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Online control of spray cooling using Cononline

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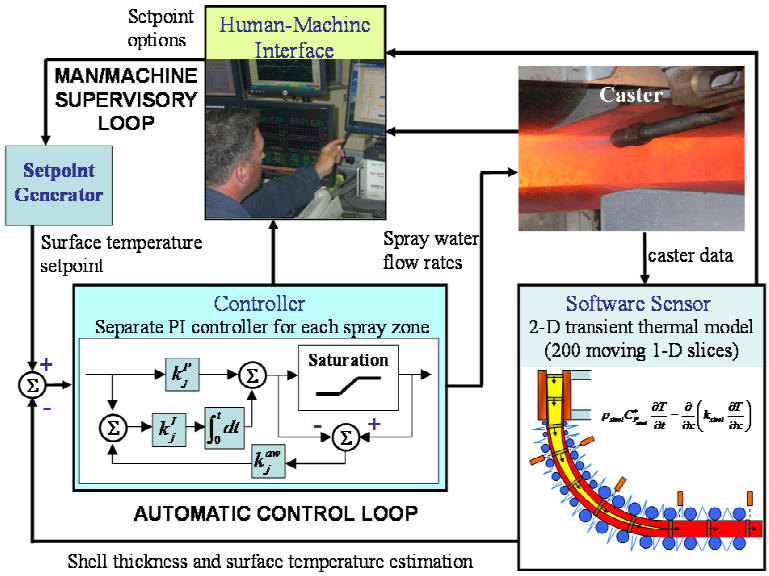
Outline

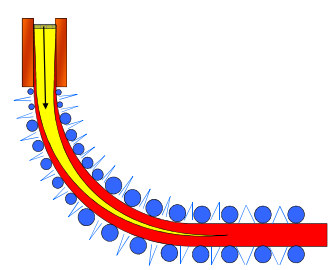
- Brief overview of Cononline project
- Challenges in dynamic control of spray cooling
  - Saturation and anti-windup
  - Setpoint choice
  - Sticker slowdowns
- Offline simulator
- Simulation example: sticker slowdown

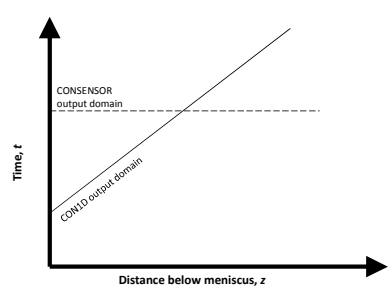
Overview



Overview: Consensor

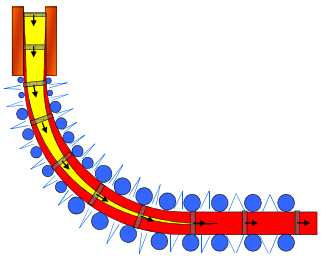
- Con1d
  - Fundamentally-based heat transfer and solidification model of continuously cast strand
  - Assumes heat transfer in axial direction is dominated by flow of material at casting speed (true at typical casting speeds
  - Simulates a 1-D "slice" through the centerline of the strand, moving down the caster at casting speed
- Goal:
  - Apply Con1d as the basis of a real-time model of the strand
  - Then, use model for "feedback" control of water cooling sprays instead of relying on pyrometers

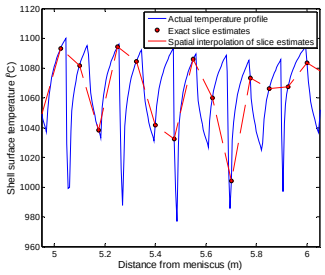


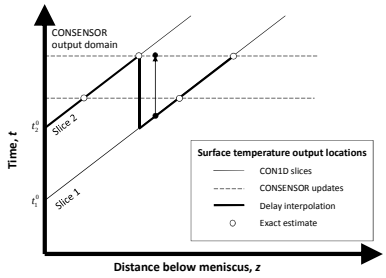


Overview: Consensor

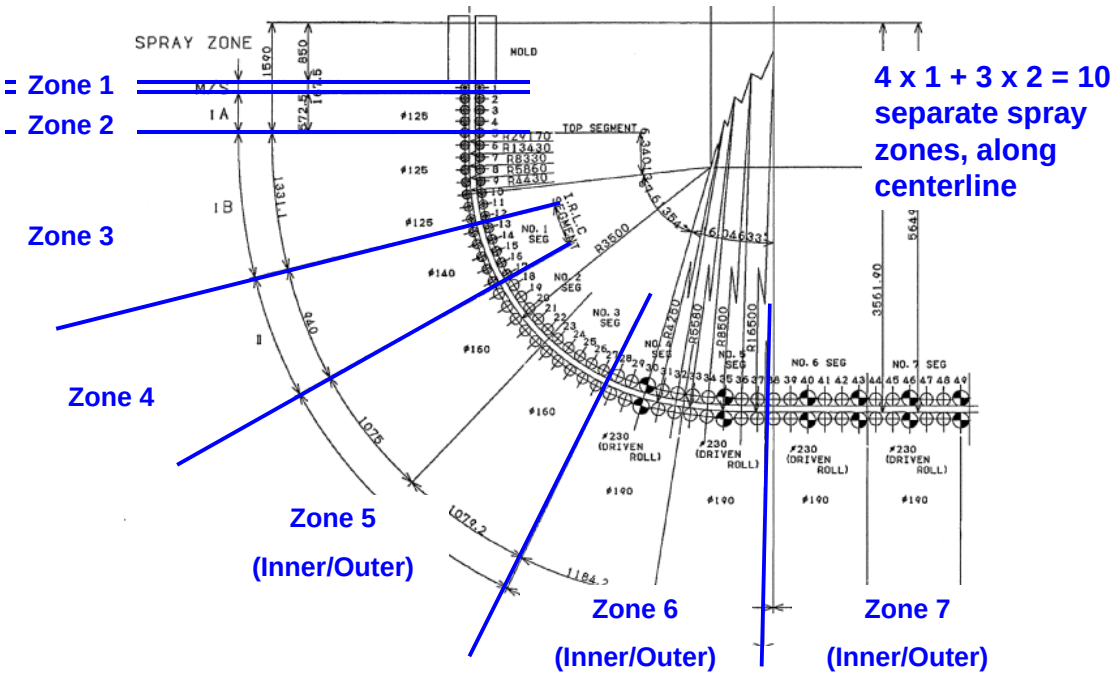
- Consensor: "Software sensor"
  - Manages 200 Con1d slices
  - Each second, gets updated casting conditions from Level 2, simulates each slice for 1 second of travel at casting speed
  - Uses "delay interpolation" for points in between slices







Nucor Decatur cooling sprays



Overview: Concontroller

- Each spray zone is controlled by a separate PI controller
- Every second, for each zone, *j*
  1. Calculate the average tracking error:

$$\Delta T_j = T_j^{\text{setpoint}} - T_j^{\text{predicted}}$$

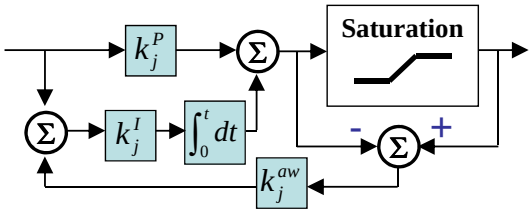
  2. Calculate the spray-water flow rate command for the next time interval, via the classic PI control law:

$$u_j(t+\Delta t) = u_j^P(t+\Delta t) + u_j^I(\Delta t)$$

$$u_j^P(t+\Delta t) = k^I \Delta T_j(t)$$

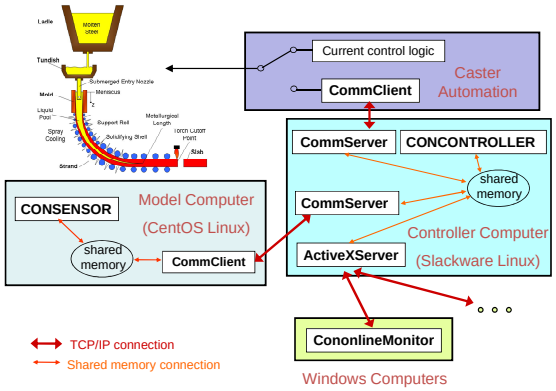
$$u_j^I(t+\Delta t) = u_j^I(t) + k_j^I \Delta T_j(t)\Delta t - k_j^{aw}\left[u_j^{measured}(t) - u_j(t)\right]$$

     - Additional term on integral is anti-windup correction to prevent delays after saturation
  3. Send spray rates to all other programs

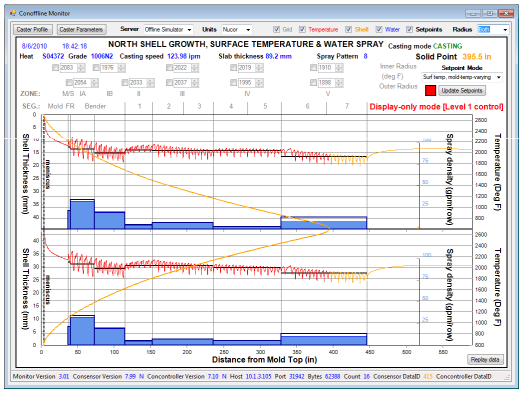


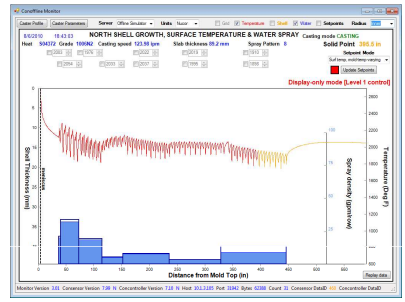
Overview: Programs

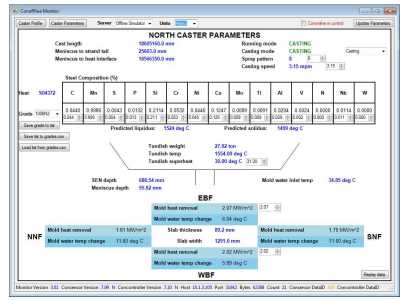
- Programs run on separate computers for stability and speed
  - Consensor runs on CentOS Linux
  - Concontroller runs on Slackware Linux
  - Communicate with each other and Level 2 via TCP/IP programs written by Rob Oldroyd (Nucor Decatur)
  - Also send information to Windows PCs via monitor programs



Overview: Monitor

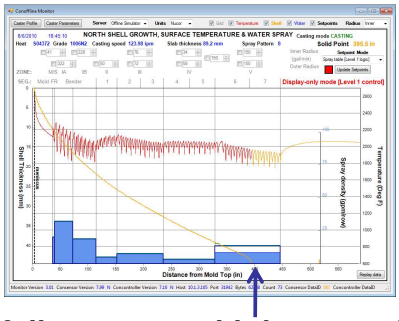






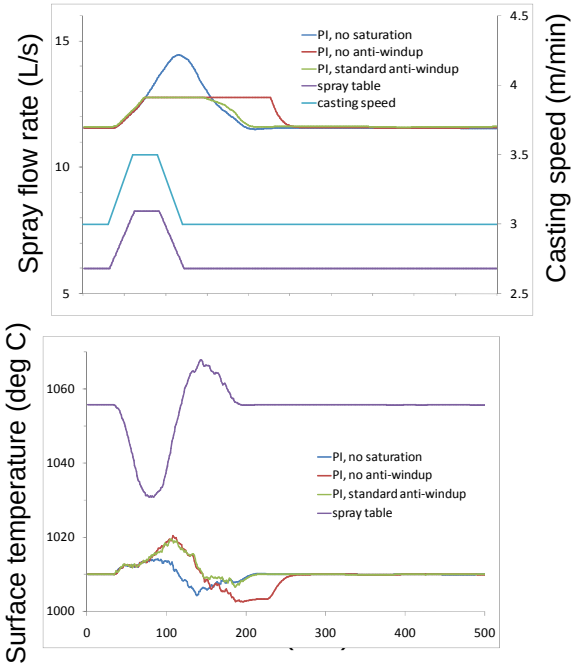
Anti-windup: benefits

- In normal casting conditions, some valves may be fully open or closed
- After the valve can't move any further, the integral controller continues to integrate (windup) and takes a while to return to normal
- Anti-windup subtracts the difference between controller and actuator to reduce this delay



Valve fully open, not hitting setpoint

Anti-windup test simulation



Anti-windup: problems

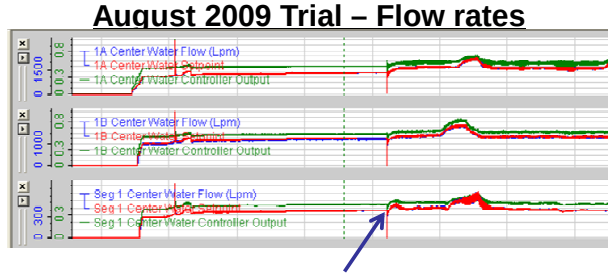
- However, too aggressive anti-windup was found to over-react to chattering in the spray valves

$$u_j^I(t+\Delta t) = u_j^I(t) + k_j^I \Delta T_j(t)\Delta t - k_j^{aw}\left[u_j^{measured}(t) - u_j(t)\right]$$

- We responded to this by averaging the error signal before anti-windup

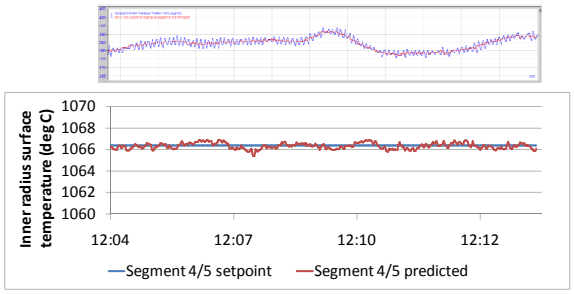
$$u_j^I(t+\Delta t) = u_j^I(t) + k_j^I \Delta T_j(t)\Delta t - k_j^{aw}\frac{1}{N}\sum_{n=0}^{N-1}\left[u_j^{measured}(t-n\Delta t) - u_j(t-n\Delta t)\right]$$

August 2009 Trial – Flow rates



Cononline turned on

July 2010 Trial – Flow rate and surface temperature



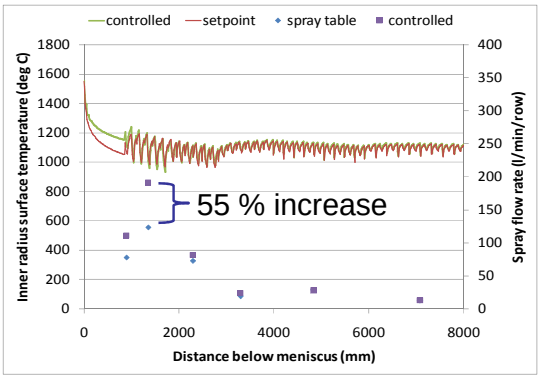
Flow rate legend
— Measured flow rate
— Concontroller suggest flow rate

Setpoints

- Cononline setpoints are based on spray table, estimate mold heat removal based on mold flux properties

$$\bar{q} = 4.63\times10^6 \mu^{-0.09} T_m^{-1.19} v_c^{0.047}\left(1 - 0.152\exp\left[-\left(\frac{0.107 - pc}{0.027}\right)^2\right]\right) (*)$$

- Formerly, interpolated setpoints in top 4 zones with respect to actual mold conditions
- Nucor Decatur wants to use Cononline to fix the temperature in the bender (zones 2 and 3)
- PI control reacts to differences in mold heat removal by changing the sprays drastically in upper zones



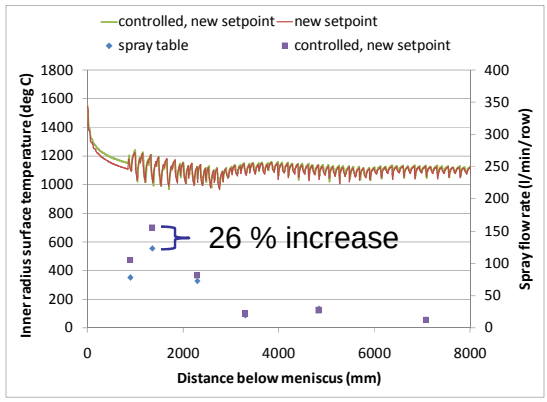
(*) C. Cicutti, M. Valdez, T. Perez, G.D. Gresia, W. Balante and J. Petroni: "Mould thermal evaluation in a slab continuous casting machine," *Proc. 85th Steelmaking Conference*, (Nashville, TN, USA), 2002, vol. 85, pp. 97-107, 282.

Setpoints

- Regenerated setpoints
  - instead of equation (*), used average recorded mold heat removal at Nucor Decatur over last year
- Results are much better, but there may be other differences to account for
  - Grade?
  - Mold flux?

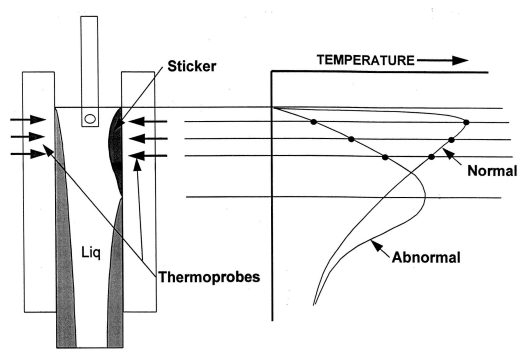
Average mold heat removal (MW/m²)

	15.7	31.5	47.2	78.7	98.4	118.1	137.8	157.5	196.8	speed (ipm)
Pattern	0.40	0.80	1.20	2.00	2.50	3.00	3.50	4.00	5.00	speed (m/min)
1		1.346	1.454	1.498	1.711	2.343	2.548			
2										
3	0.0106	1.656	1.462	1.367	1.734	2.363	2.526			
4		1.967	1.666	1.642	1.83	2.442	2.569			
5							2.69			
6			1.385	1.653	1.777	2.143	2.374			
7	6.0735	1.346	1.408	1.605	1.837	2.226	2.393			
8		1.624	1.371	1.531	1.794	2.146	2.352			



Sticker slowdowns

- Dynamic controller also may have problems dealing with unusual casting conditions, e.g. sticker slowdowns
- Sticker detection:
  - Shell surface touches mold hot face, leading to thin spot in shell
  - Nucor Decatur breakout detection alarm is triggered when mold thermocouples drop suddenly in temperature
  - Typically have more false positives than actual detections
- Caster response:
  - Immediately slowed to 20 ipm to prevent breakout
  - Sprays are taken from spray table at 80 ipm (higher spray rates than 20 ipm) to prevent bleeders

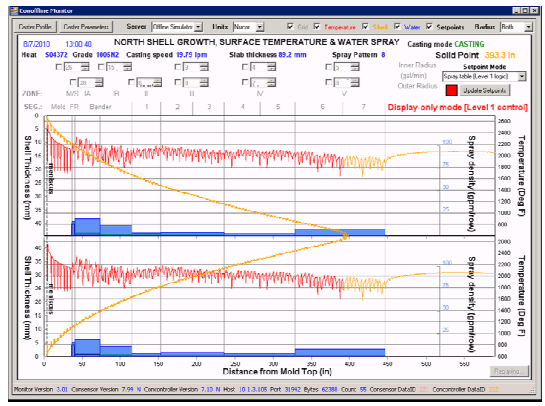


(Ed Szekeres)

Sticker slowdowns

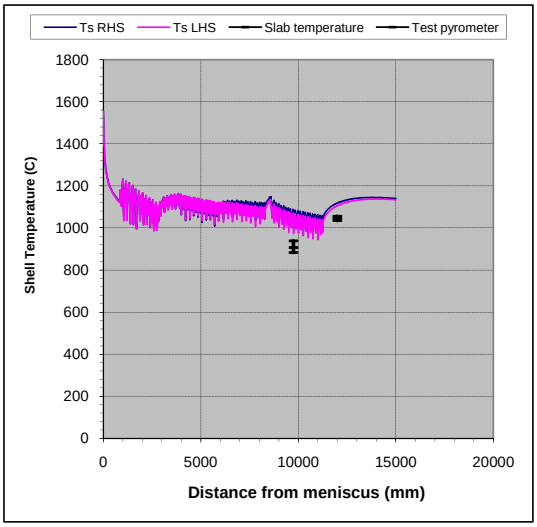
- Cononline response
  - Cononline is only given average heat removal rate in mold, so it does not predict the localized thin spot in the shell
  - Because of sudden drop in temperature due to the slowdown, the PI controller reaction is turn all sprays down
- Added some extra logic to Concontroller to handle this:
  - In first three zones (through the bender) the controller uses the 80 ipm flow rates instead of applying temperature control

Light blue boxes: spray table at 80 ipm
Dark blue outlines: spray table at 20 ipm

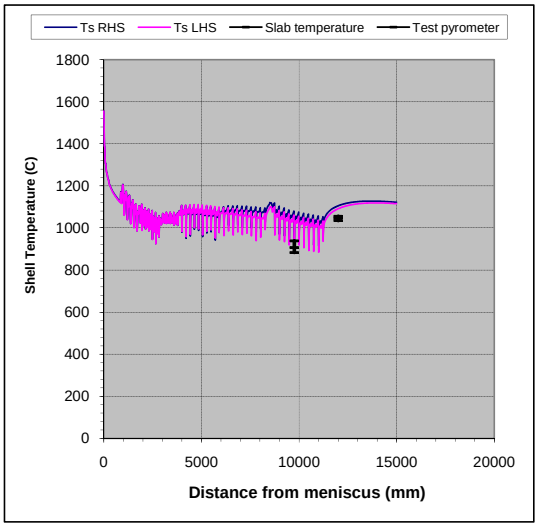


Tuning Con1d to Nucor Decatur caster: pyrometers

Original heat transfer coefficients



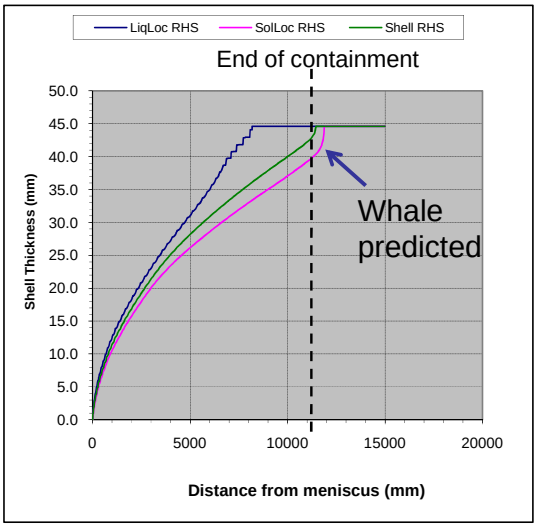
New heat transfer coefficients



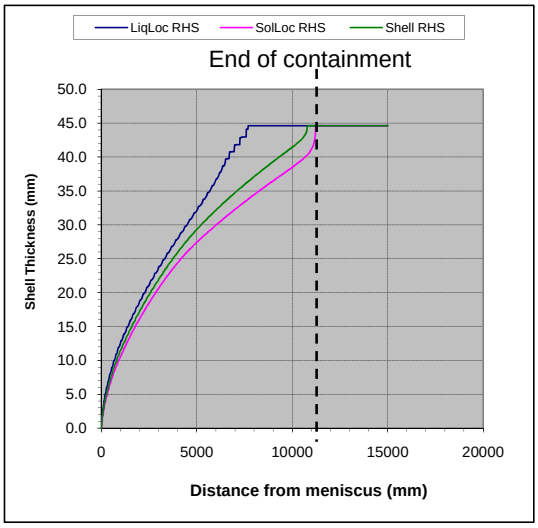
(Xiaoxu Zhou)

Tuning Con1d to Nucor Decatur caster: shell

Original heat transfer coefficients



New heat transfer coefficients

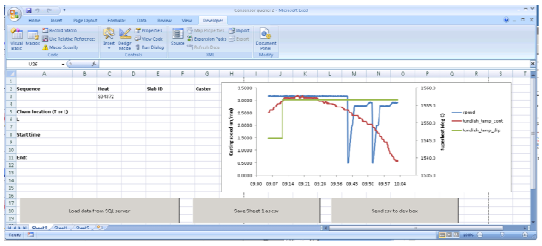


(Xiaoxu Zhou)

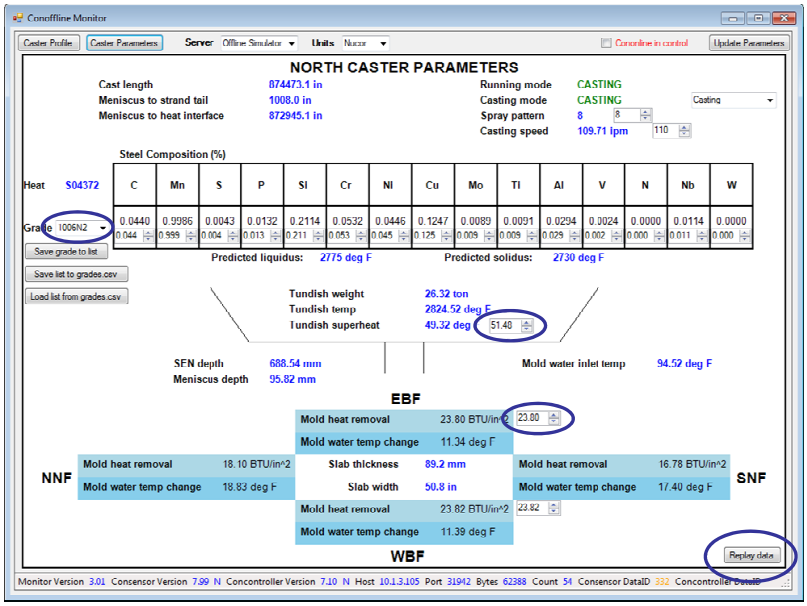
Offline simulator

- Implementing Cononline as an offline simulator
  1. "Offline" monitor allows direct user input of casting conditions
  2. Database querier in Excel pulls conditions by caster, sequence, heat, slab, and/or time and date, sends to "replay" program that feeds data to Consensor
- Potential uses:
  - Testing out new casting practices prior to implementation
  - Defect or event investigation
  - Operator training

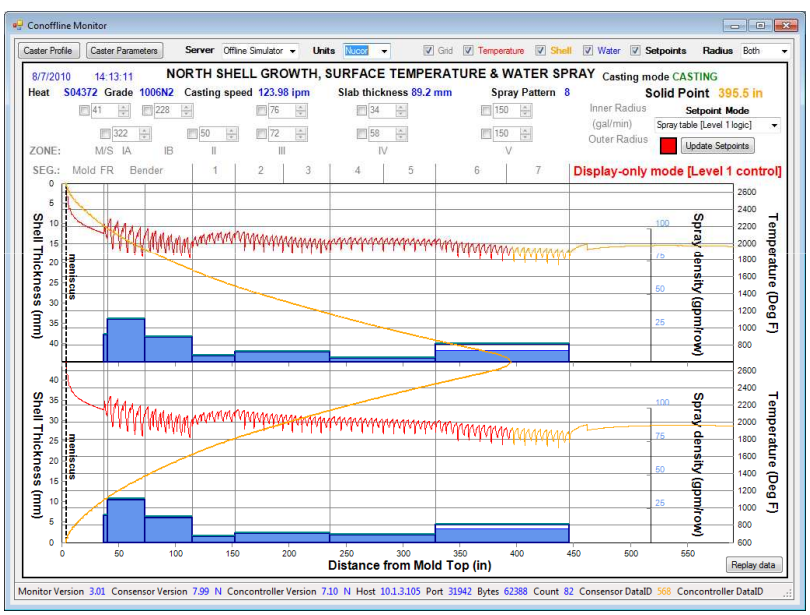
Nucor Decatur database querier



Offline simulator



Simulation – Sticker slowdown



Thank you

- NSF grants
  - GOALI DMI 05-00453 (Online)
  - GOALI CMMI-0900138
- CCC students
  - Xiaoxu Zhou, Huan Li (former student), Sami Vapalahti, Hemanth Jasti
- Nucor Decatur
  - Level 2 programmers: Rob Oldroyd, Teri Morris, Kris Sledge, James
  - Metallurgists: Ron O'Malley, Bob Williams
  - Electrical: Steve Dunnavant, George, Bill James, Jeff White
  - Caster supervisors and operators: Scott Ridgeway, Caster Green, Rodney Thrasher, Bryan Thornton, Josh
  - Everyone else
- Continuous Casting Consortium members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)