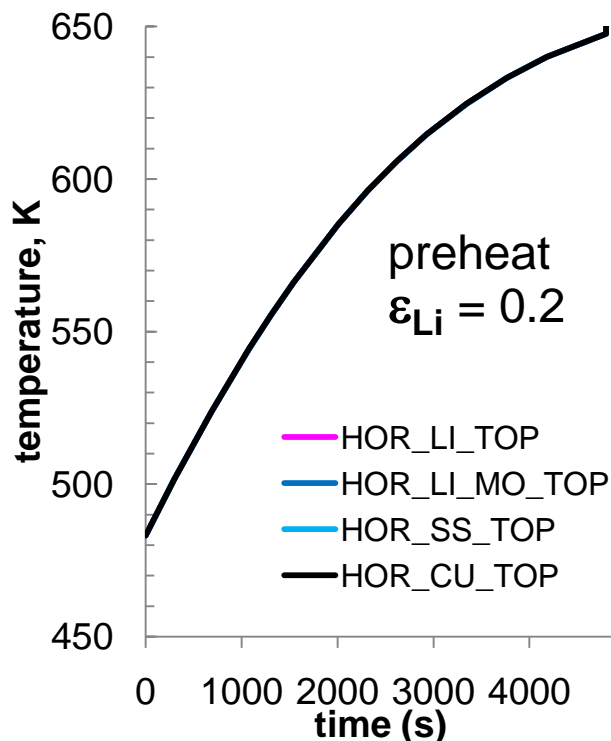
Poloidal distribution of **temperature** on the surface of the LLD model at several times during the 4-s shot.





# Sample of Results for R75cm 20MW/m<sup>2</sup>

- 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/m<sup>2</sup> copper heats slightly, but Li surface is almost 120 higher.

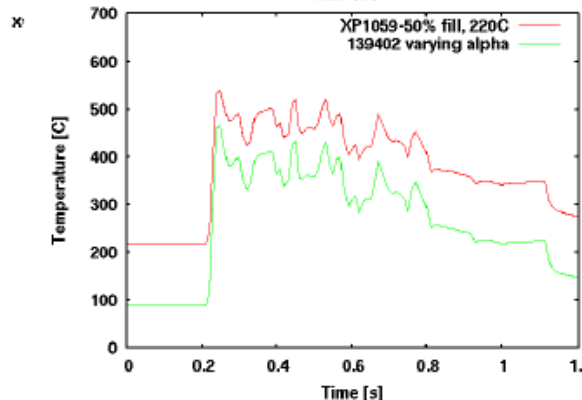
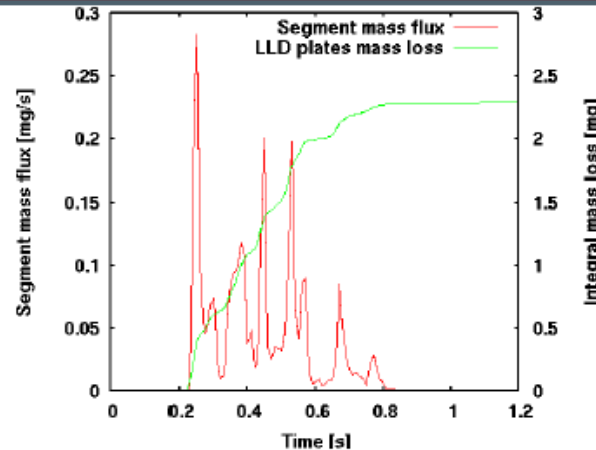
# LLD plate heating during XP1041-A

College W&M  
 Colorado Sch Mines  
 Columbia U  
 Cornell U

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

## 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 ( $\alpha \rightarrow 1$ )



0.801495, 723.361

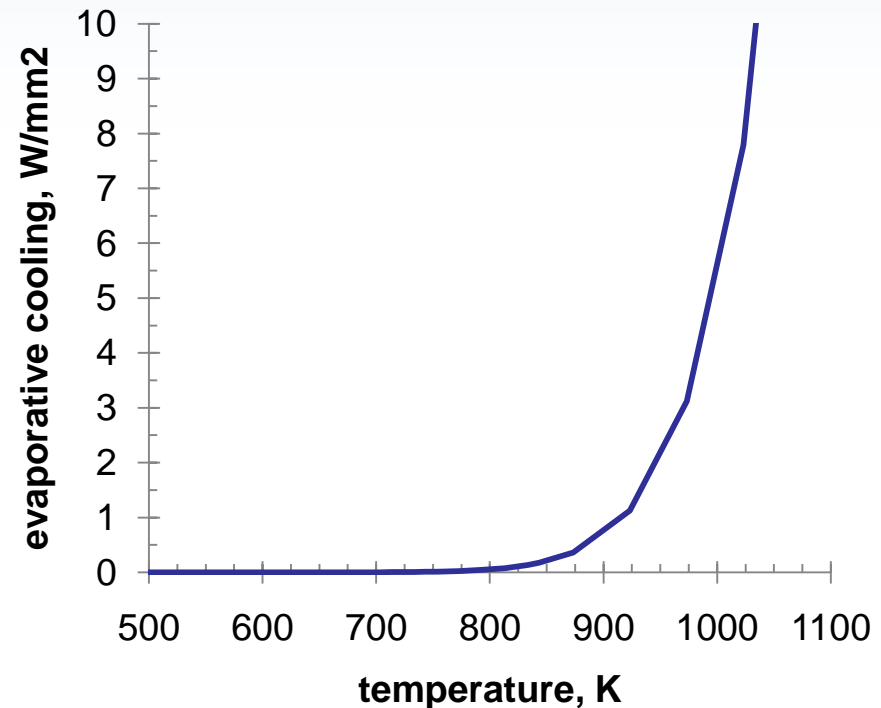
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 Fukui U  
 Hiroshima U  
 Hyogo U  
 Kyoto U  
 Kyushu U  
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 NIFS  
 Niigata U  
 U Tokyo  
 JAEA  
 Hebrew U  
 Ioffe Inst  
 RRC Kurchatov Inst  
 TRINITY  
 KBSI  
 KAIST  
 POSTECH  
 ASIPP  
 ENEA, Frascati  
 CEA, Cadarache  
 IPP, Jülich  
 IPP, Garching  
 ASCR, Czech Rep  
 U Quebec



# 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.



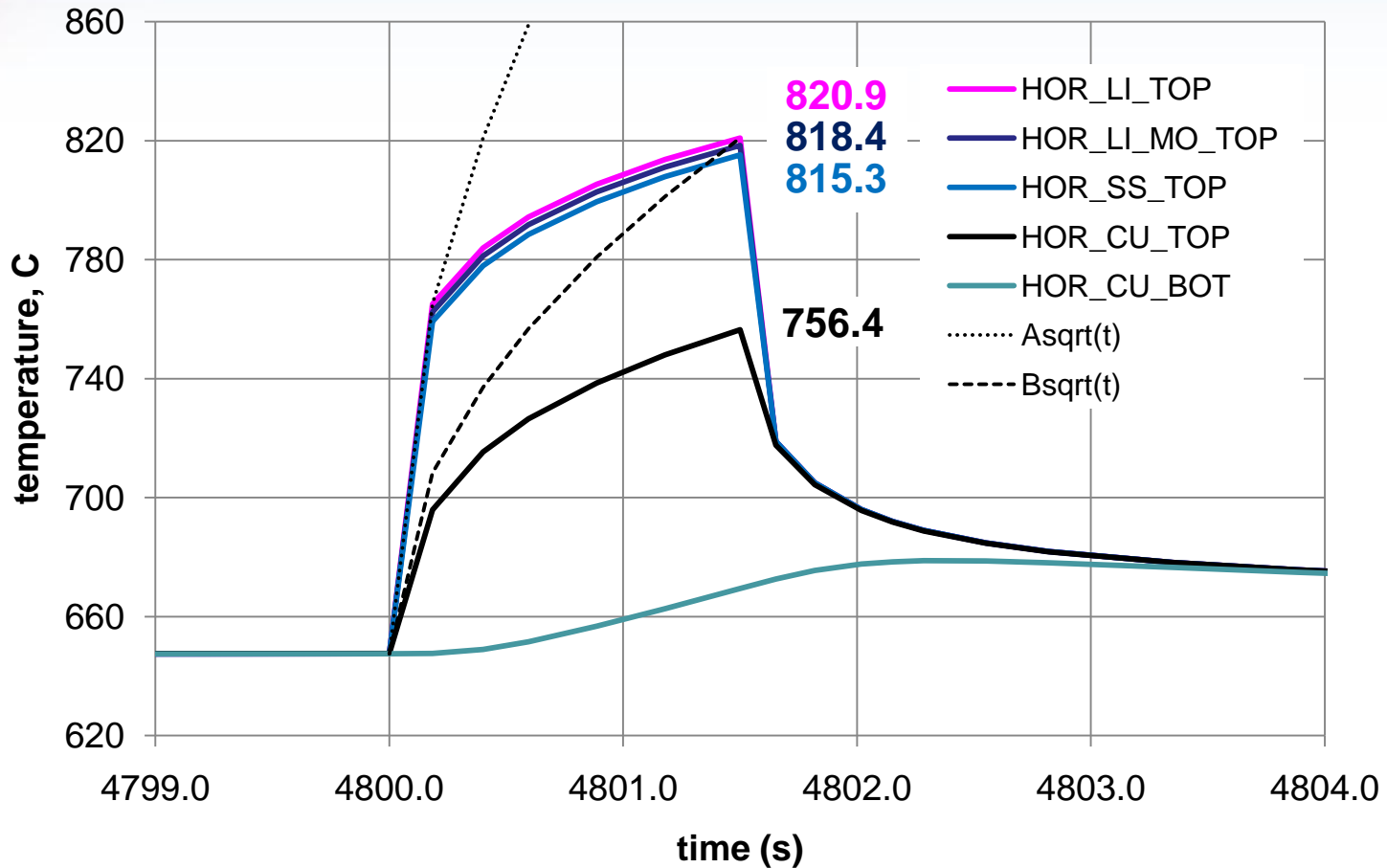
$$\text{Cooling (W/mm}^2\text{)} = 595.7 * [10^{(8-8143/T)}] / \text{SQRT}(6.941 * T)$$

Based on the expression for vapor pressure of  $3.5\text{E}22 * [10^{(8-8143/T)}]$  from Jensson et al. (old HEDL Report) and the equation below.

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

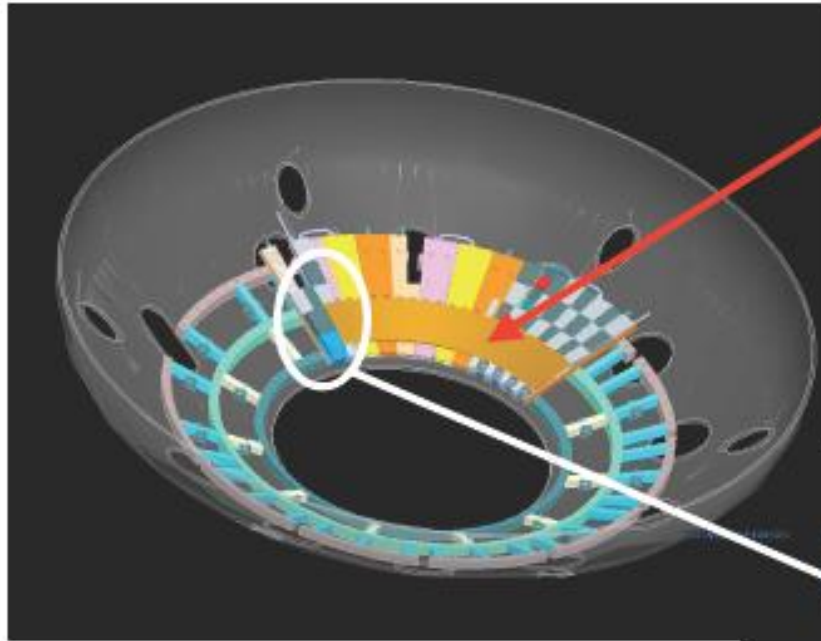


# Sample of Results for R75cm 5.4MW/m<sup>2</sup>

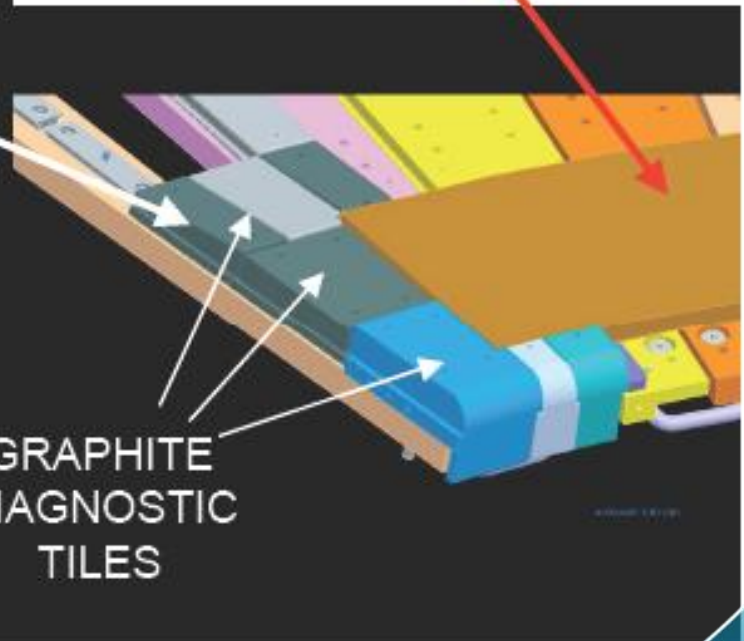


In 1.5s at 5.4MW/m<sup>2</sup> heat penetrates into top of Cu plate, but not back.  
Li surface is almost 65°C higher than the Cu.  
Heating does not follow  $C \cdot \text{SQRT}(\text{time})$ .

# 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 porous flame sprayed Mo



Behind the LLD are rails that support the passive plates 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 one 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

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

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

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

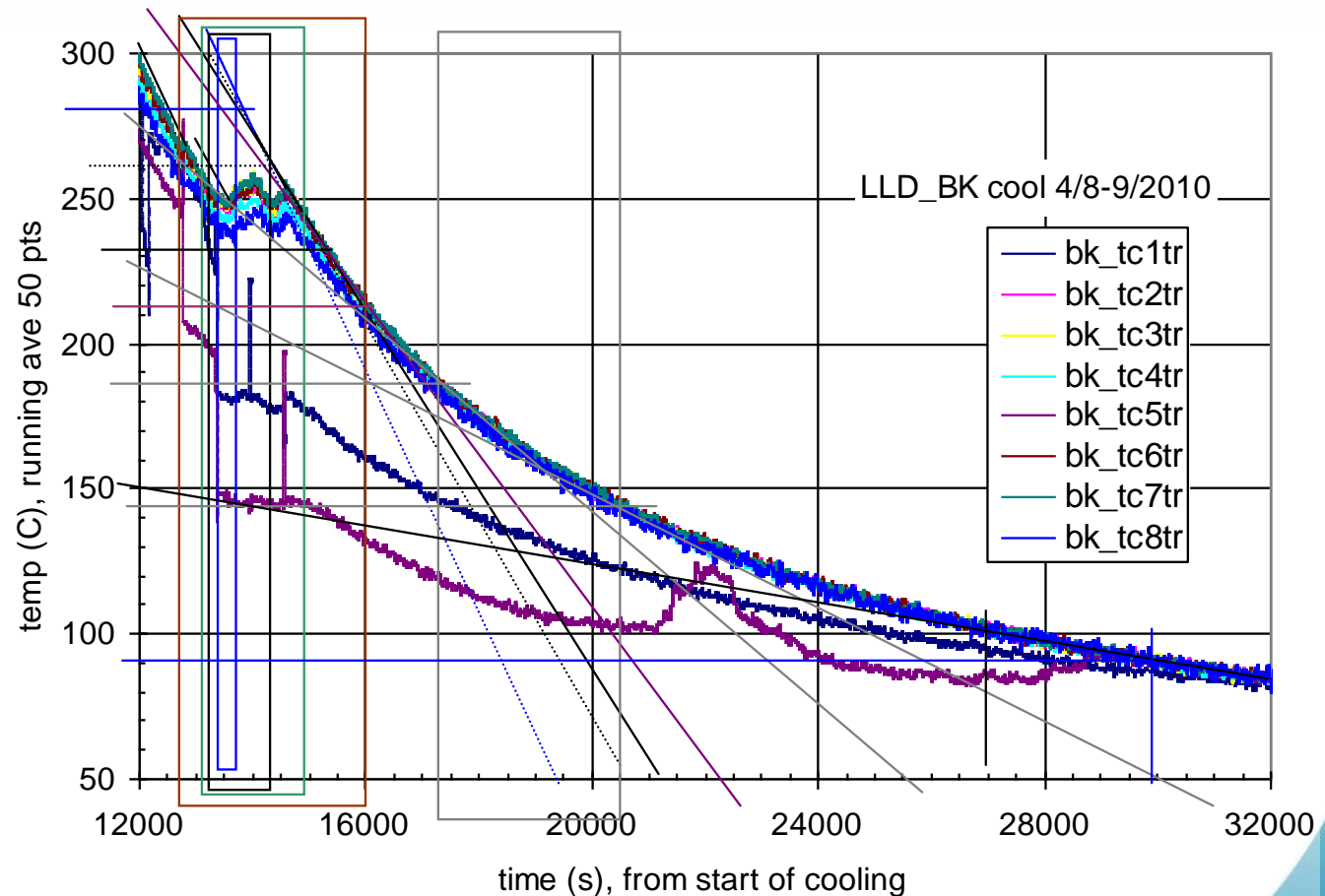
RE Nygren 26apr2010 note from Heat Transfer, Alan Chapman 4<sup>th</sup> Ed.



# TCs during long cooling of LLD section BK

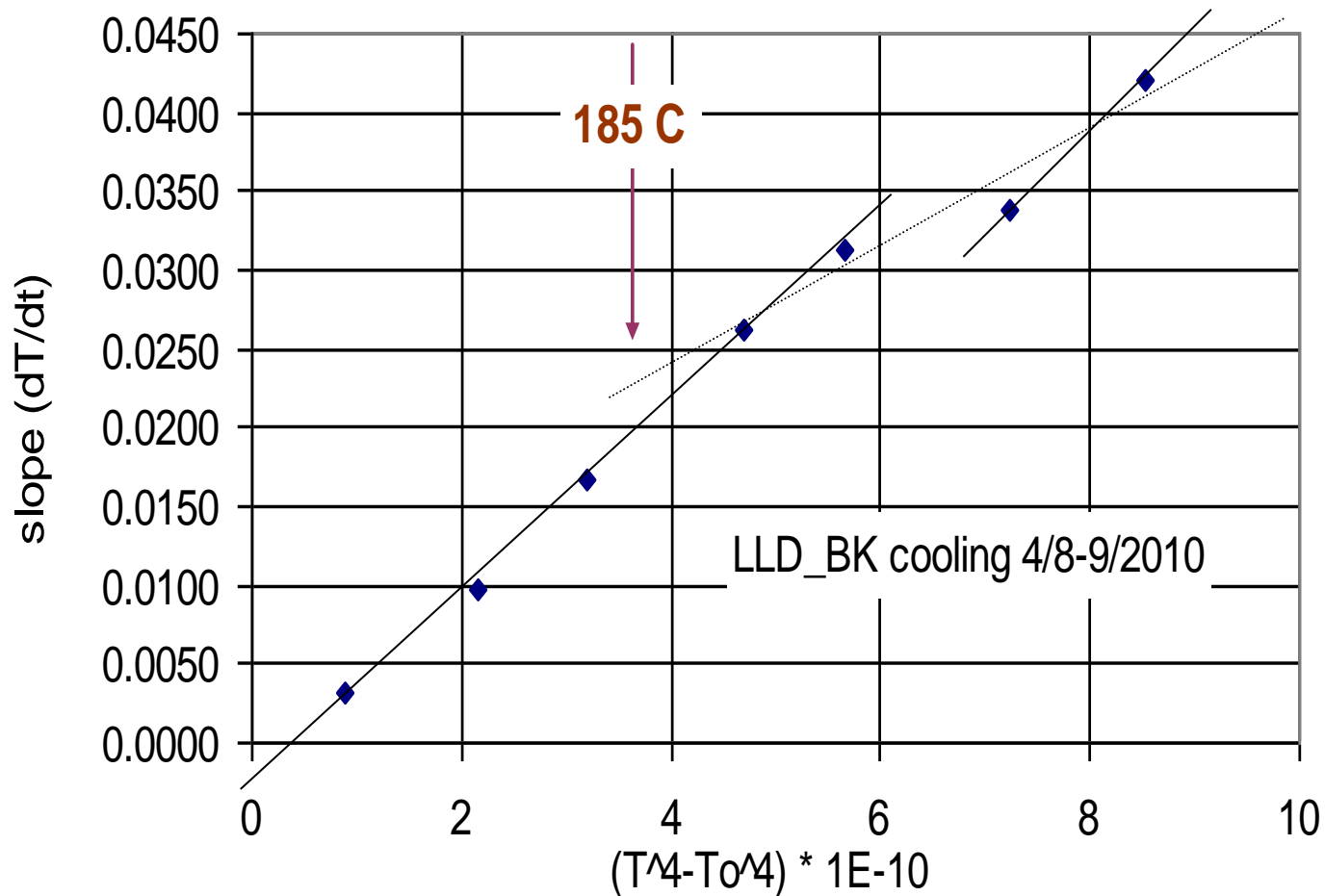
(1PM on April 8 until after midnight)

**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.



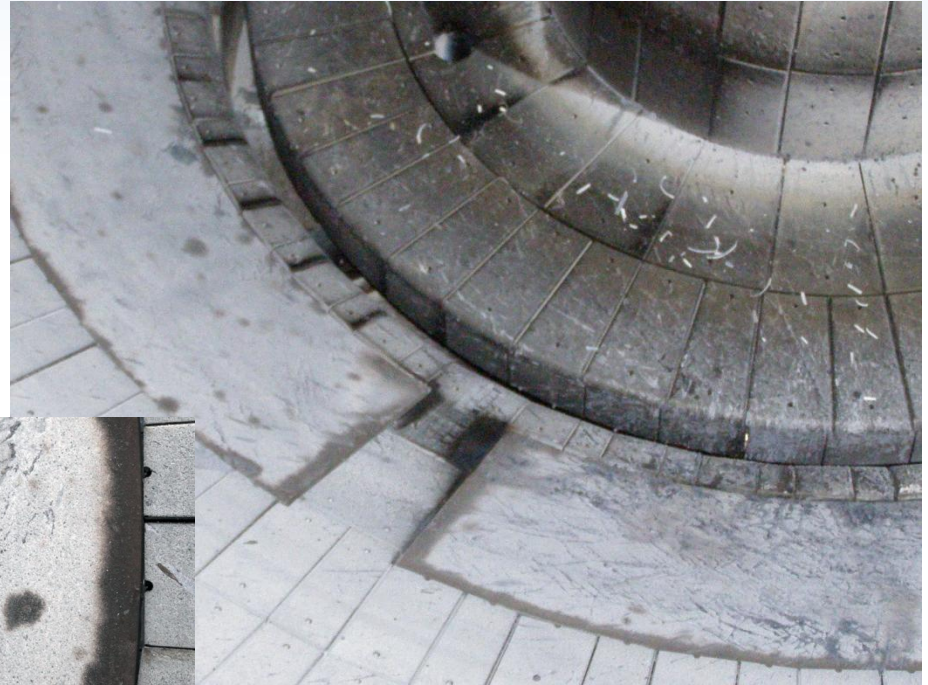
# TCs during long cooling of LLD section BK

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

