ZCO-71: *Galvanizing Bath Management for Advanced High Strength Steels*

Florin Ilinca and Kintak Raymond Yu
Automotive and Surface Transportation
National Research Council Canada

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Overview

- Project objectives
- Current status of the work on Task 1
- Current status of the work on Task 3
- Future work

Project tasks

- Task 1: Mn effects on galvanizing bath management
- Task 2: Effects of pre-oxidation pre-treatment cycles on galvanizing bath Fe management
- Task 3: Effects of strip entry temperature and galvanizing bath management on coating quality

Summary of previous progress report (June 2015) Task 1: Mn effects on galvanizing bath management

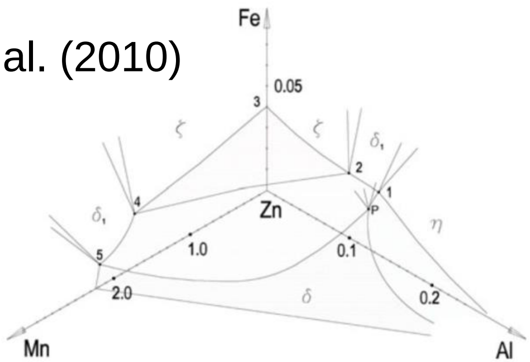
1. Galvanizing bath management for conventional steels
   - Bath maintained around 460ºC
   - Bath contains either 0.11 to 0.13% Al for galvannealing (GA) or 0.16 to 0.25% for galvanizing (GI)
2. High Mn bath management
   - Mn is the most important alloying element in AHSS
   - Most AHSS, such as TRIP (transformation Induced Plasticity), DP (Dual Phase) and CP (Complex Phase) steels contain Mn from 1.0 to 2.5 wt.%
   - TWIP (Twinning Induced Plasticity) steels contain up to 25% Mn

There is a need for models describing the solubility limit and formation of precipitates in the Zn rich corner of the Zn-Fe-Al-Mn diagram.

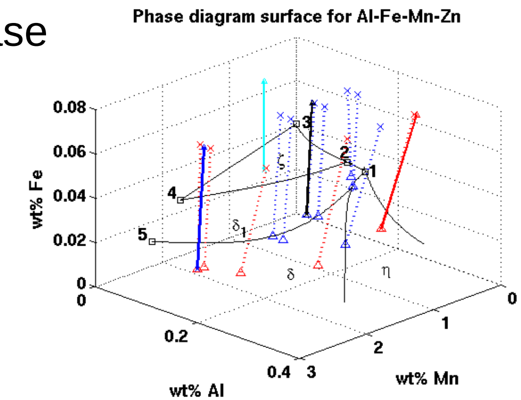
Summary of previous progress report (June 2015)
Task 1: Mn effects on galvanizing bath management

Searching routines were developed for the Zn rich corner of the Zn-Fe-Al-Mn system.

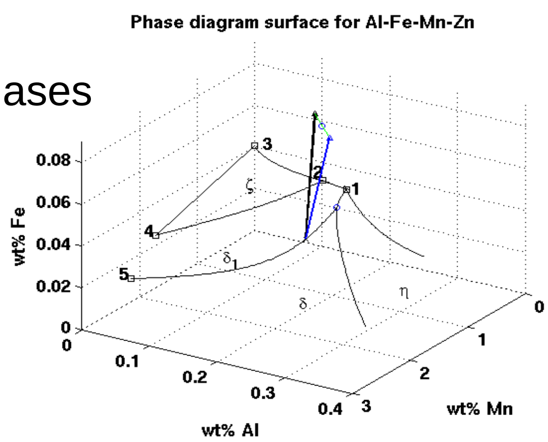
Gao et al. (2010)



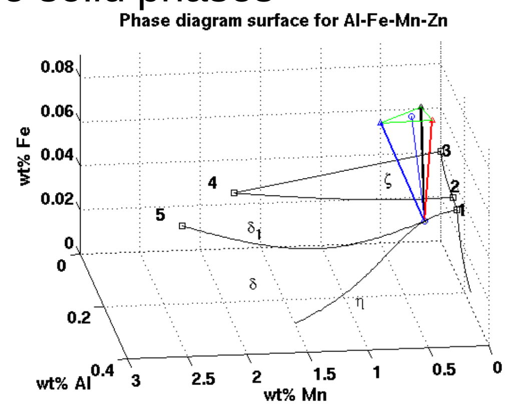
(1) Single phase



(2) Two solid phases



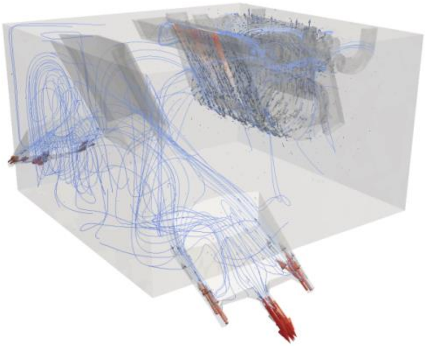
(3) Three solid phases



N. Gao, Y. H. Liu, and N.-Y. Tang, "An experimental study of the liquid domain of the Zn-Fe-Al-Mn quaternary system at 460 °C," J. Phase Equilibria Diffus., vol. 31, no. 6, pp. 523–531, 2010.

New progress report (October 2015)
Task 1: Mn effects on galvanizing bath management

Experimental data for the Zn-Fe-Al-Mn system is very scarce and the study has to be based on assumptions



Data is very limited:

1. For Zn-Fe-Al-Mn system at a temperature other than 460ºC
2. For Mn dissolution rate of the AHSS steel

Assumption:

1. The Mn dissolution rate is considered as:

Mn dissolution rate = Fe dissolution rate × Relative Mn content in the strip

For example, the relative Mn content for a $20\%wt\ Mn_{steel}$ *will be :*

$$\frac{[Mn]_{steel}}{[Fe]_{steel}} \approx \frac{\%wt\ Mn_{steel}}{100 - \%wt\ Mn_{steel}} = \frac{20}{100-20} = 25\%$$

Special thanks to Daniel Liu (Tech Metals Ltd.) for providing feedback on Mn dissolution dynamics

2. The same assumption is made for the initial condition for the bath concentration.

For example, if the $[Fe]_{bath}$ *is at the knee point, the* $[Mn]_{bath}$ *for a 20%wt Mn steel will be:*

$$[Mn]_{bath} = [\mathrm{Fe}]_{bath} \times 25\% \approx 0.0277\%wt \times 25\% = \mathbf{0.0069\%wt}$$

Task 1: Mn effects on galvanizing bath management

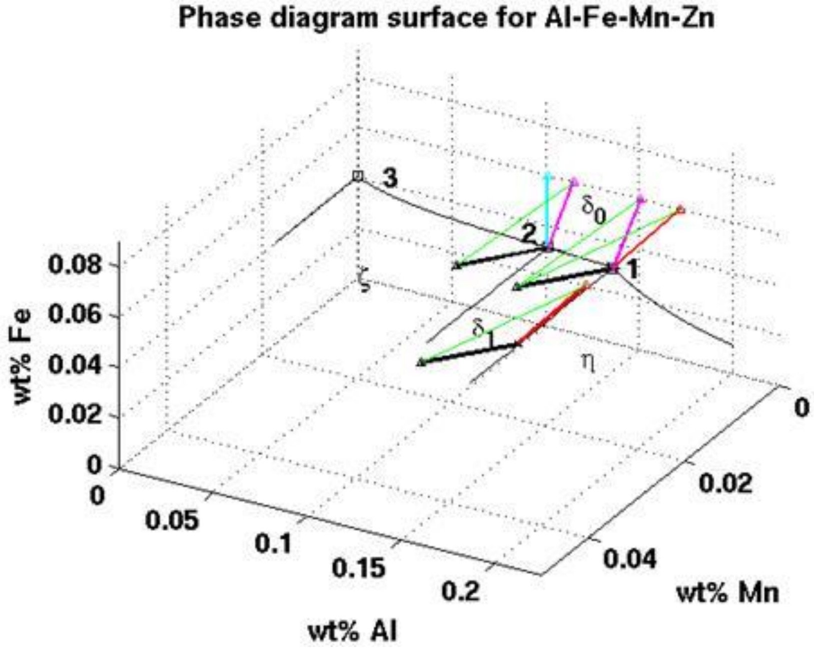
The very low Mn concentration allows some further simplifications.

1. Search regions **involve 3 solid phases**:
   a) The η-phase (Fe2Al5)
   b) The δ_1-phase (Fe(Mn)Zn10)
   c) The δ_0-phase (FeZn10)

2. The knee point boundary line between the η-phase and the δ_1-phase can be well approximated using a simple **straight** line.

3. If we assume further that such approximation is valid for the **near-by temperature**, one can use the **well known Zn-Fe-Al system** for the present studies.

4. Based on continuity of the Zn-Fe-Al ternary system we may still have single phase, two-phase and three-phase regions.



Note:

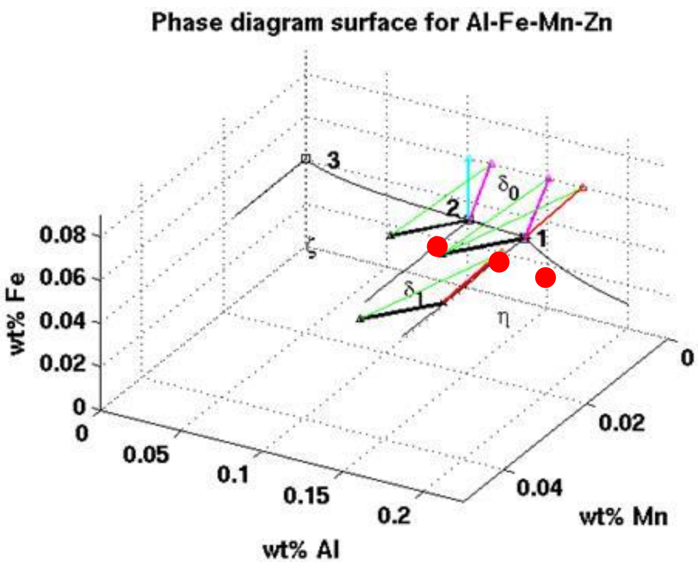
*At higher [Mn], the knee point is expected to be shifted to higher [Al] with a lower Fe solubility limit. (Personal communication with **Daniel Liu from Tech Metals Ltd**.)*

NRC·CNRC

Task 1: Mn effects on galvanizing bath management

The presence of the Mn can greatly increase the dross generation rate.

Bath Avg. Dross (460°C)		0.12%wtAl		0.14%wt Al		0.16%wt Al	
%wt Mn steel	%wt Mn bath	Kg	%wt	kg	%wt	kg	%wt
0.0	0.0	**21.83**	9.00E-03	4.11	1.69E-03	4.47	1.84E-03
2.0	5.5E-04	39.23	1.62E-02	4.11	1.69E-03	4.47	1.84E-03
10.7	3.3E-03	**46.80**	1.93E-02	4.11	1.69E-03	4.47	1.84E-03
18.0	6.1E-03	**46.81**	1.93E-02	4.11	1.69E-03	4.47	1.84E-03



Gao et al. (2010) observed and confirmed that Mn dissolves in various solid phases differently:

- Mn is not very soluble in the η-phase.

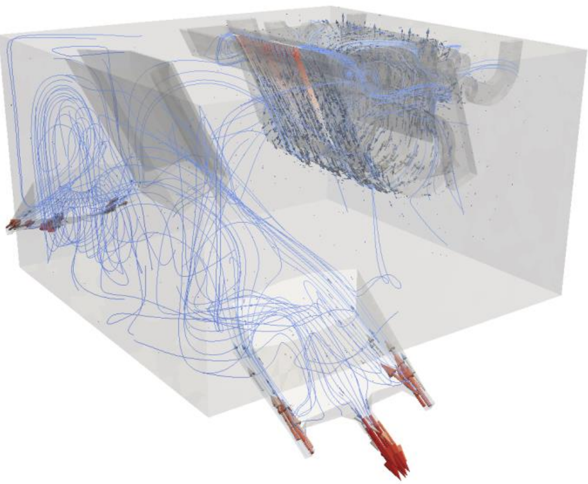
  $\Rightarrow$ The galvanizing (GI) process is essentially not affected.

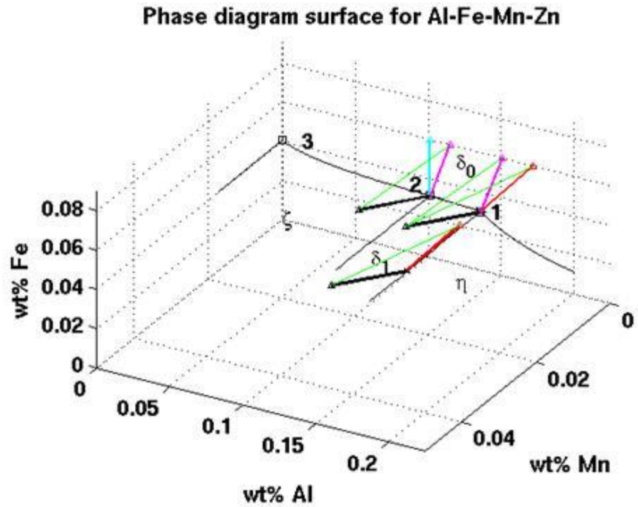
- But, it can substitute up to as high as 75% of Fe in the δ_1-phase

  $\Rightarrow$ Much more dross can be generated for the galvannealing (GA) process.

N. Gao, Y. H. Liu, and N.-Y. Tang, J. Phase Equilibria Diffus., vol. 31, no. 6, pp. 523–531, 2010.

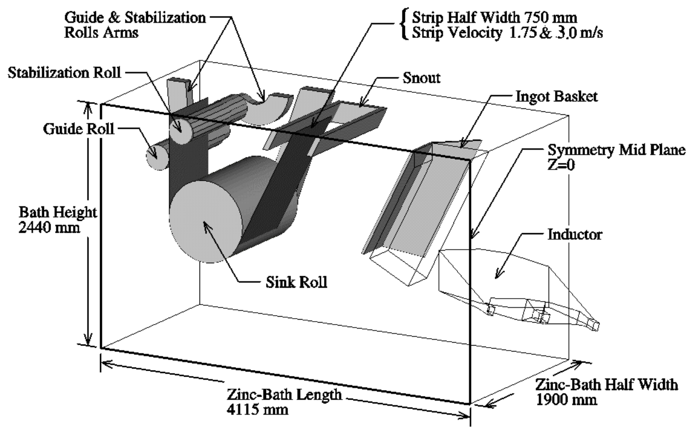
Task 1: Summary

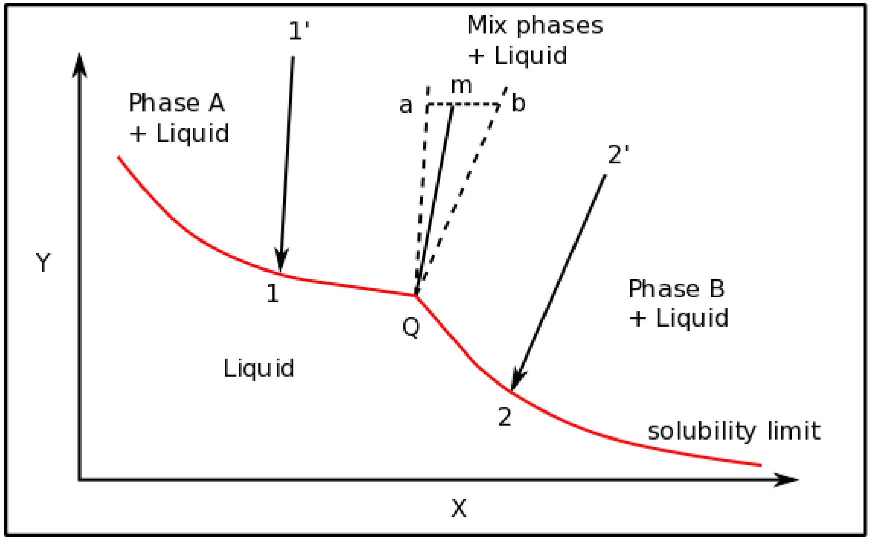




- Effects of the Mn for dross production is evaluated based on assumed Mn dissolution rate.
- Impact of dross formation depends on the type of dross that can be formed.
- For the δ-phase, the dross generation can become nearly double due to the substitution of Fe by the Mn in the δ-phase.

Summary of previous progress report (June 2015)
Task 3: Effect of strip entry temperature





AHSS may have very different strip entry temperature T_{strip}

> **Effect on dross generation needs to be studied**

NRC·CNRC

Summary of previous progress report (June 2015)
Task 3: Effect of strip entry temperature

- Numerical studies: T_{strip}={420, 440, **460**, 480, 500ºC} for conventional steel

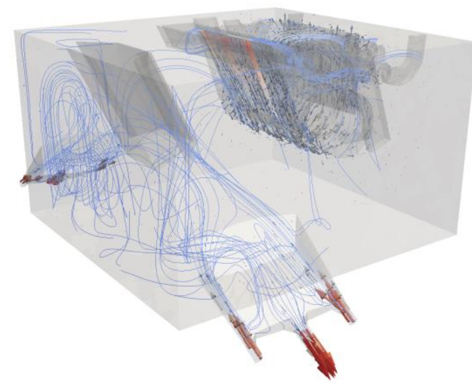
T_{strip} has influence on

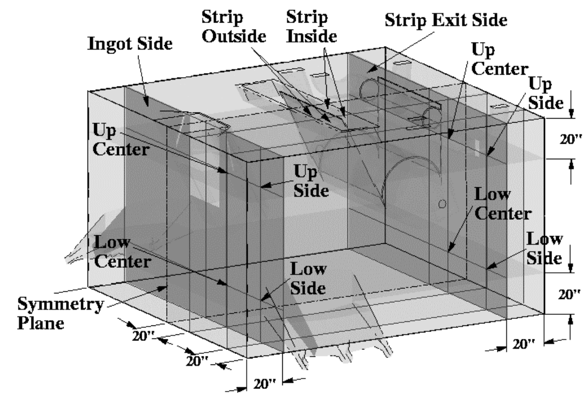
⇒ Global heat balance: Inductors power setting should be adjusted accordingly

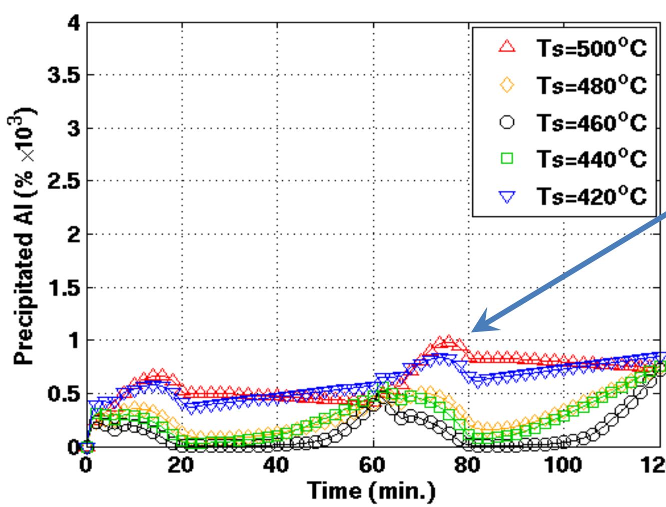
⇒ Temperature distribution in the bath: significant impact in the snout, above the sink roll and in the inductors side

⇒ Rate and location of dross formation

To minimize dross formation, must carefully consider location and settings of inductors or other means of controlling temperature distribution







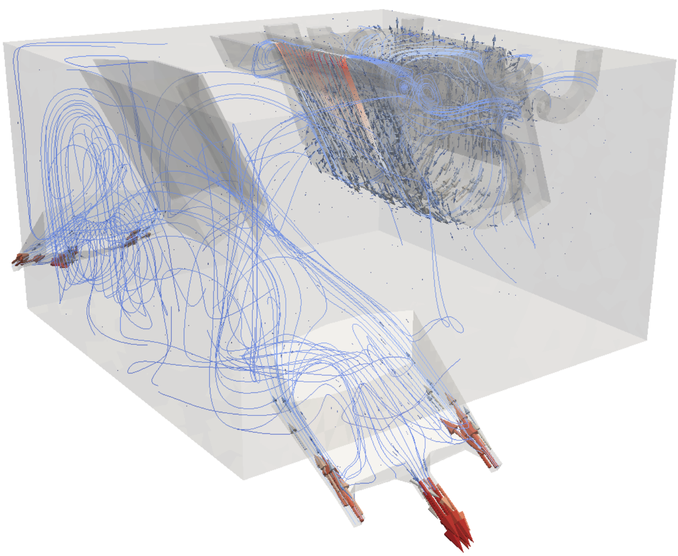
Dross generation mainly during ingot melting for T_{strip}=420ºC and 500ºC

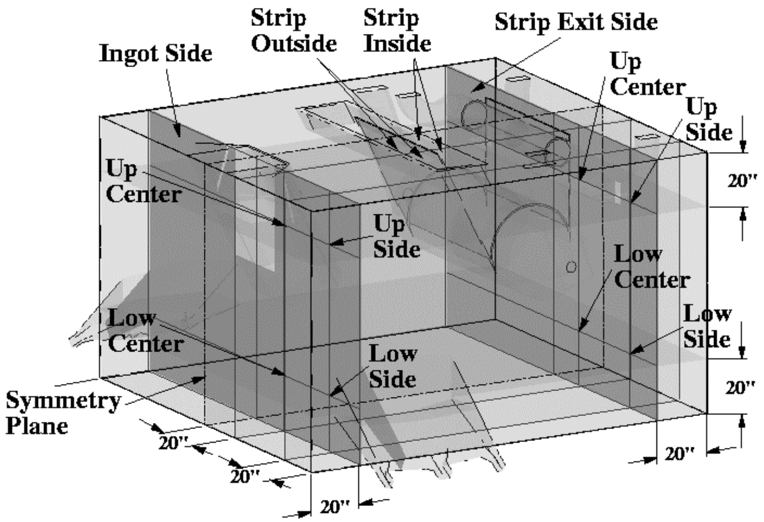
Dross generation during the period without ingot melting for T_{strip}=440ºC and 480ºC

New progress report (October 2015)
Task 3: Effect of strip entry temperature

Current investigation

- Validation of heat and mass transfer on the Sorevco bath
- Analysis of the local heat transfer between the steel strip and the bath
- Effect of strip entry temperature for gradual ingot loading

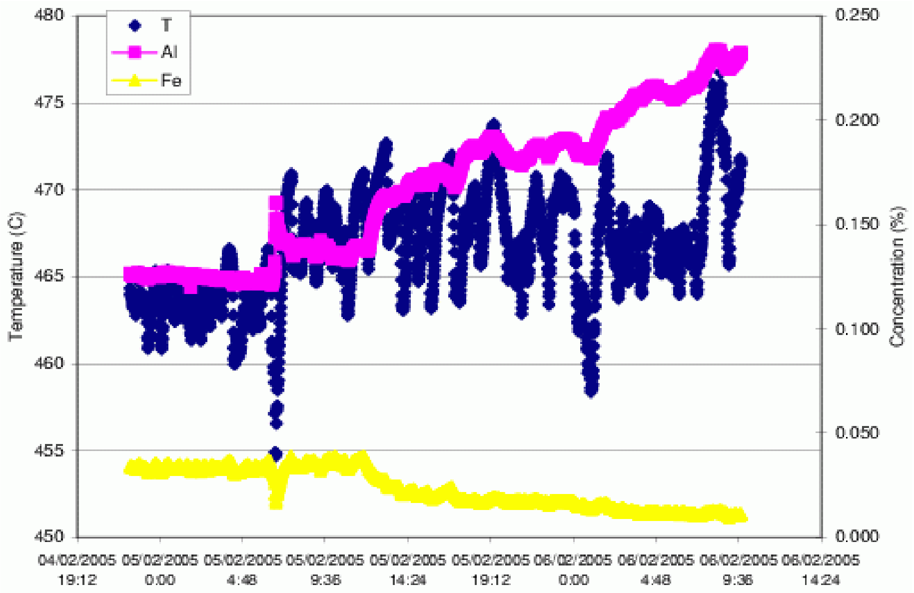


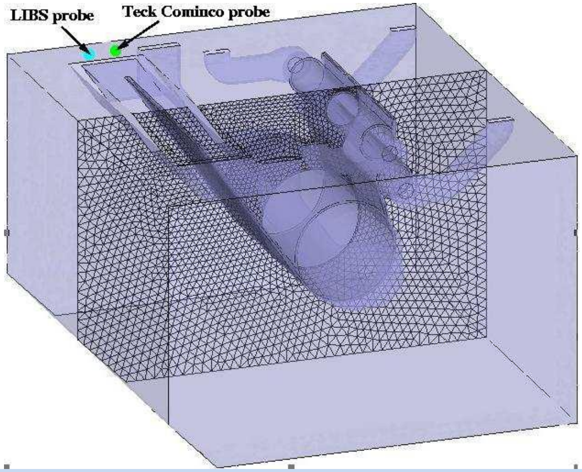


Validation of the heat and mass (Al, Fe) transfer model on the Sorevco bath

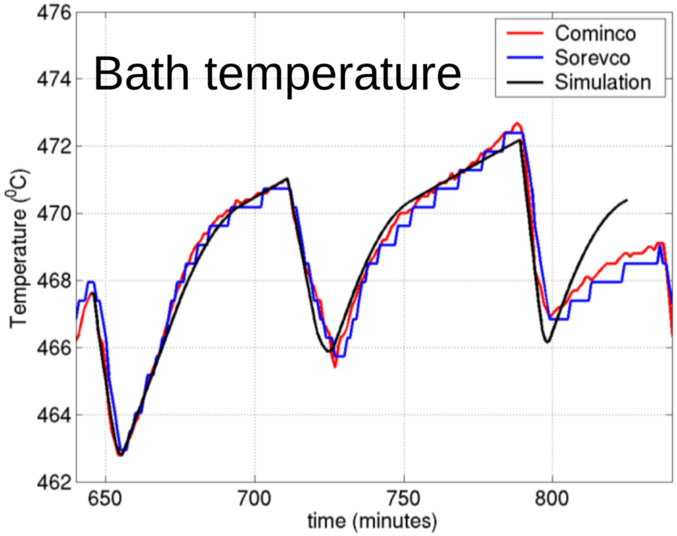
Test conditions:

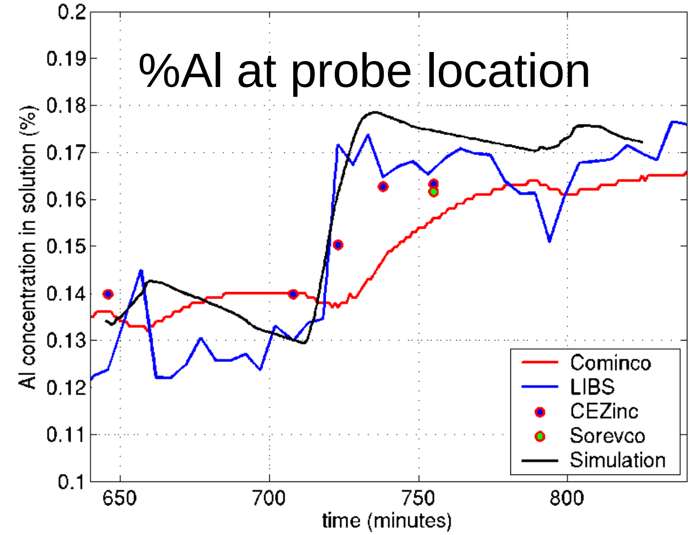
- GA (0.125%Al) to GI (0.215%Al) transition
- Melting ingots have 1%Al (white) or 4.5%Al (blue)
- The mean bath temperature is 470ºC
- Strip enters the bath at 495ºC

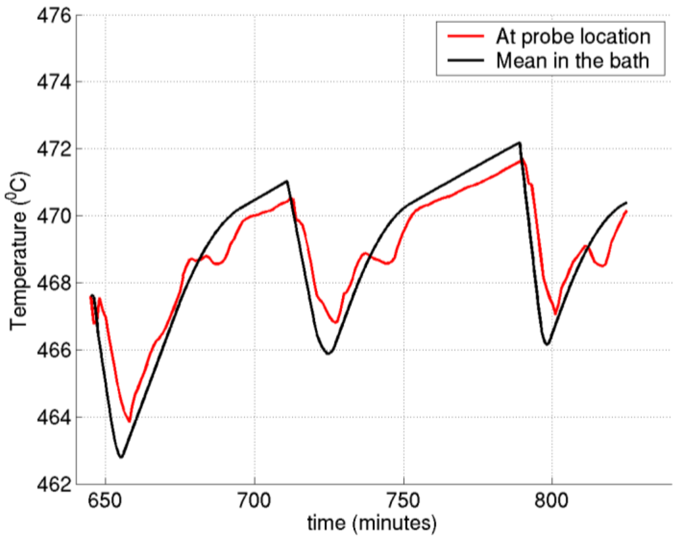


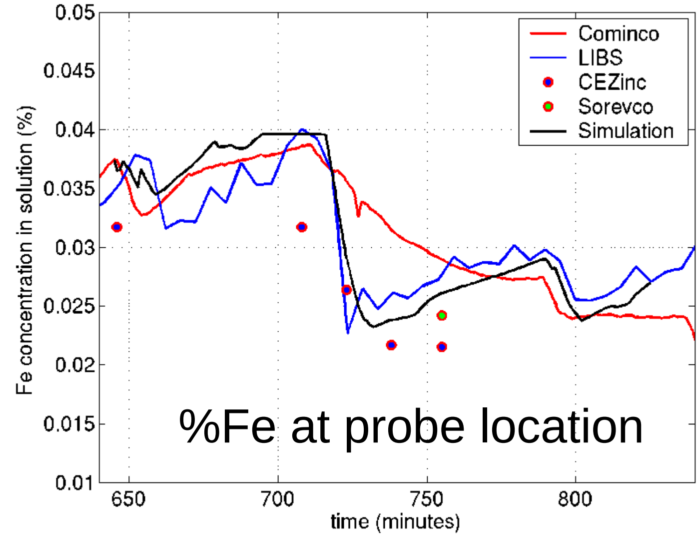


Validation of the heat and mass (Al, Fe) transfer model on the Sorevco bath





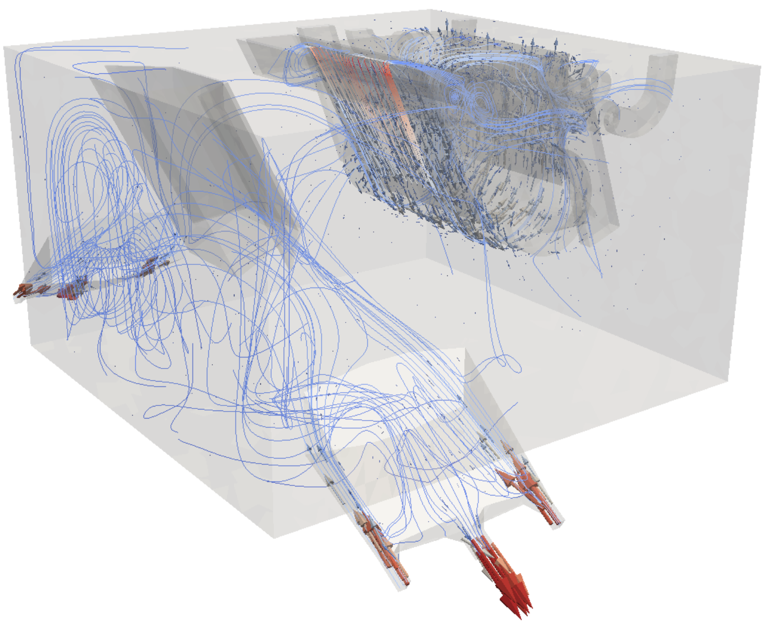




NRC·CNRC

The details of the heat transfer phenomenon at the strip entry area is highly complex.

- Validation of heat and mass transfer on the Sorevco bath
- **Heat transfer model of steel strip**
- Effect of strip entry temperature for gradual ingot loading



Factors for the strip heat transfer:

- Local flow characteristics (large local velocity gradient)
- Different flow dynamics on the external/internal sides of the strip
- Presence of free surface affecting flow and heat transfer

The overall impact of the strip heat transfer can be well approximated if the heat transfer rate is known.

- Heat transfer of the strip should be determined by convection and conduction
- Convection + Conduction **>** Conduction only

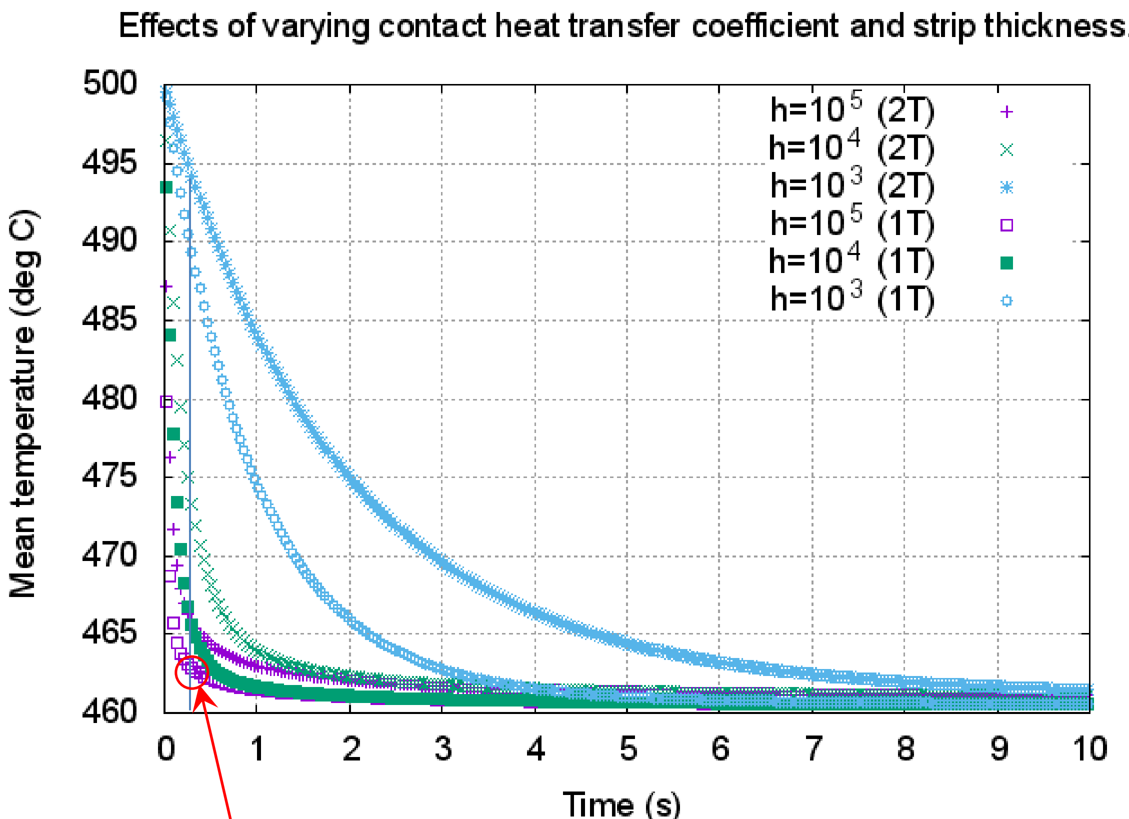
The heat transfer rate of conduction problem provides the **lower (slower) bound** of the heat transfer rate.

NRC·CNRC

The rate of heat transfer is quite fast, even though only the conduction heat transfer is considered.

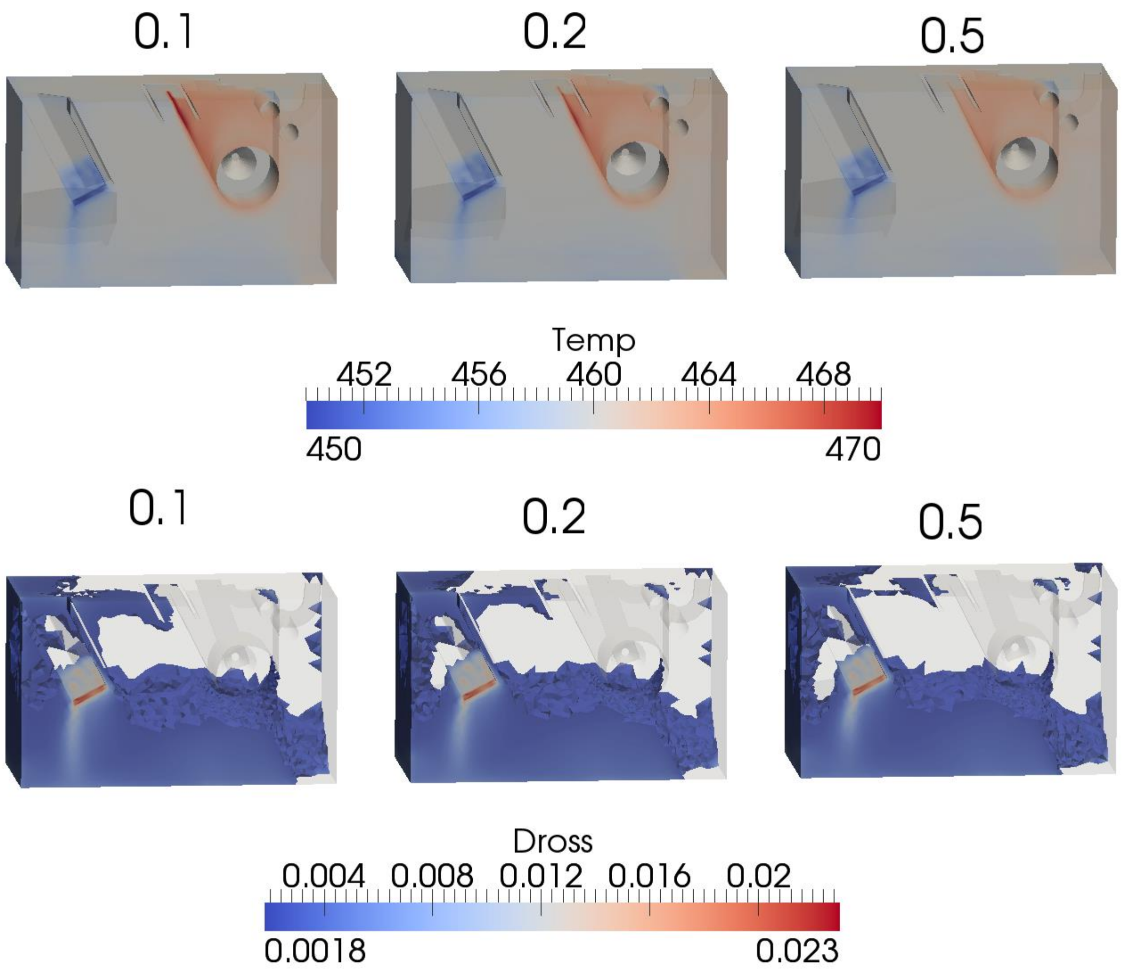
Parameters varied:

- Strip thickness.
- Contact effectiveness.



Generally, the 0.5mm strip reaches the mean bath temperature within **0.2 second**.

A “heat lost time” of 0.2 sec is considered which provides a realistic heat transfer condition

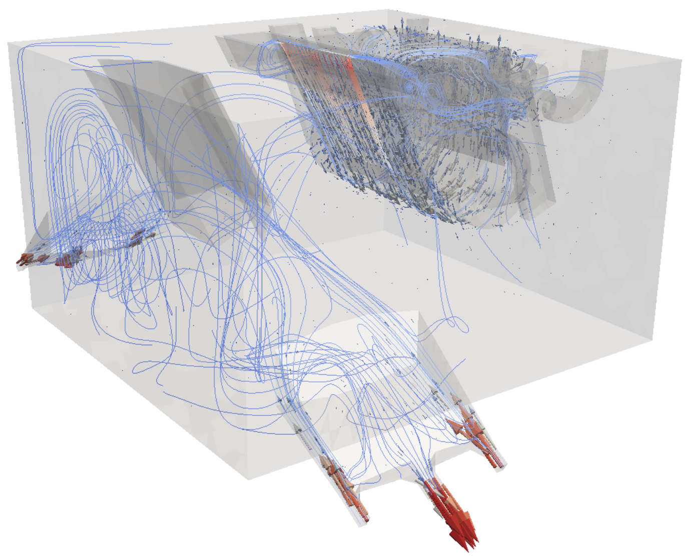


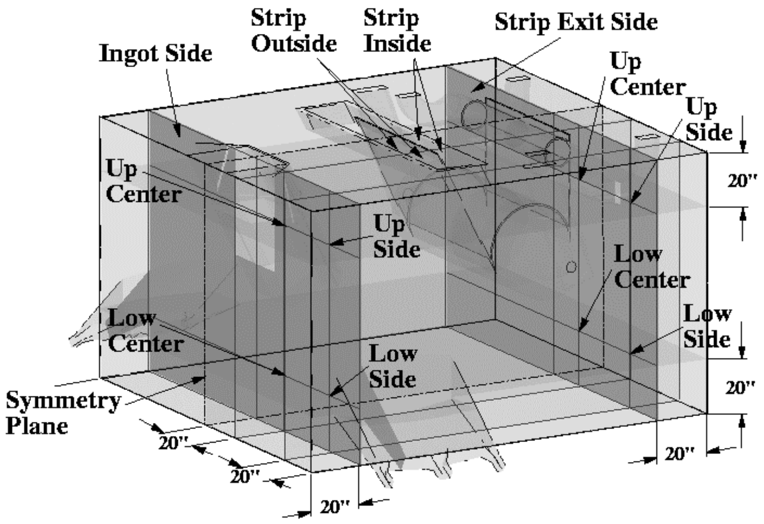
- A shorter time results in a hotter temperature on bath top surface; especially above the sink roll.
- All three cases have almost the same overall dross generation pattern.
- 0.2s provides a realistic dross production case around the strip area.

$$1.75m/s \times 0.2s = 0.35m$$

Task 3: Effect of strip entry temperature

- Validation of heat and mass transfer on the Sorevco bath
- Heat transfer model of steel strip
- **Effect of strip entry temperature for gradual ingot loading**



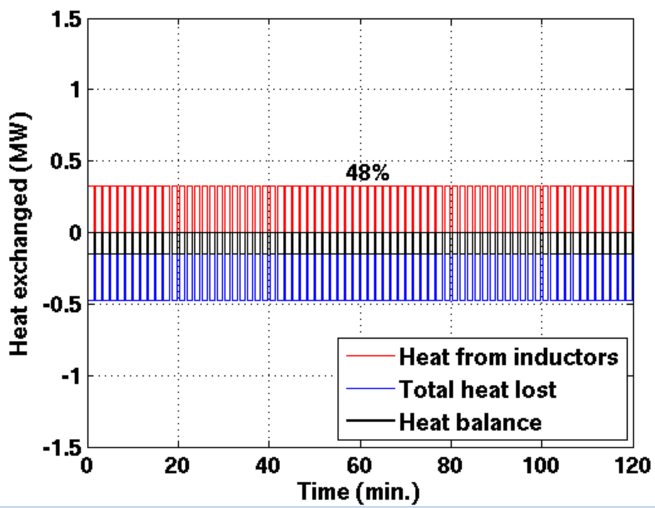


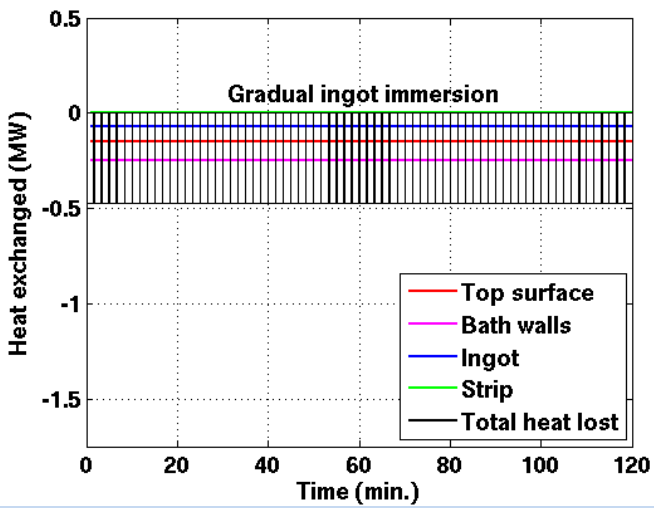
NRC·CNRC

The gradual ingot loading cases require comparable total energy as those of the periodic loading ones

The operation of the inductors is adjusted to have the mean bath temperature maintained.

	Gradual			Periodic (Equivalent)		
T_{strip} (°C)	Flow rate	$T_{increase}$ (°C)	Power	$Power_{melt}$	$Power_{no-melt}$	$Power_{eq}$
420	100%	+15.6	78%	100%	67%	78%
440	100%	+12.5	63%	100%	44%	63%
460	100%	+9.5	48%	100%	22%	48%
480	100%	+6.4	32%	64%	18%	33%
500 (a)	100%	+3.5	18%	35%	11%	19%
500 (b)	40%	+8.7	18%	35%	11%	19%

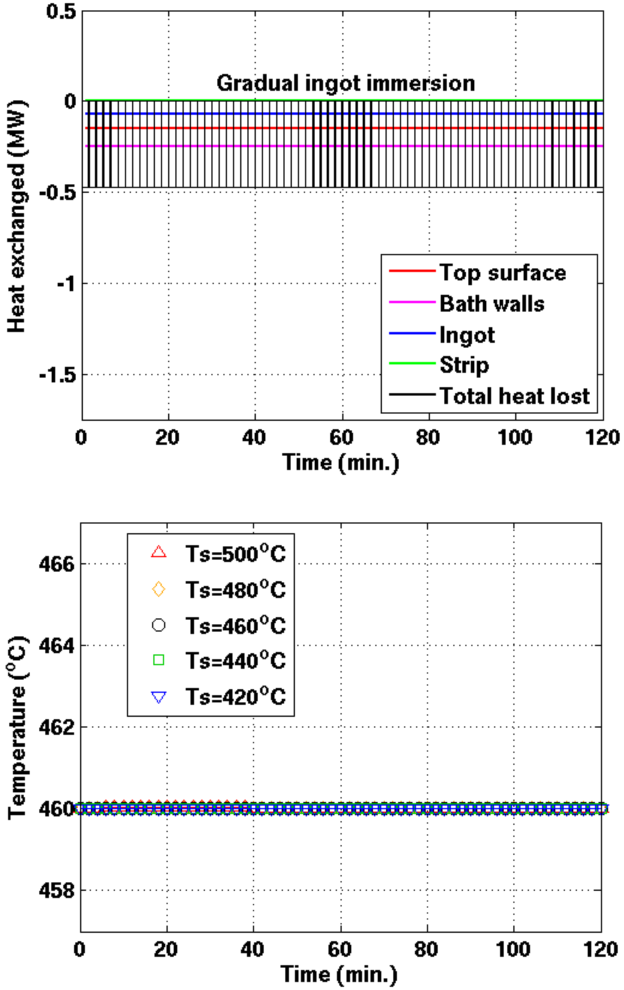




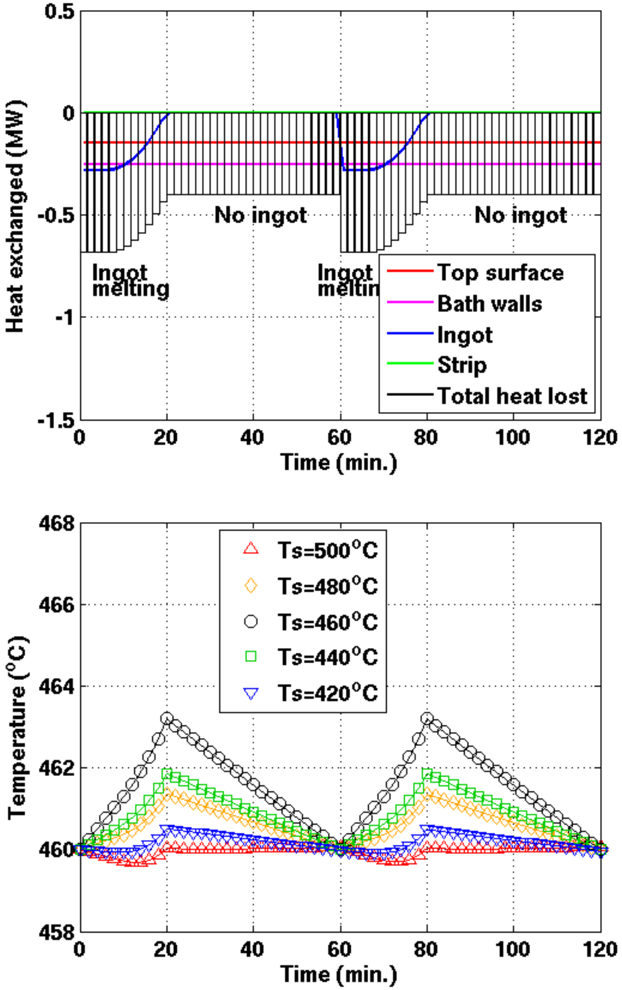
NRC·CNRC

The power consumption of the gradual ingot loading are very even for ingot melting and there is no over heating

Gradual



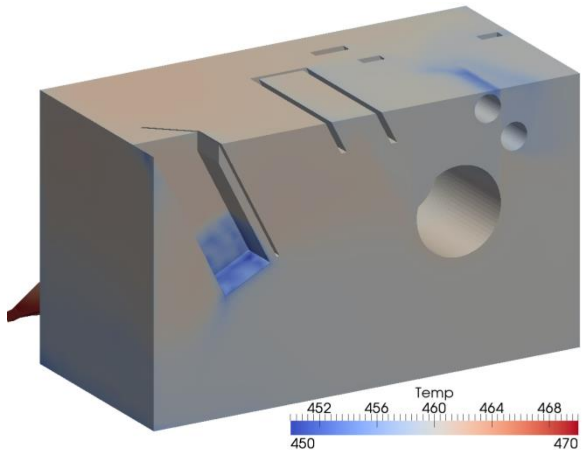
Periodic



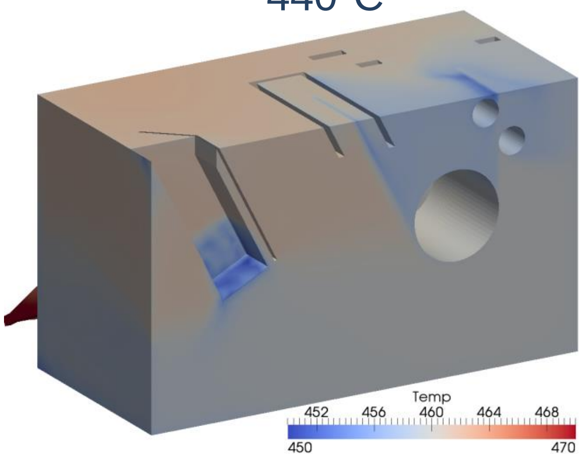
The temperature distributions are characterized by those at the ingot loading and the strip entry areas

At 120 mins

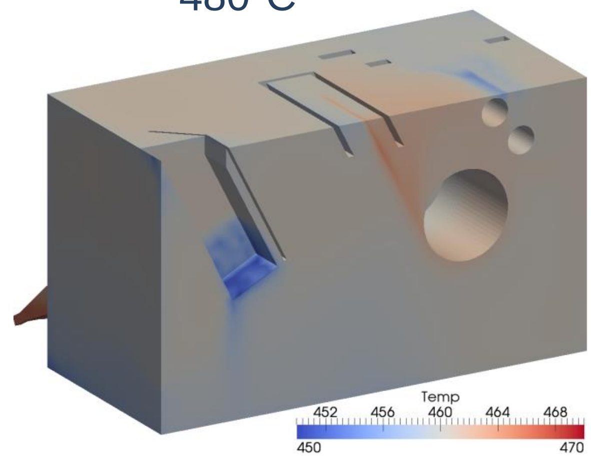
460^{o}C



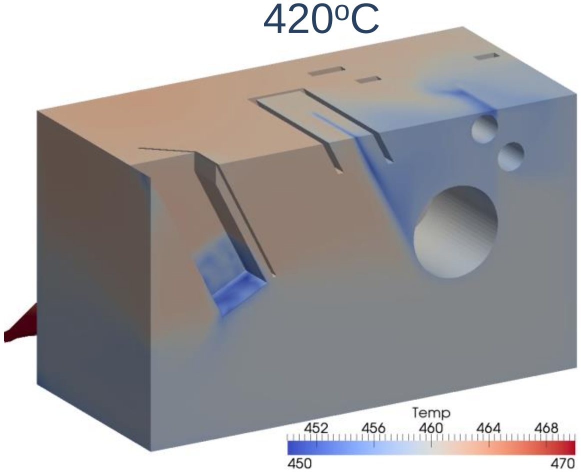
440^{o}C



480^{o}C

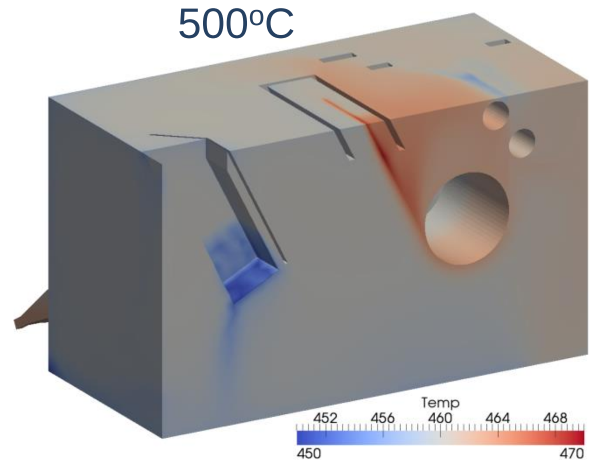


420^{o}C



Temperature scale
(450^{o}C – 470^{o}C)

500^{o}C

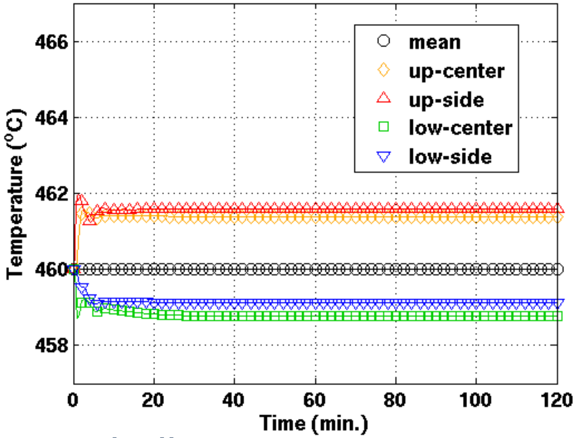


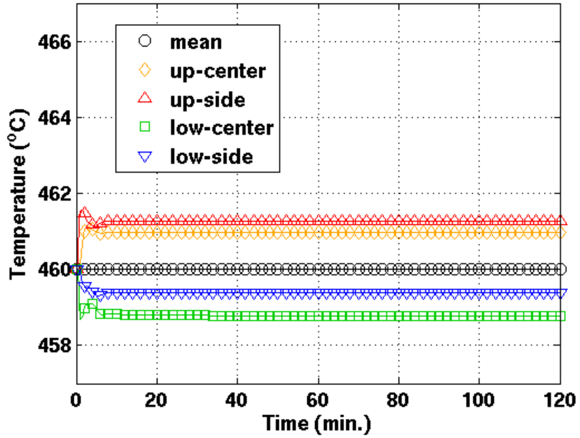
Temperature profiles in the ingot loading side

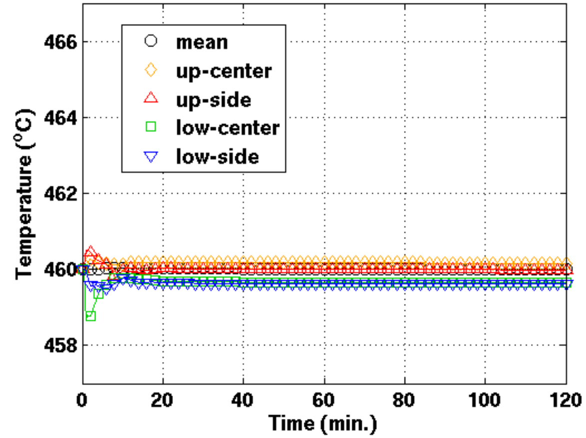
Ingot side

440ºC | 460ºC | 500ºC

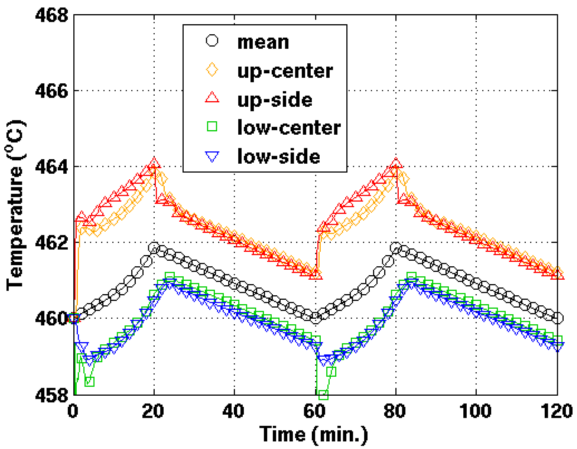
Gradual

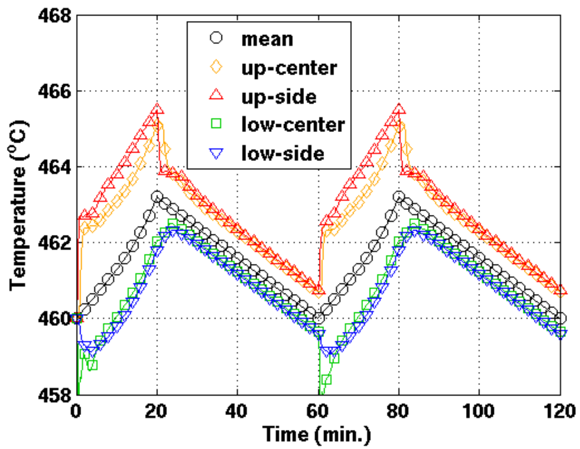


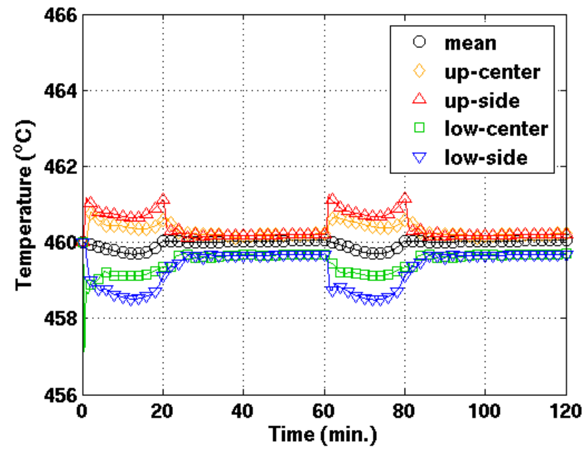




Periodic







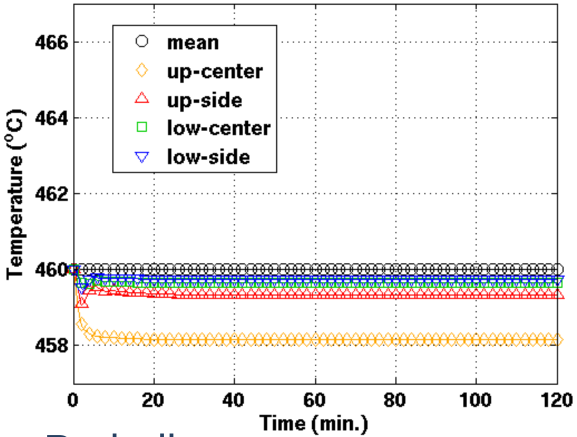
NRC·CNRC

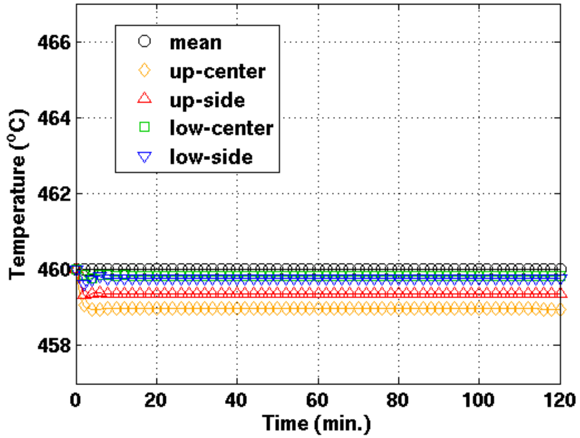
Temperature profiles in the strip exit side

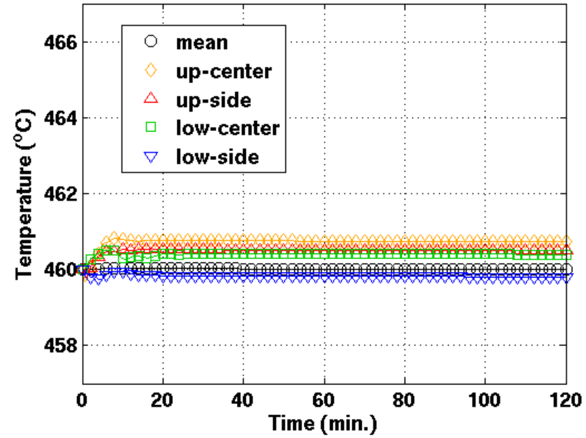
Strip exit

440ºC | 460ºC | 500ºC

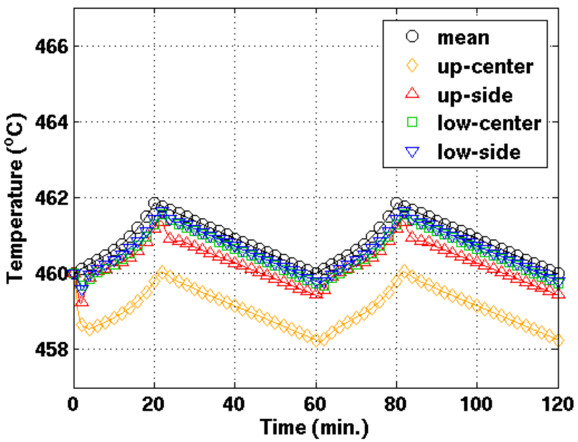
Gradual

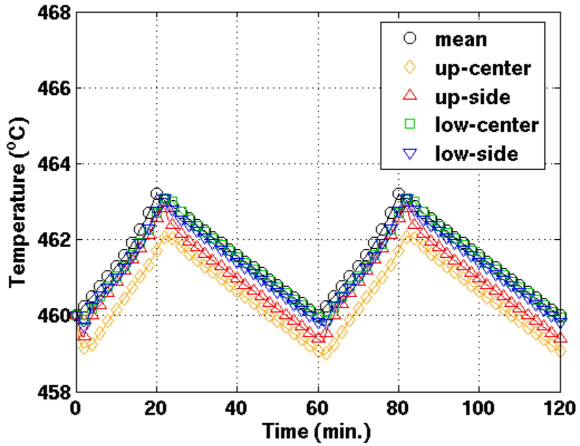


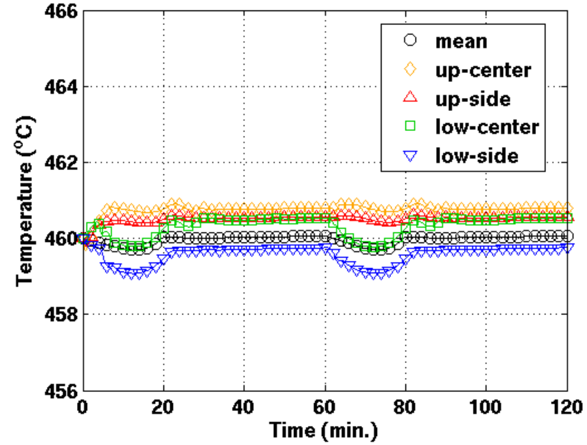




Periodic







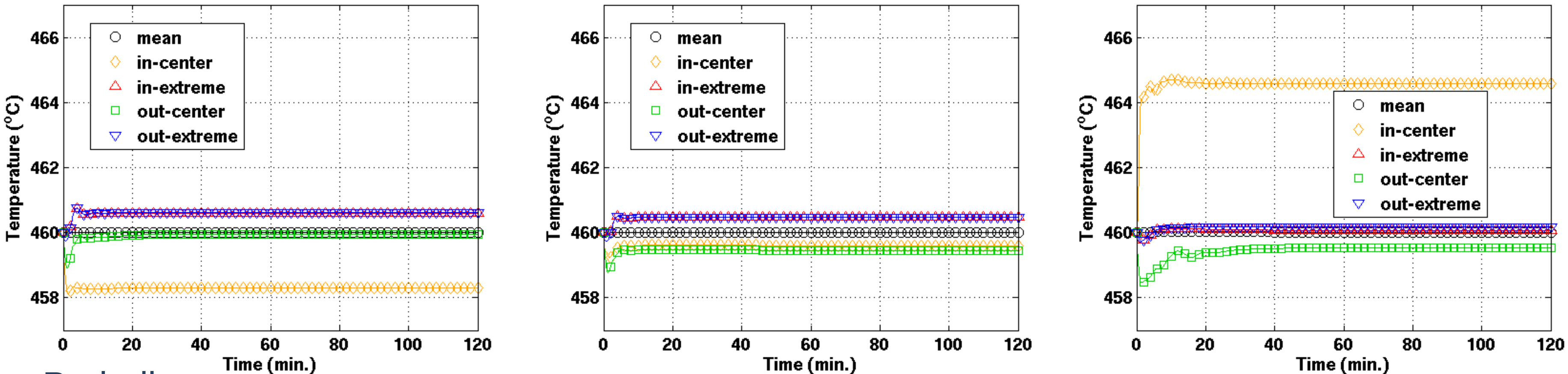
NRC·CNRC

Temperature profiles in the snout region

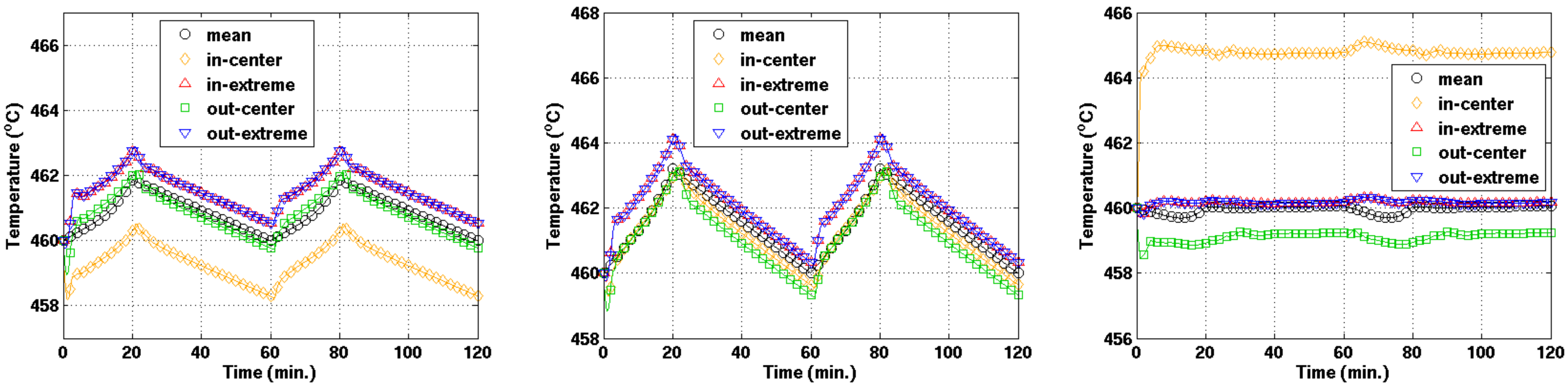
Snout region

440^oC 460^oC 500^oC

Gradual



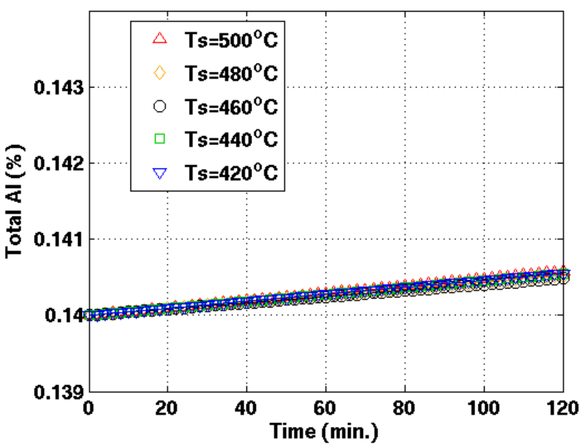
Periodic

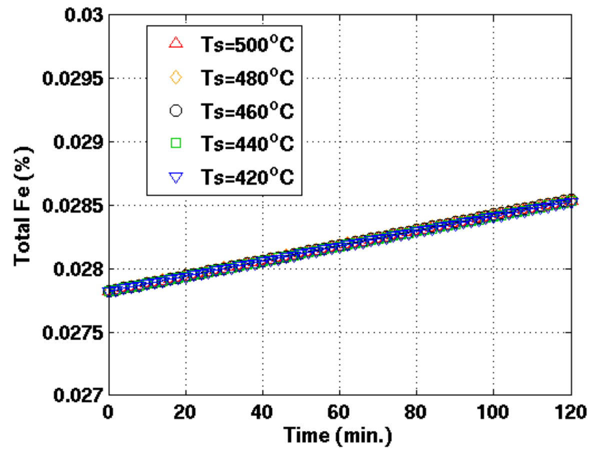


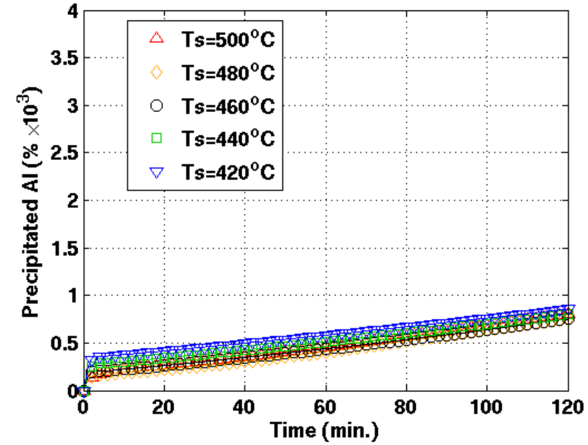
NRC·CNRC

The gradual loading cases of all strip temperatures produce dross at constant rates

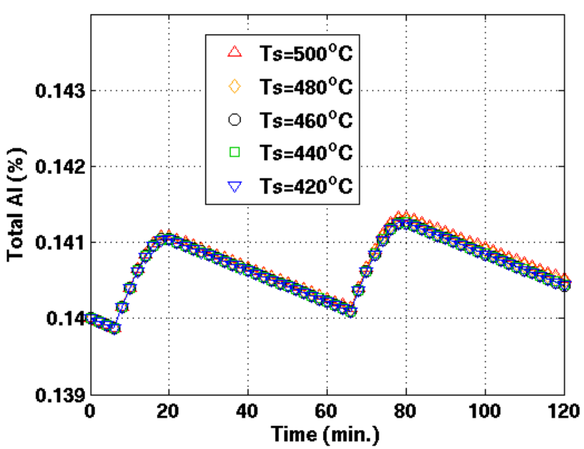
Gradual

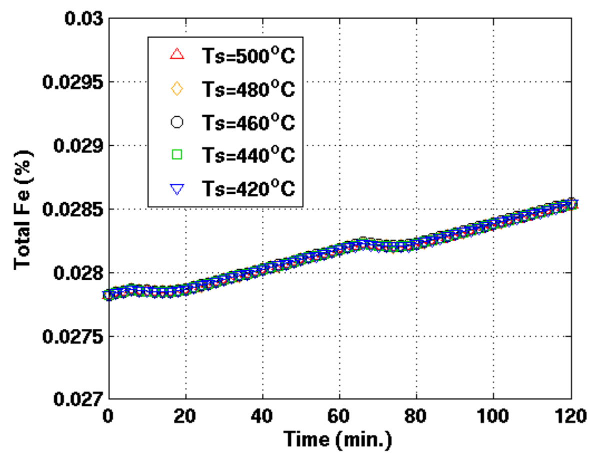


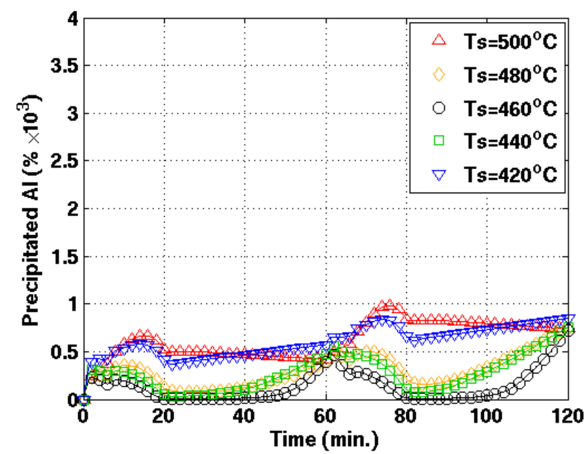




Periodic



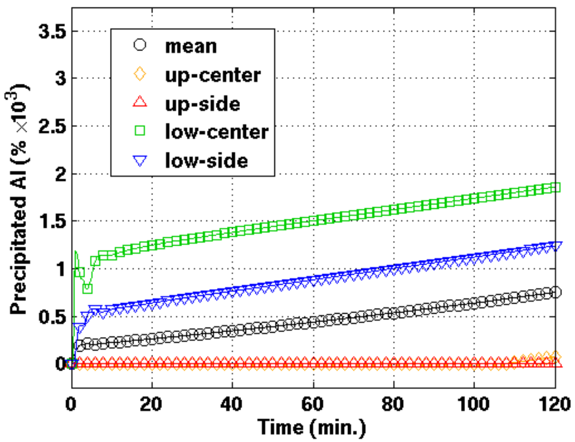




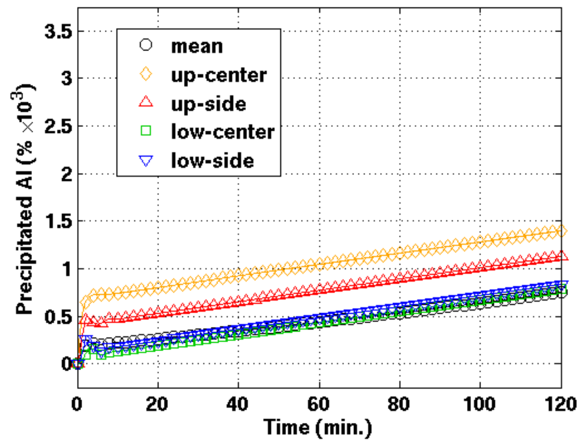
There are differences in dross distribution after 120 min between gradual and periodic ingot loading

Gradual 460°C

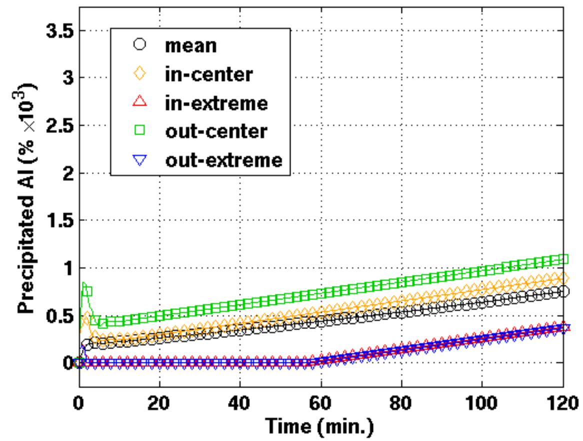
Ingot side



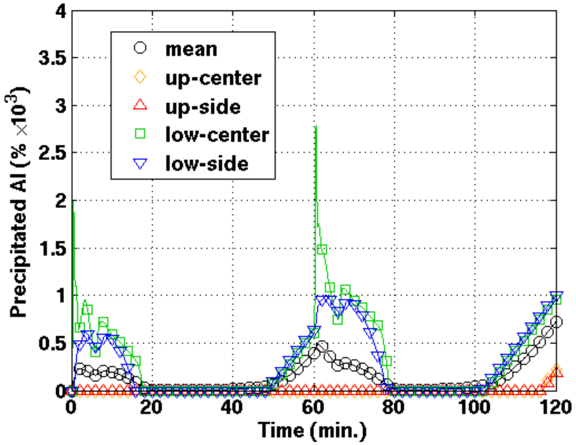
Strip exit

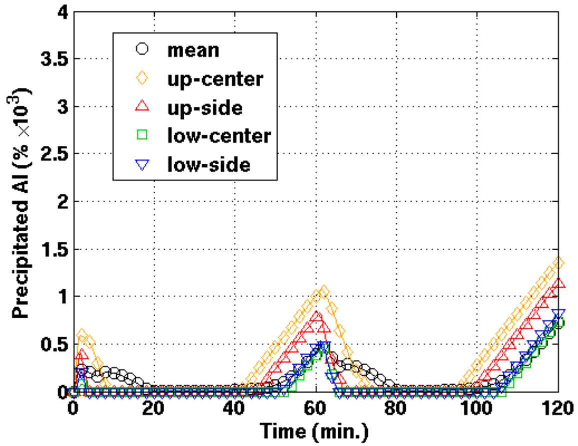


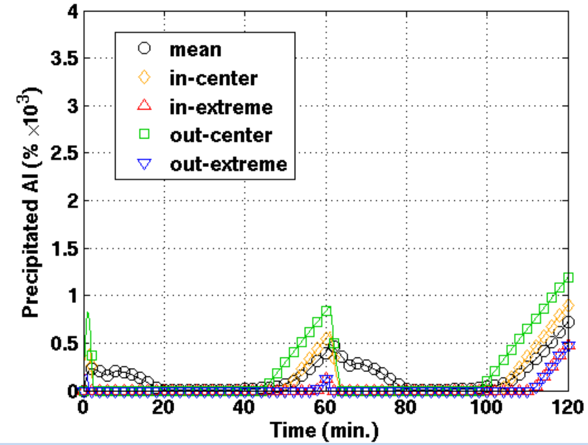
Snout region



Periodic 460°C



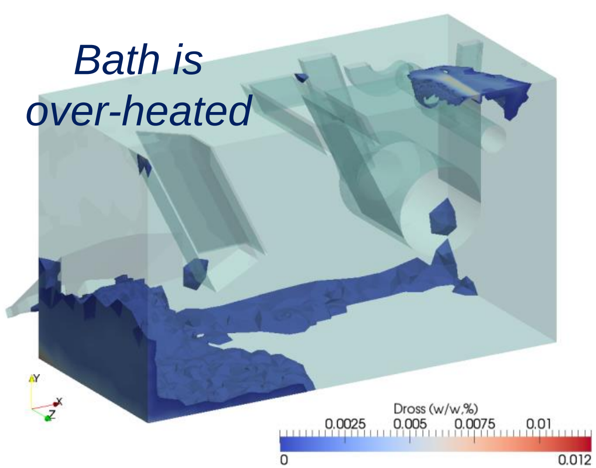




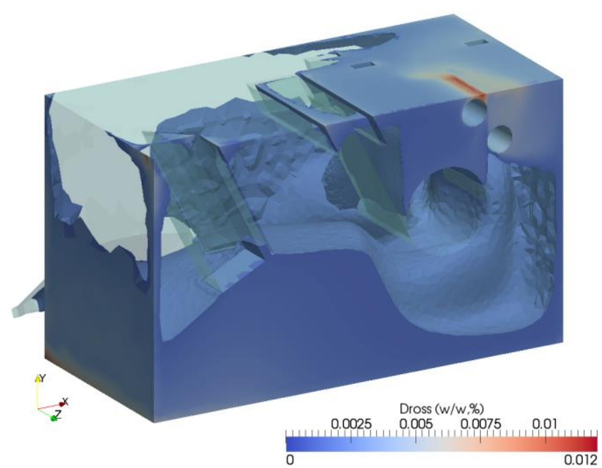
The dross formation history is very different for gradual and periodic ingot melting

Bath Avg. Dross	Periodic (80 mins)		Periodic (120 mins)		Gradual (120mins)	
T_{strip} (°C)	kg	%wt	kg	%wt	kg	%wt
420	1.56	6.44e-4	4.75	1.96e-3	4.66	1.92e-3
440	0.61	2.52e-4	4.25	1.75e-3	4.34	1.79e-3
460	0.09	3.91e-5	4.03	1.66e-3	4.11	1.69e-3
480	1.18	4.86e-4	4.11	1.69e-3	4.04	1.67e-3
500 (a)	4.62	1.90e-3	4.02	1.66e-3	4.25	1.75e-3
500 (b)	4.62	1.90e-3	4.02	1.66e-3	4.31	1.78e-3

Periodic

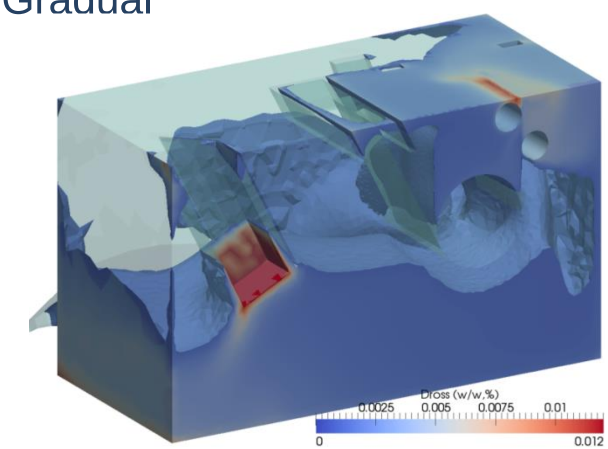


460°C @ 80 mins



460°C @ 120 mins

Gradual

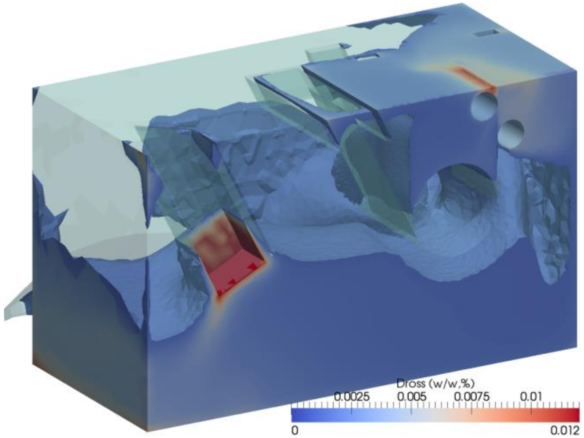


460°C @ 120 mins

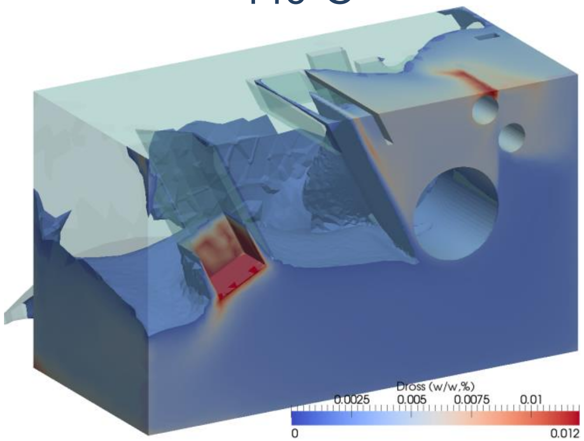
Regions with higher dross generation rates are the areas with lower bath temperatures.

<u>**120 mins**</u>

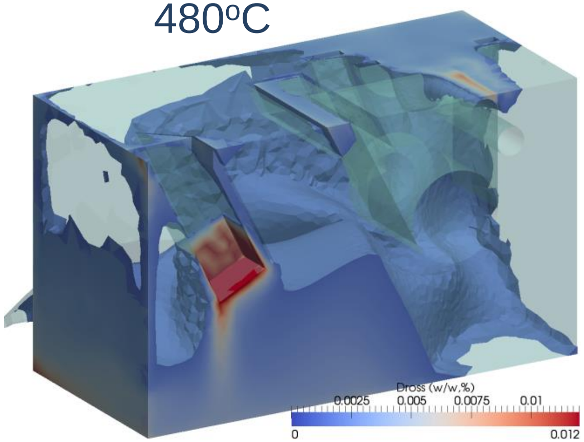
460ºC



440ºC

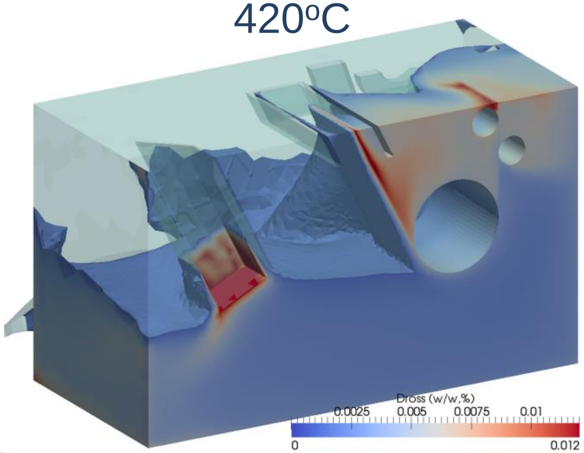


480ºC

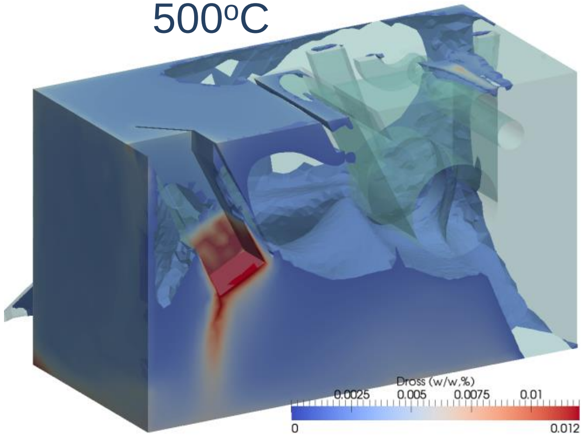


Dross scale
(0 – 0.012) %wt

420ºC



500ºC

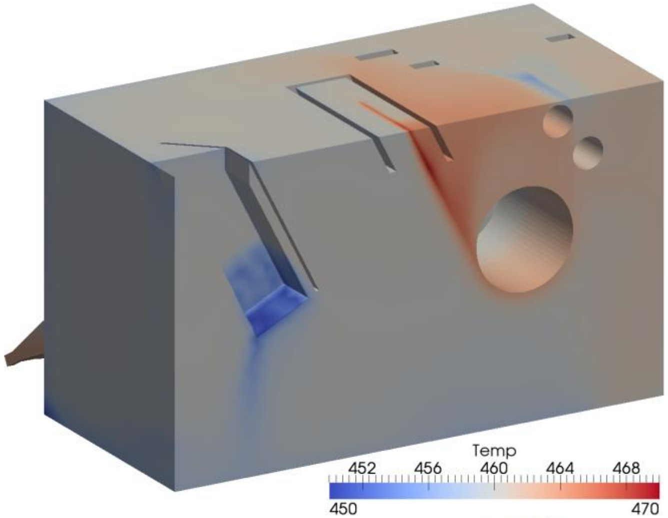


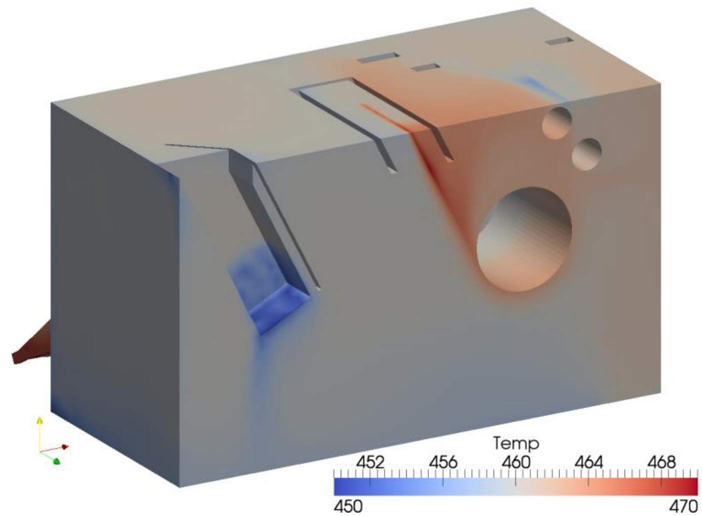
Differences in inductors operating conditions for 500ºC strip entry temperature

500ºC (a): 100% Vel, 3.5ºC

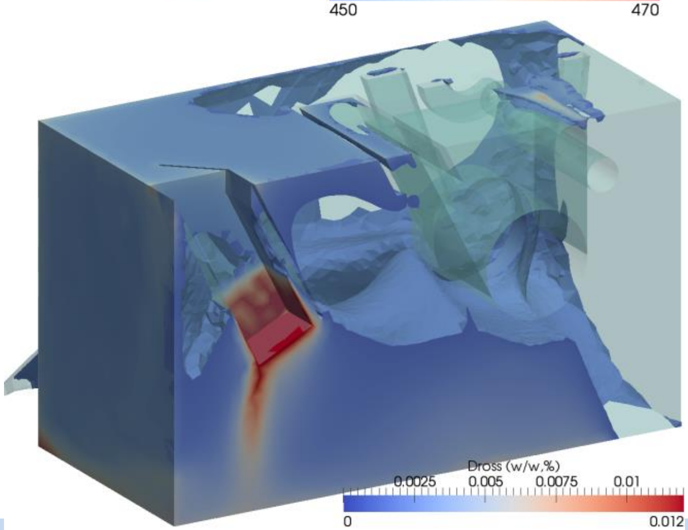
<u>120 mins</u>

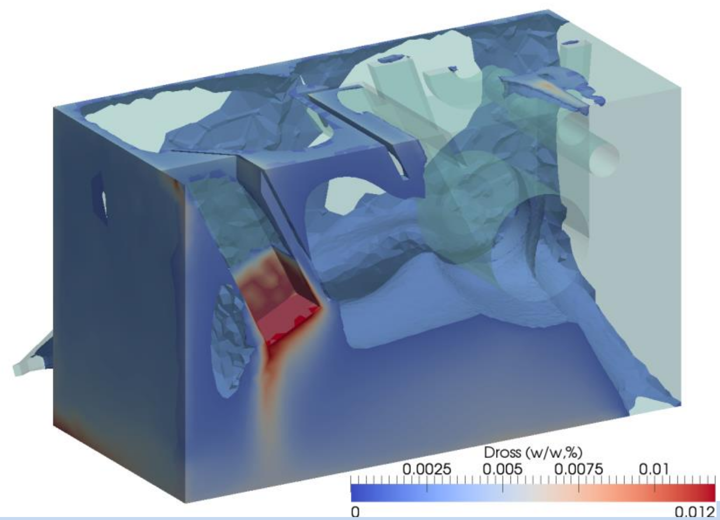
500ºC (b): 40% Vel, 8.7ºC





Temperature scale
(450ºC – 470ºC)

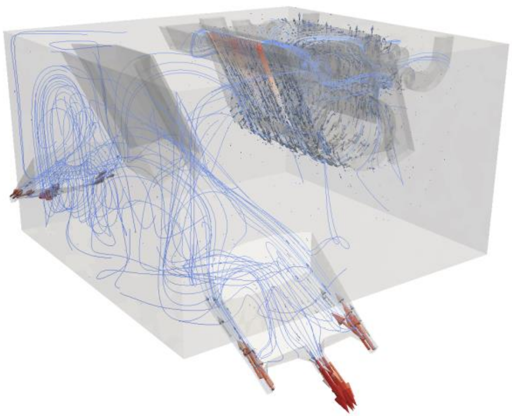


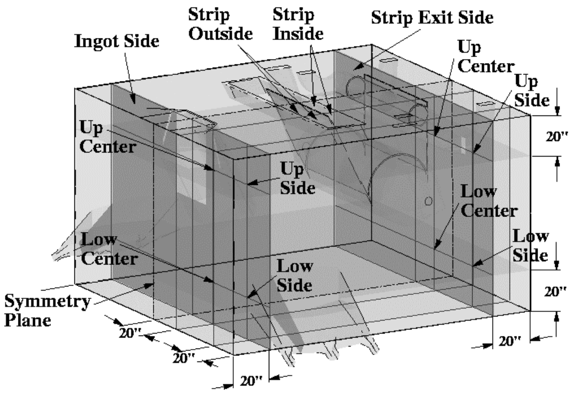


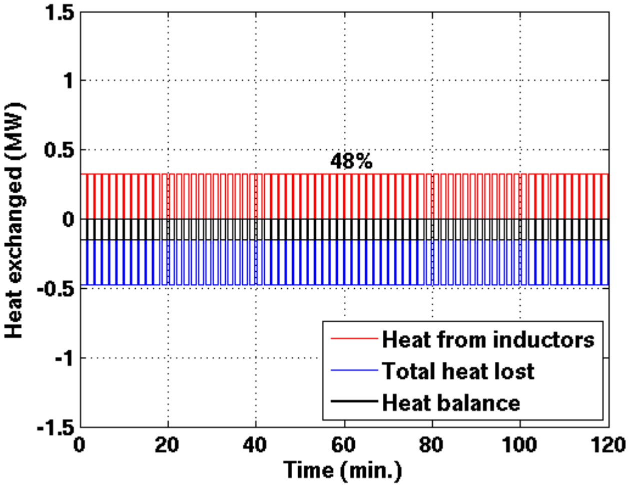
Dross scale
(0 – 0.012) %wt

Task 3: Summary

- Numerical studies: T_{strip}={420, 440, **460**, 480, 500°C} for conventional steel







Effect of gradual ingot loading:

⇒Global heat balance: Inductors power setting requires different adjustments; generally need about **the same average power** as the periodic ingot loading configurations.

⇒At various locations temperature remains constant with time: temperature gradients more significant in the snout, above the sink roll and in the inductors side.

⇒Constant temperature with time leads to **constant dross production rates**.

To **minimize dross** formation, need to carefully consider location and settings of inductors or other **means of controlling temperature distribution**

Future work on Task 1: Mn effects on galvanizing bath management

- Verify new dross formation data (if available from sponsors) to validate and correct if needed the models
- Transfer developed model to be included in work for tasks 2 and 3

Future work on Task 2: Effects of pre-oxidation pre-treatment cycles on galvanizing bath Fe management

- Case Western University study (ZCO-65) as reference for the Fe content (dissolution rate) for oxidation-reduction annealing compared to reduction-only annealing
  - Results indicate Fe level in the range 0.28-0.32 (wt%) with oxidation vs 0.08-0.09 (wt%) w/o oxidation

- Modeling work:
  - Models for Fe dissolution rate based on pre-oxidation pre-treatment
  - Full galvanizing bath model including Fe, Al and Mn concentration distribution
  - Investigate impact on bath management of the increased Fe inputs after pre-oxidation pre-treatment
  - Impact on dross generation
  - Perform a parametric study w.r.t Fe dissolution rate
  - Bath management recommendations

Future work on Task 3: Effects of strip entry temperature and galvanizing bath management on coating quality

- Further modeling work:
  - Effect on dross generation for Mn level corresponding to AHSS

Thank you

Florin Ilinca, Ph.D.
Team leader
Simulation and Numerical Modeling
Tel: 450-641-5072
Florin.ilinca@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca