Online Control of Spray Cooling Using CONONLINE

Control System Design & Performance

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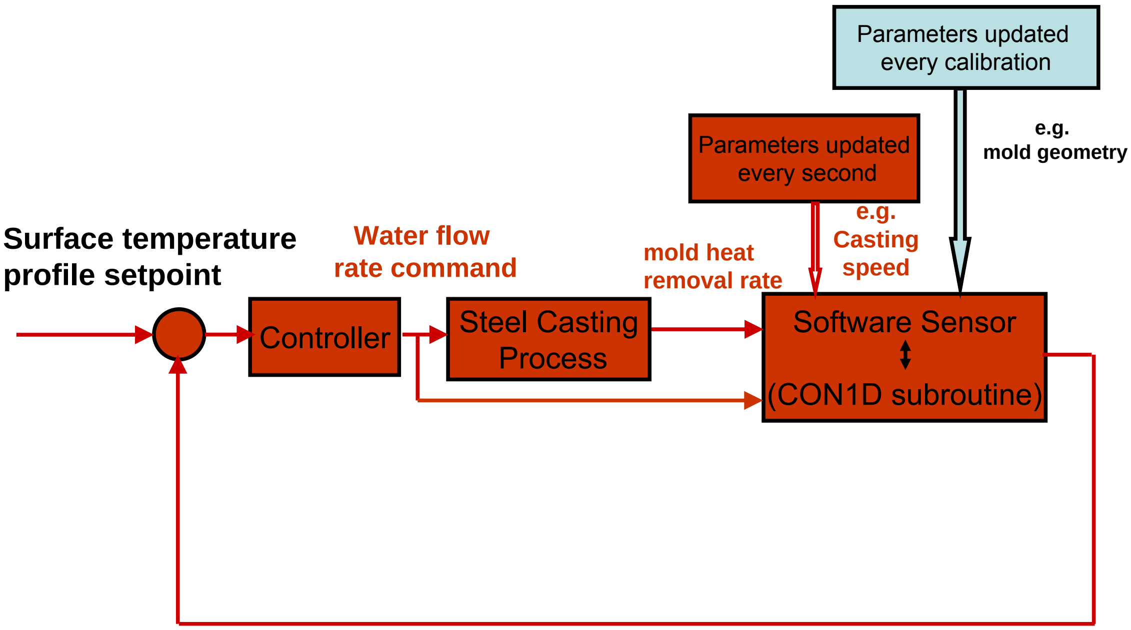
Outline

- Project overview
- CONONLINE Development
  - Software sensor
  - Monitor
  - Controller
- Setpoint generation
- Example simulation
- Ongoing work

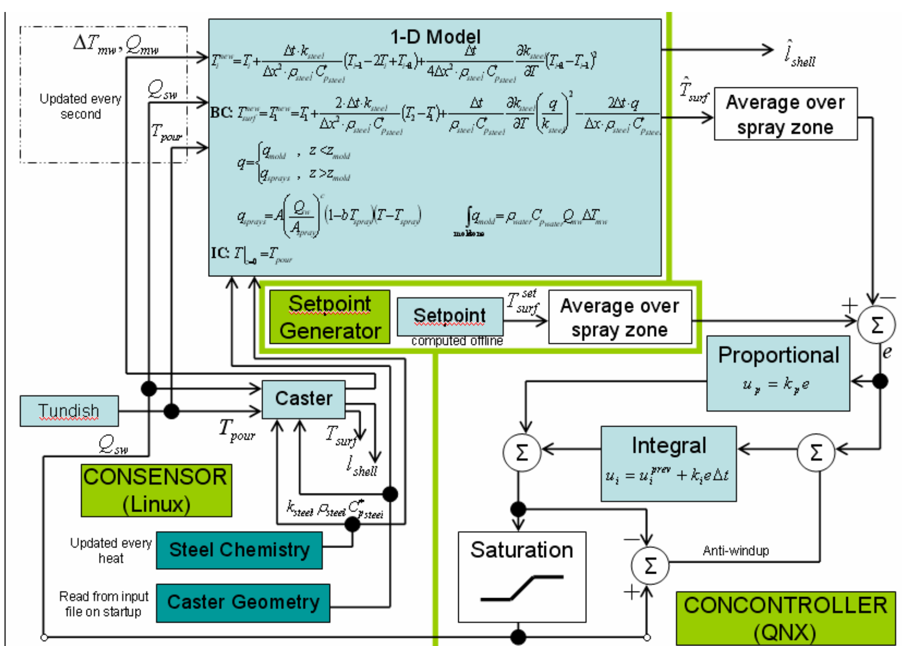
Approaches to Secondary Cooling Control

1) **Manual control:**
   - Operator sets of water flow rates
   - Difficult at high casting speeds when response times must be short
2) **Casting-speed-based control:**
   - Set water flow rates according to casting speed
   - Results in non-optimal cooling during transient conditions
3) **New Software-sensor-based control:**
   - Create "software sensor," an accurate, real-time computational model to base control on
   - Conventional feedback control has not yet been successfully implemented due to unreliability of optical pyrometer sensors.

New Control System Strategy

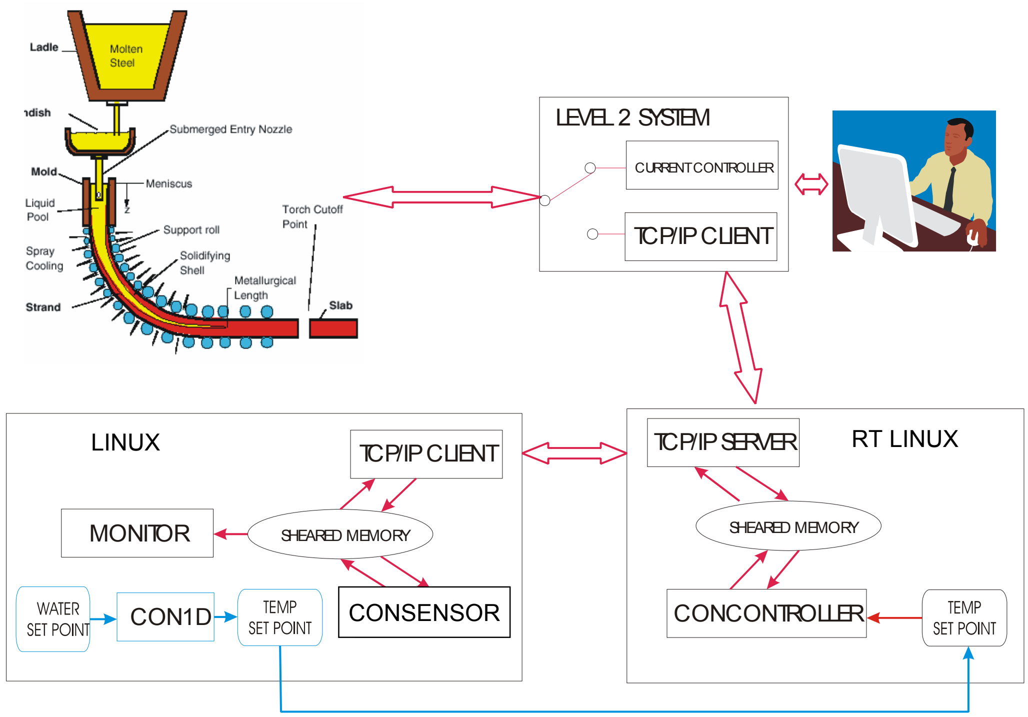


System Architecture



Computational Block Diagram

System Overview



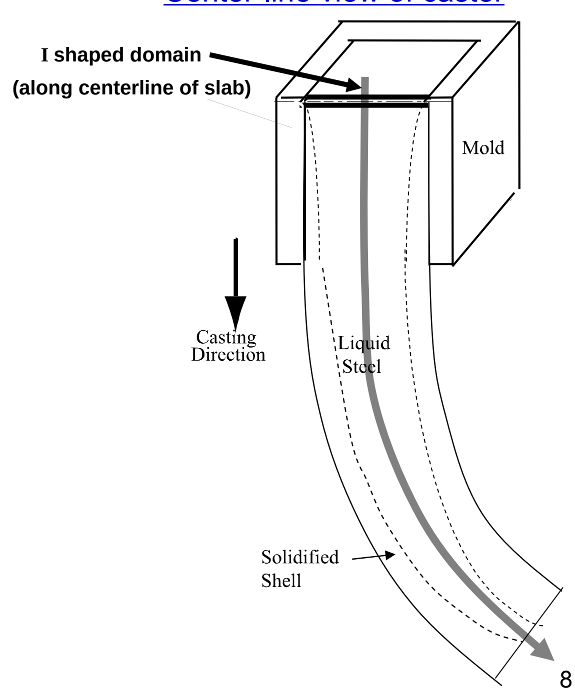
CON1D: Overview

- Fundamentally based transient finite-difference model:

$$\rho_{steel} Cp^*_{steel} \frac{\partial T}{\partial t} = k_{steel} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{steel}}{\partial T} \left(\frac{\partial T}{\partial x} \right)^2$$

- CON1D predicts:
  - shell thickness
  - temperature distribution
  - total heat removal
  - heat flux profiles
  - mold water temperature rise (to match measurements)

Center-line view of caster

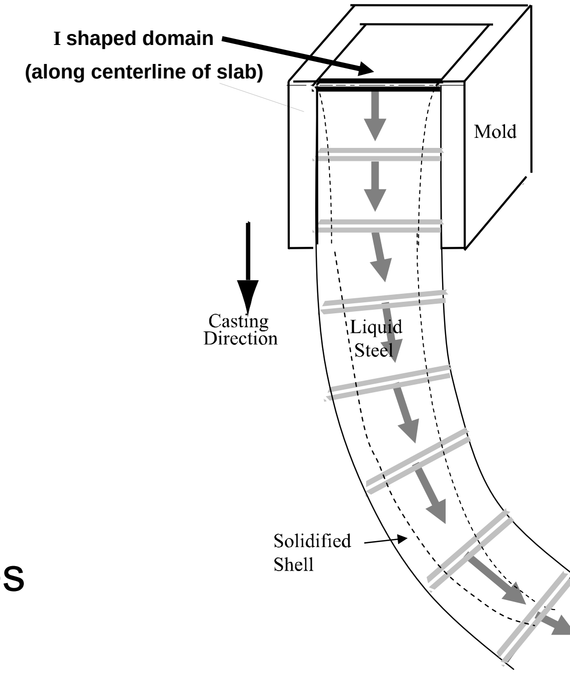


CON1D: Application

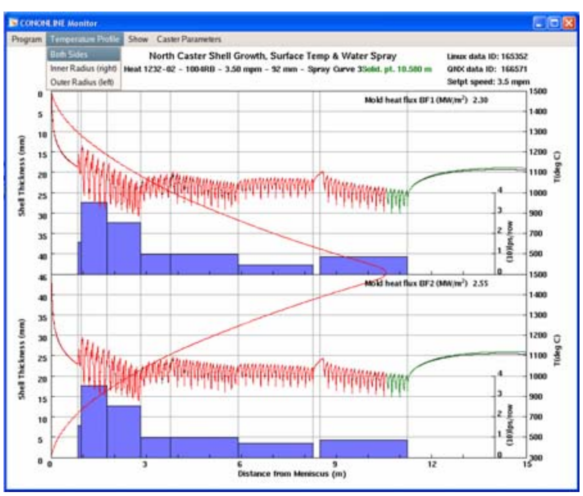
- CON1D program:
  - runs through entire caster in ~ 0.5 s
  - predicts temperature and other phenomena for only one slice at a time
  - we need the temperature profile of the whole slab

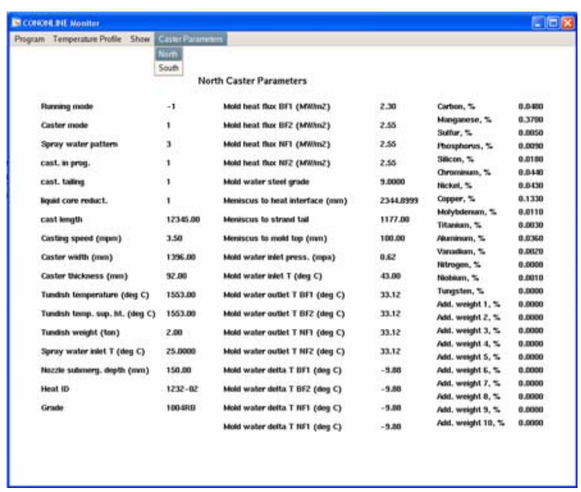
- Solution: multiple slices

Center-line view of caster

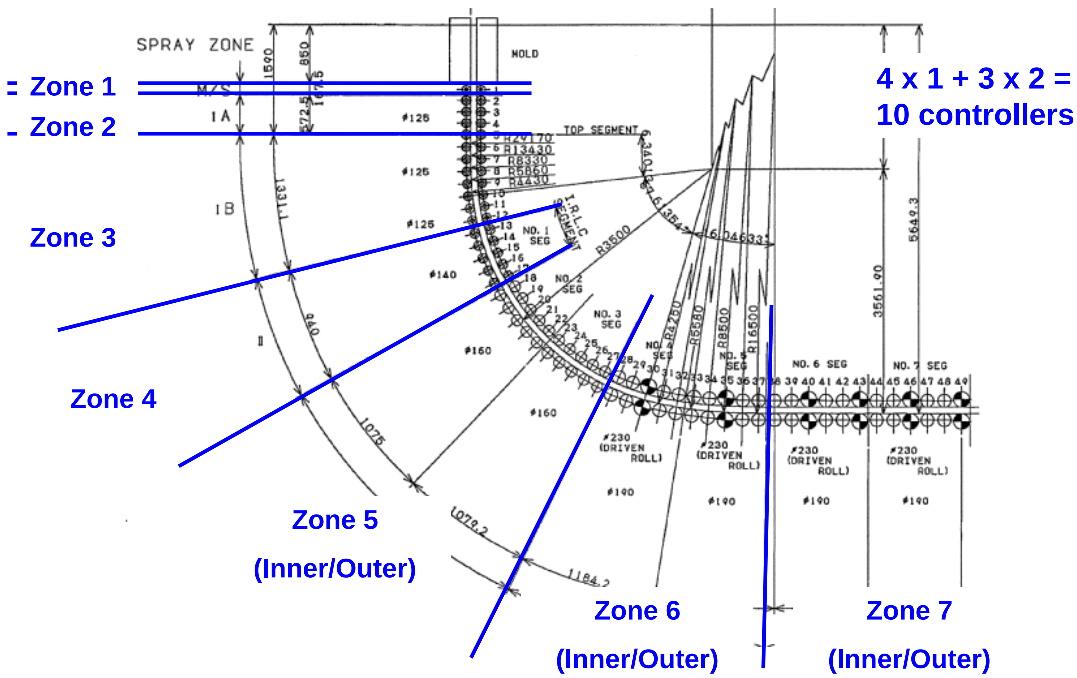


CONONLINE Display





Caster



Controller Design

- Zone-based design: 10 subcontrollers, one for each spray zone

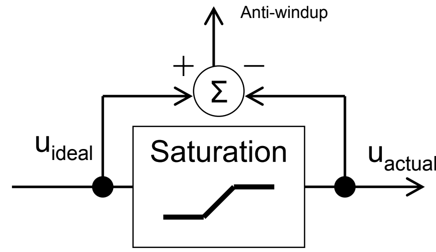
- **Controller Algorithm:** At each second of time:
  1. Obtain surface temperature profile from CONONLINE.
  2. For all 10 zones:
     i. Compute the zone-based surface temperature average T_{avg} for current zone. And form the tracking error $T_{err} = T_{avg} - T_{sp}$
     ii. Use T_{err} to compute the water flow rate command = Nominal_flow + Δflow(t),

$$\Delta flow\,(t) = k_p T_{1err}\,(t) + k_i \int_0^t T_{1err}\,(s)\,ds$$

  3. Send all water flow rate commands to CONONLINE, Caster, and Monitor

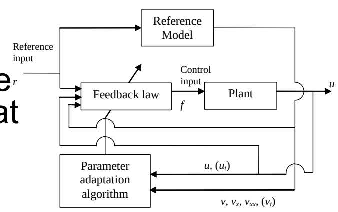
Improvements to Controller

- Anti-windup
  - Actuator saturation can lead to windup of integral controller
  - Simple anti-windup scheme added

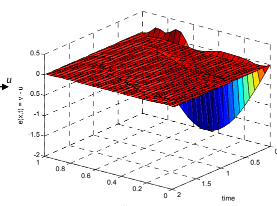


- Optimal/Adaptive control law development
  - In progress
  - Adaptive control laws have been designed for 1-D heat equation with spatially varying parameters

Control Law



Performance



- Metallurgical length (ML) control

Transient ML Control

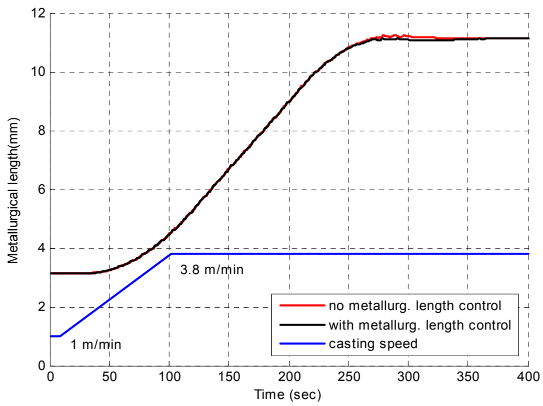
- Prevent overshoot of metallurgical length (ML):
  - A small amount of ML overshoot (0.1m) results under good temperature control
  - Can trade the performance of temperature control for metallurgical length control by **temperature setpoint conditioning**
  - Requires steady state ML within bounds
  - For 6th, and 7th spray zones, $T_{sp\_c} = T_{sp} \cdot (1 - drop)$
    - $drop = c_1 \cdot (v_{solidpt})^{c_2} \cdot (z_{solidpt} - c_3)^{c_4}$

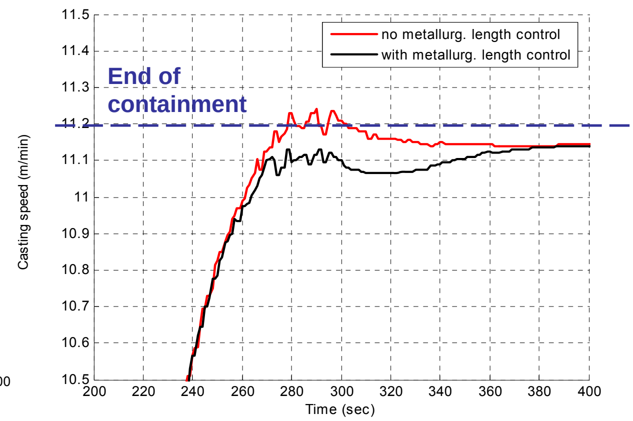
$$\text{if} \begin{cases} v_{solidpt} > 0 \quad \text{and} \\ z_{solidpt} - c_3 > 0 \end{cases}$$

$$\text{else}, drop = 0$$

Transient ML Control: Performance

- Metallurgical length overshoot eliminated





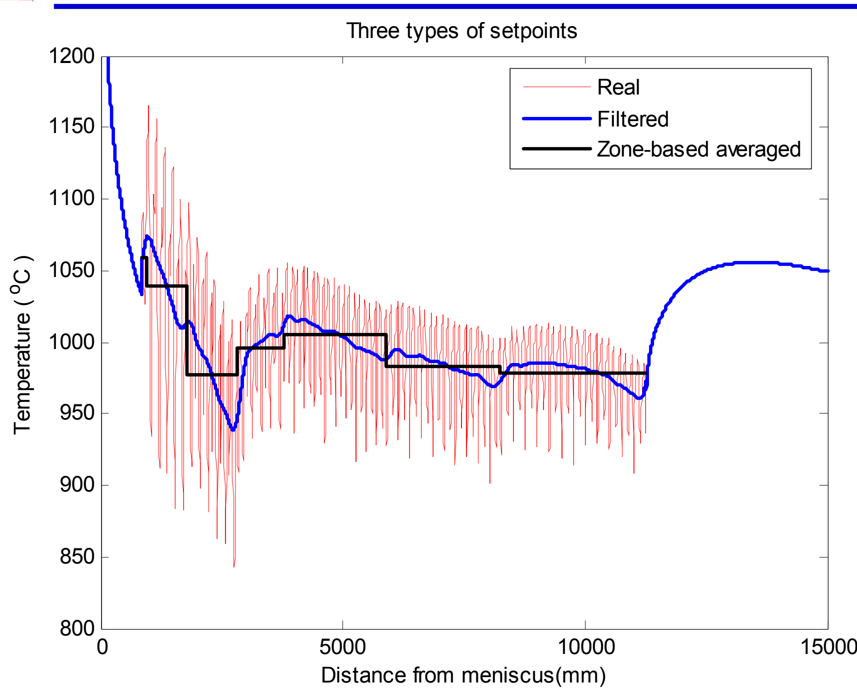
Intelligent ML Control

- Transient control depends on setpoints being “safe” conditions
- Open problem: ensuring metallurgical length behavior automatically
  - Conflict between setpoint tracking and metallurgical length tracking?
  - “Envelope” for system: known safe running conditions hard-coded into controller?
  - Moving boundary control of Stefan problem?

Setpoint Generation

- From Nucor: spray water flow rate set points
  - Empirically based, from past experience
  - Casting-speed-dependent
- Convert to surface temperature profiles
  - Output from CON1D becomes temperature setpoint
  - Conditions:
    - 9 Casting speeds
    - 8 Spray patterns

Temperature setpoints



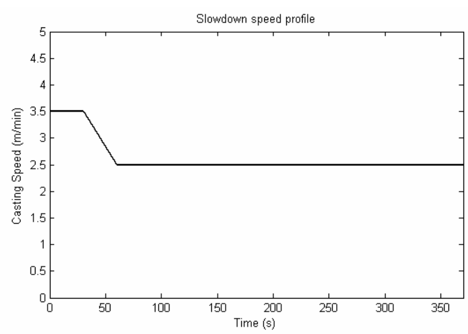
Problems With Setpoints

- Type of setpoints
  - Should setpoints be based off spray tables or desired temperature profiles?
- Casting speed variations
  - Should different speeds have different temperature profiles?
- Mold heat flux variations
  - Setpoint generator assumes heat flux equal to standard conditions (eg from Ciccuti et al)

$$Q_G = 4.63 \cdot 10^6 \mu^{-0.09} T_{flow}^{-1.19} V_C^{0.47} \left\{ 1 - 0.152 \exp\left[-\left(\frac{0.107 - \%C}{0.027} \right)^2 \right] \right\}$$

  - But, in practice, mold heat flux may vary
  - How should model compensate?

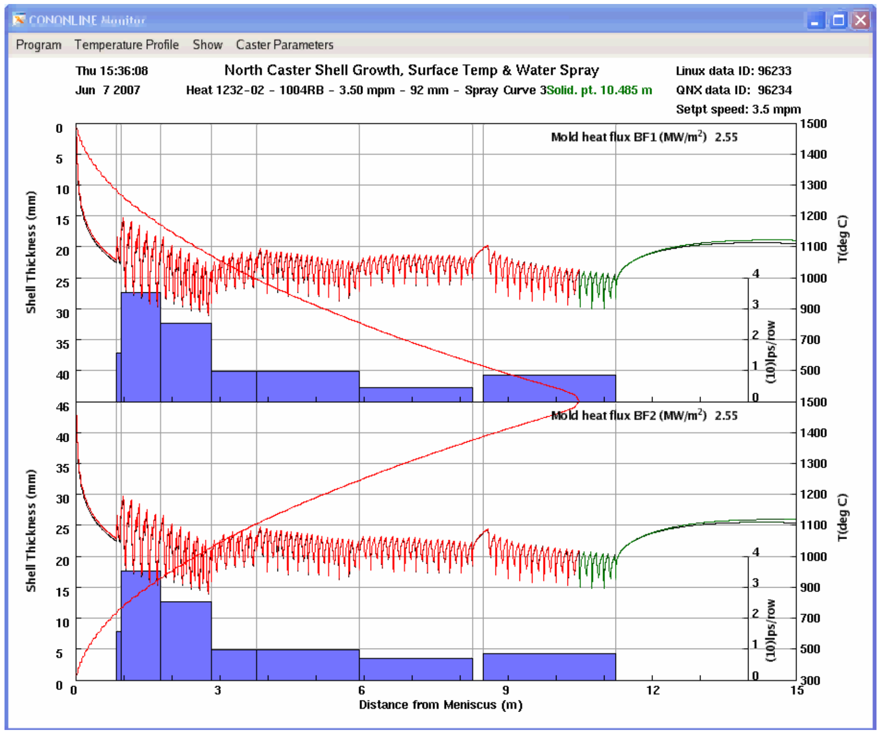
Simulation: Sudden Slowdown



- Compare
  - Casting-speed-based controller: setting water flow rate proportional to casting speed
  - Model-based PI controller: speed-proportional setpoints
  - Model-based PI controller: speed-independent setpoints

Slowdown: Casting-speed-based Controller

Sped up 12x



Slowdown: PI Controller, Speed-dependent Setpoints

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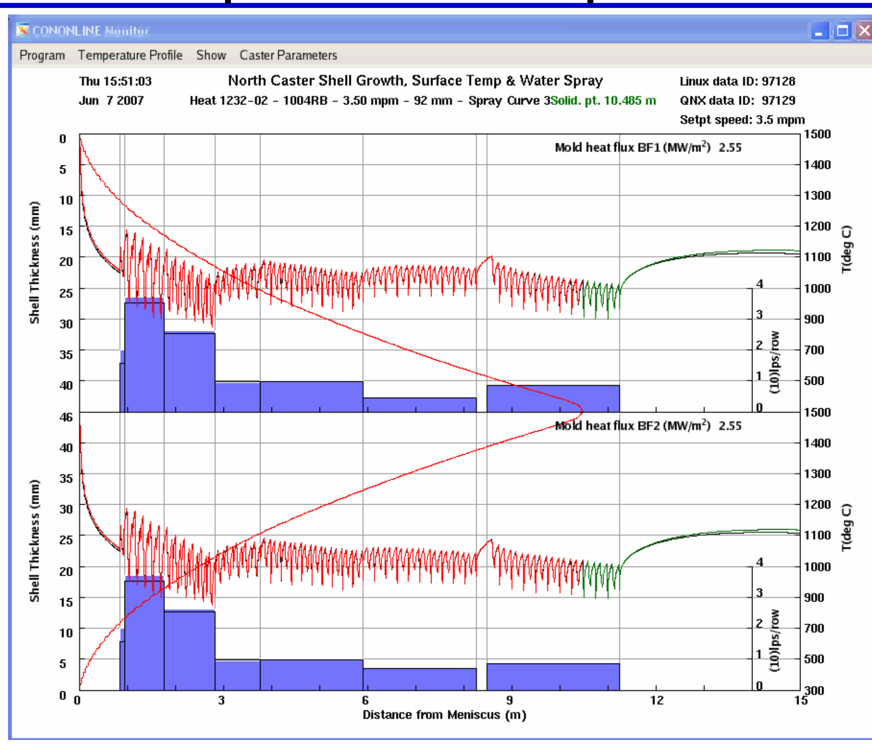
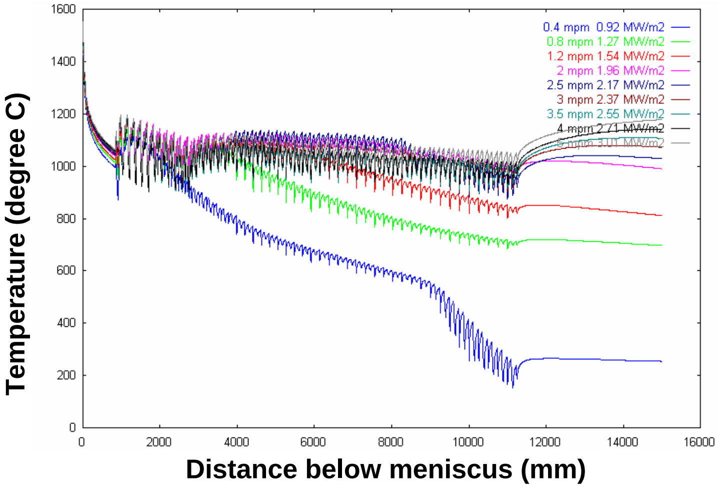


Casting Speed



- For 2 – 5 m/min, temperature setpoints are approximately constant
- Suggests that constant temperature setpoint is desired
- Take representative casting speed as setpoint for all casting speeds

Slowdown: PI Controller, Speed-independent Setpoints

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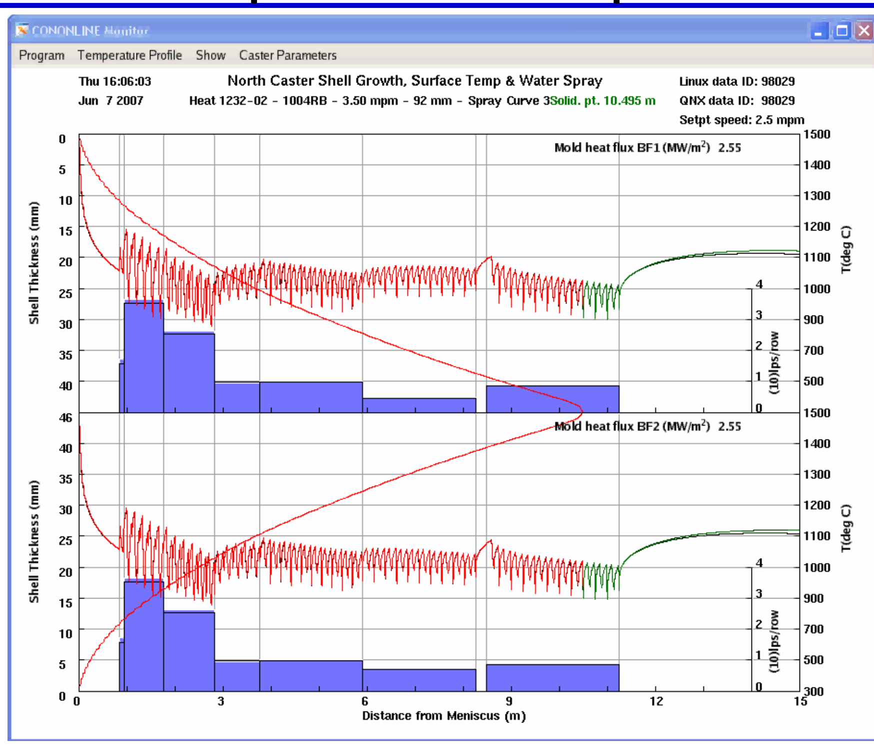
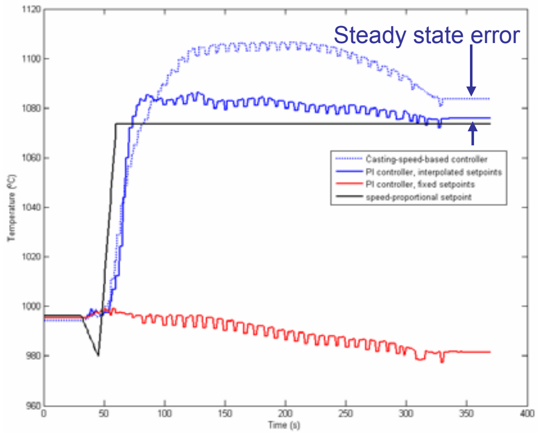


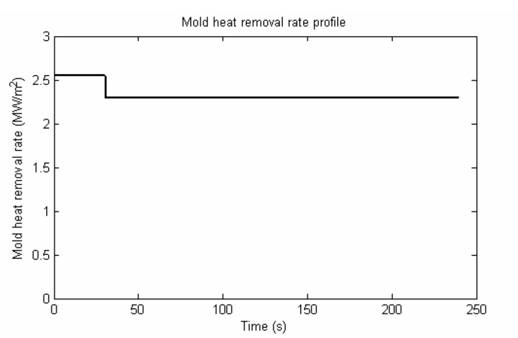
Slowdown: Comparison

Inner radius surface temperature at end of containment



- Casting-speed-based controller causes temperature overshoot
- Transient behavior is tracked closer with model-based controllers
- Steady-state error is caused by mold heat removal rate variatons

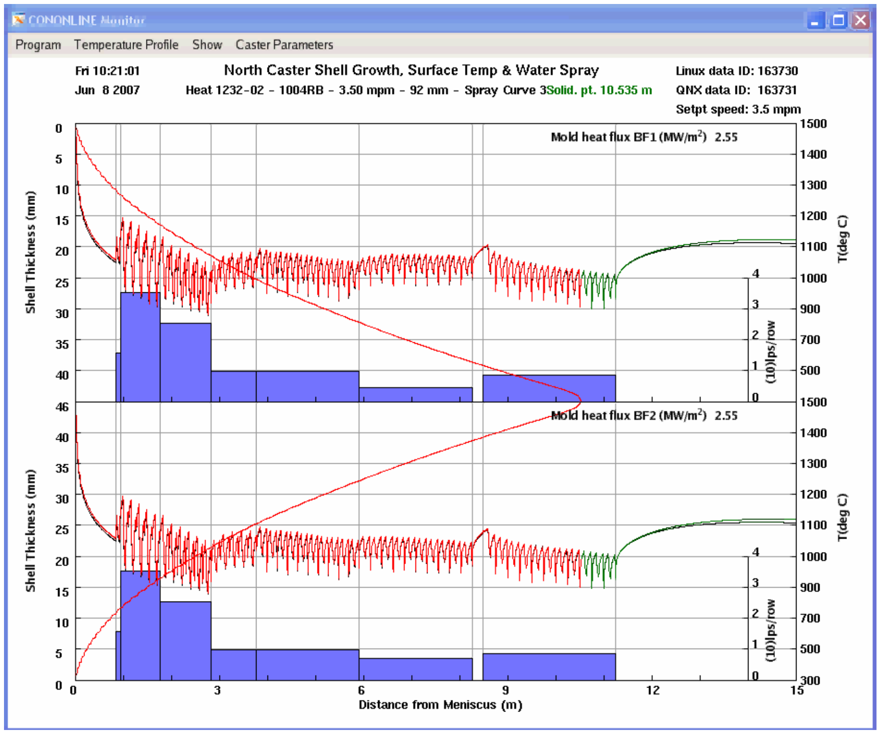
Simulation: Mold Heat Removal Rate Drop



- Mold heat removal rate (MHRR) on inner radius, broad face drops 10% at 30 seconds
- Compare
  - Casting-speed-based controller: setting water flow rate proportional to casting speed
  - Model-based PI controller: Fixed setpoints
  - Model-based PI controller: Mold-exit-temperature-dependent setpoints

MHRR Drop: Casting-speed-based Controller

Sped up 10x



MHRR Drop: PI Controller, Fixed Setpoints

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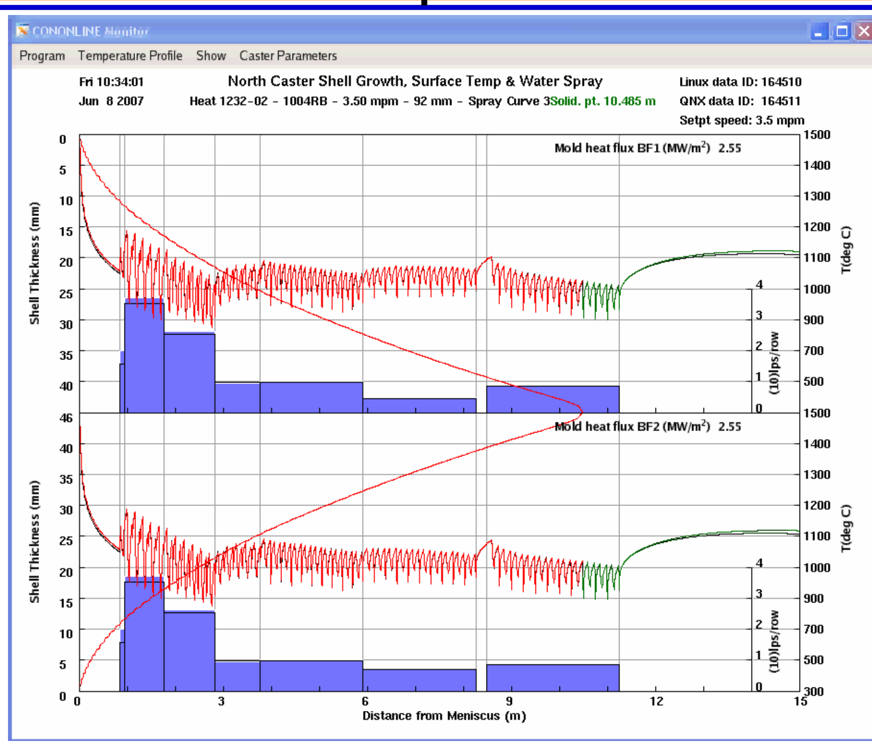
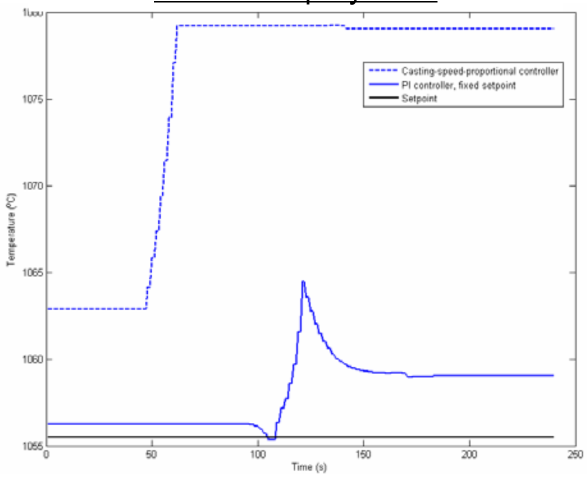


Continuous Casting Consortium

Mold Heat Removal Rate Drop: Comparison

Inner radius surface temperature at end of 3rd spray zone

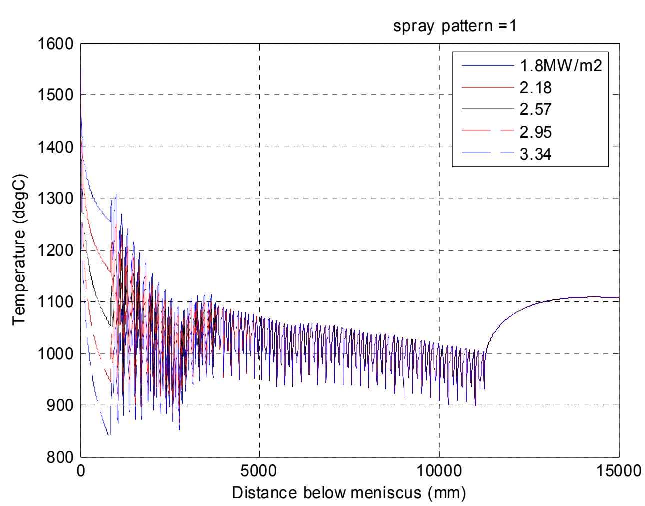


- Fixed setpoint controller tries to hold temperature constant despite change in mold exit temperature
- Can overcool strand and create detrimental transients in top regions of caster – even worse if mold heat flux varies continuously

Continuous Casting Consortium

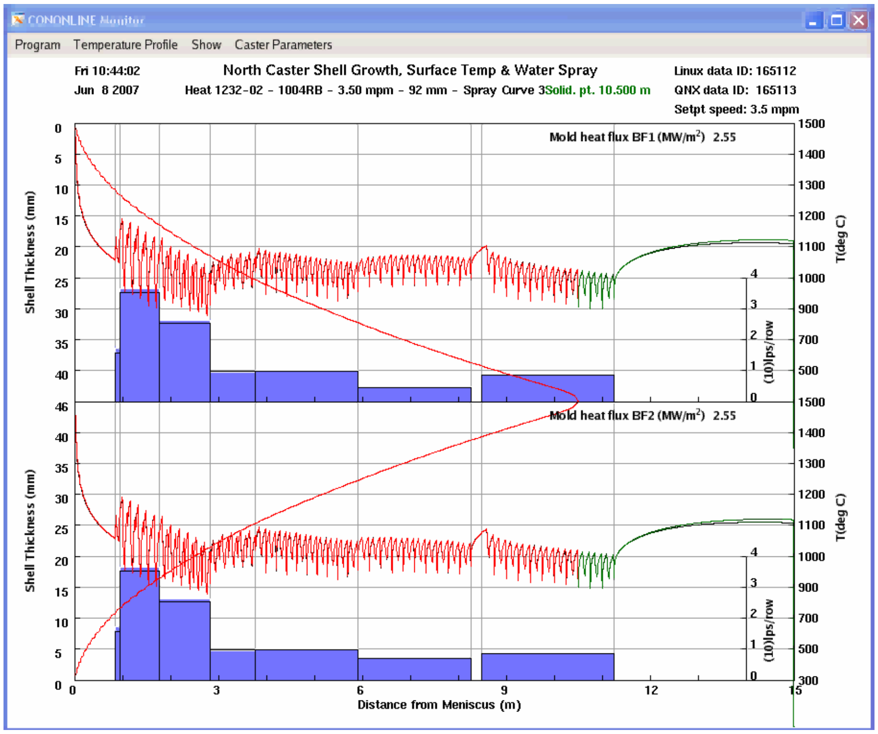
Vary Setpoints with Mold Exit Temperature

- Run setpoints for $\pm$ 15%, $\pm$ 30% of estimated heat flux
- Interpolate setpoints in first three zones based on mold exit temperature
- Keep standard setpoints for last four zones



MHRR Change: PI Controller, MET-dependent Setpoints

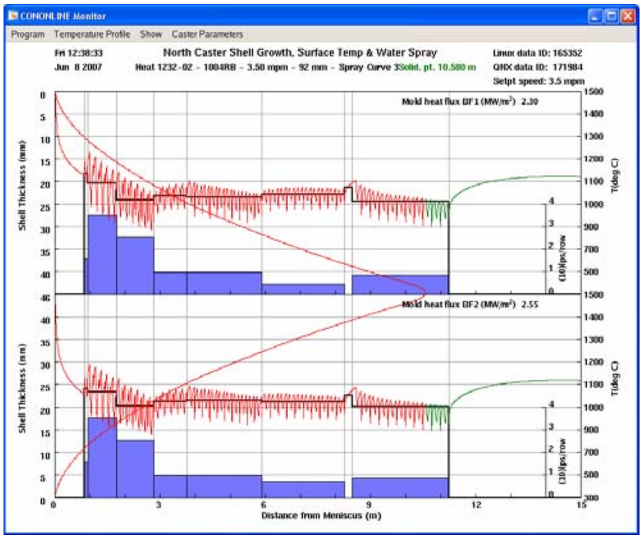
Sped up 10x

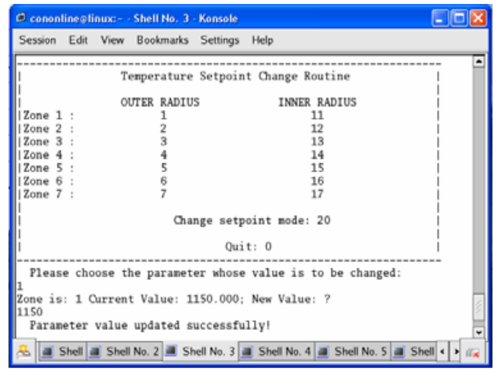


Organizing Setpoints

- First method
  - Calculated from spray tables
  - Stored as 2D index: speed and pattern
  - Setpoints linearly interpolated with casting speed
- Current method
  - Calculated from spray tables
  - Stored as 3D index: speed, pattern, mold exit temperature
  - Typical casting speed used to calculate setpoint
  - Allowing for different mold exit temperatures avoids over-responding at top of caster
- Next method
  - Stored as temperature setpoints
  - Allow for operator to change setpoints online

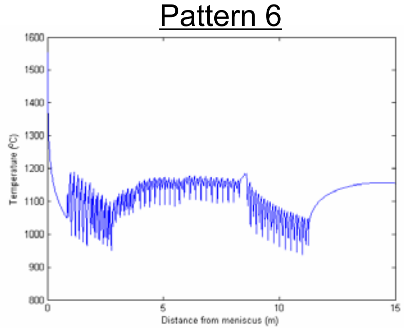
Shared Memory Setpoints



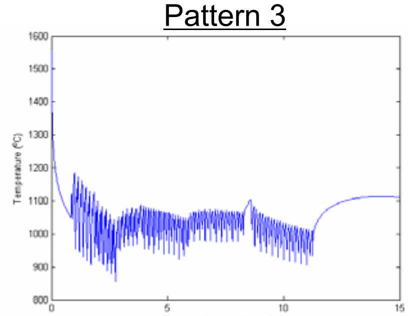


Simulation: Spray Pattern Change

Pattern 6



Pattern 3



- Change from pattern 6 (low-sprays, high temperatures) to pattern 3 (high-sprays, low temperatures) at 30 seconds
- Compare
  - Casting-speed-based controller
  - Model-based PI controller: speed-independent setpoints, interpolated by mold exit temperature

Spray Pattern Change: Casting-speed-based Controller

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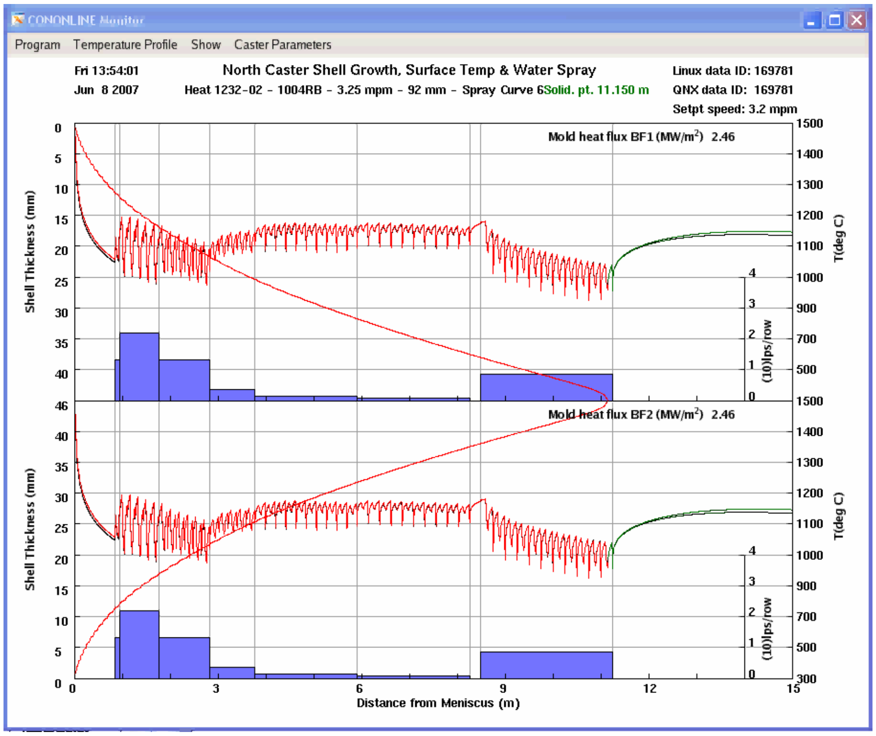

Spray Pattern Change: Model-based Controller

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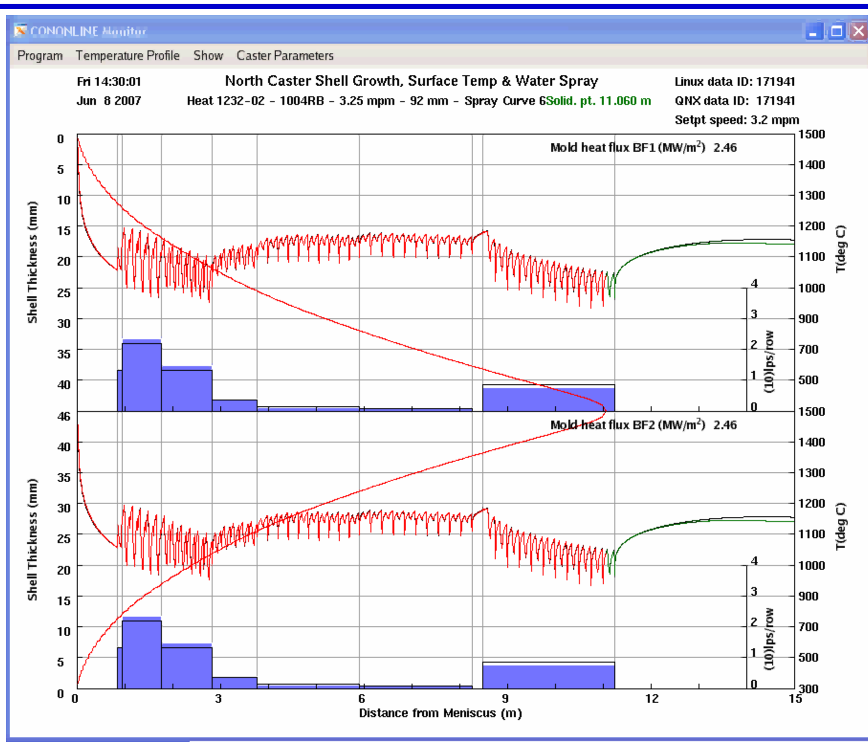
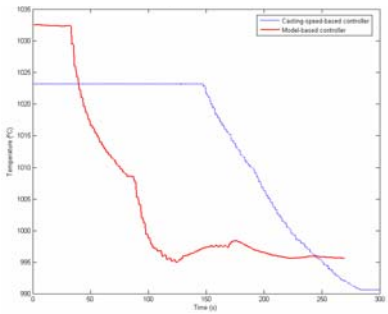
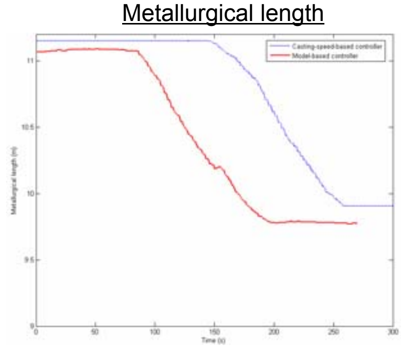


Spray Pattern Change: Comparison

Inner radius surface temperature at end of containment



Metallurgical length



- Spray pattern changes at 30 seconds from 6 (low sprays) to 3 (high sprays)
- Model-based controller tracks temperature more quickly than casting-speed-based controller
- However, metallurgical length still takes time to respond to spray change

Conclusions

- Control objectives must be carefully considered
  - CONONLINE can track temperature setpoints well, but this does not guarantee metallurgical quality or prevention of whales (ML control)
  - Choice of temperature setpoints is important, and is not always obvious
- Further work:
  - Incorporate heat transfer coefficients from lab experiments and plant measurements to improve accuracy
    - Huan's work
  - Develop off-line system to model plant separately from software sensor and study effect of differences
  - Improved control logic
    - Optimal or adaptive control?