Model-Based Control and Virtual Sensing with Application to a Vertical Furnace

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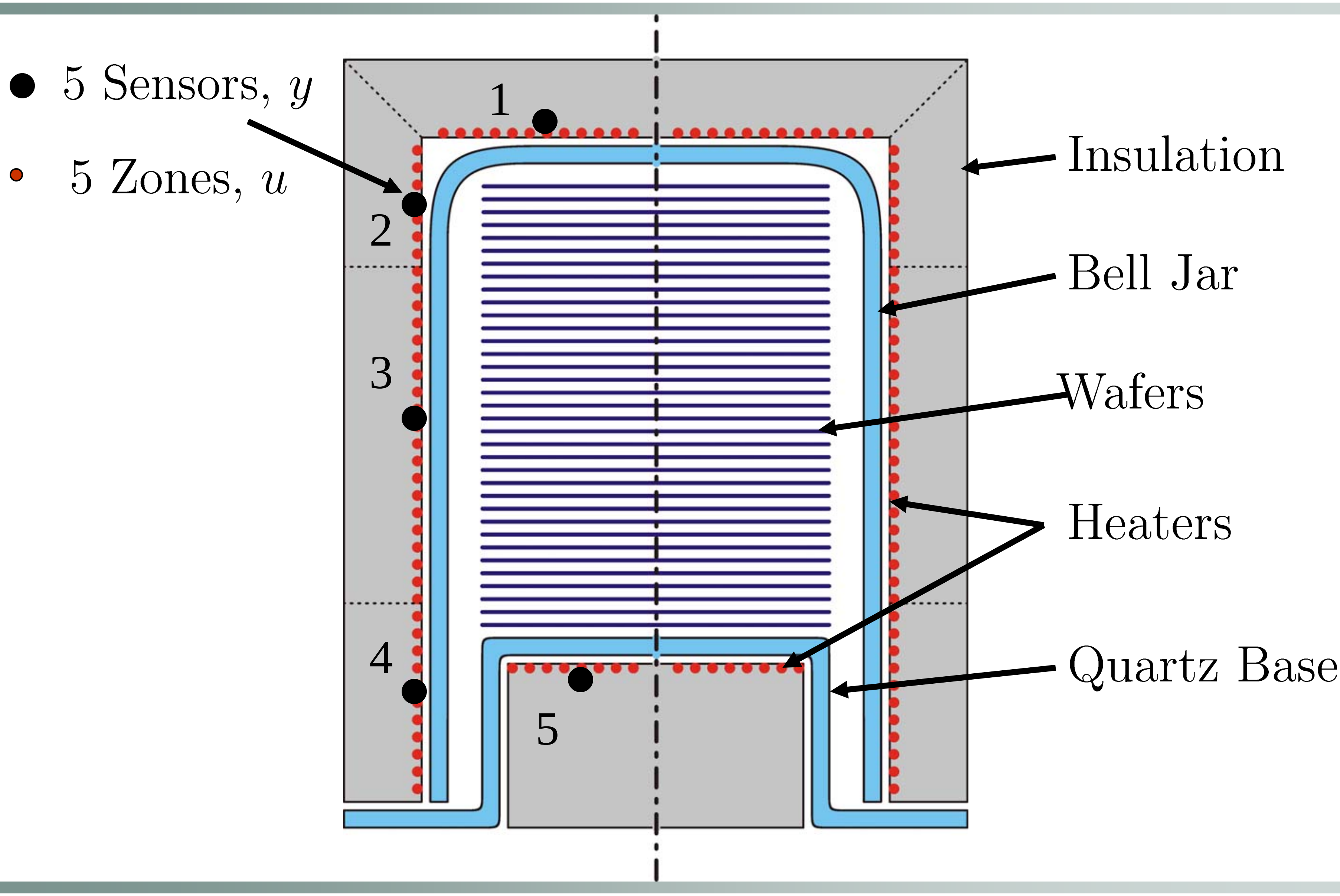
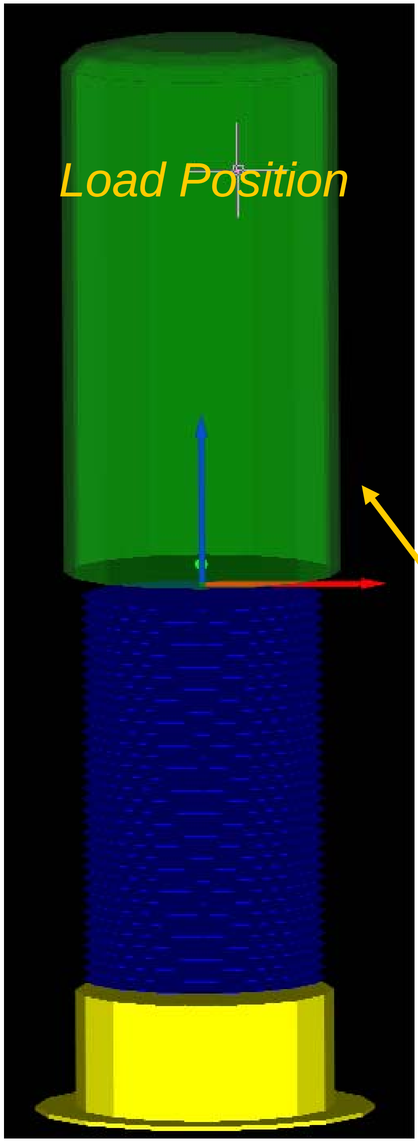
Overview

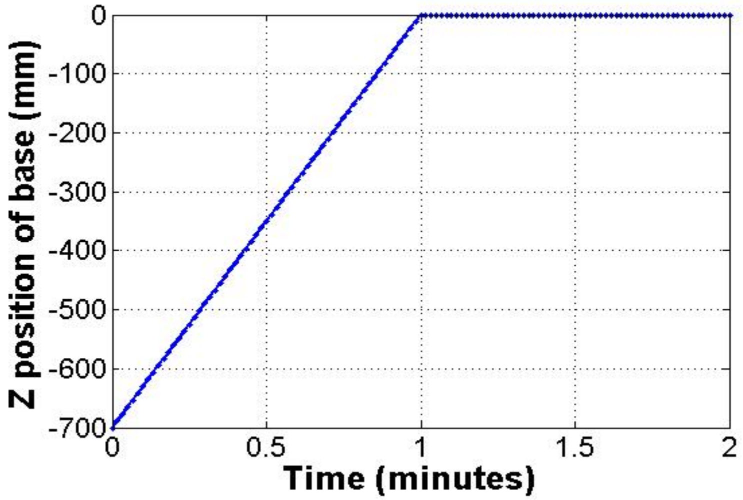
- Vertical Furnace Model
- Closed-loop Simulation
- Temperature Uniformity
- Sensor Failure
- Estimator Design
- Failure Accommodation
- Summary

The Vertical Furnace

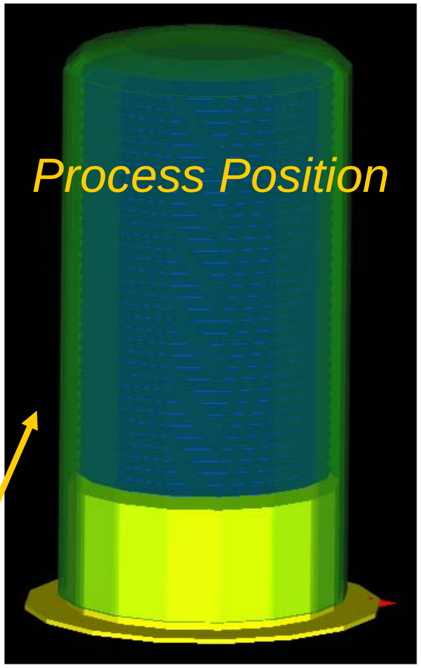


Load Position vs Process Position





Elevation



Surrounding heaters and insulation not shown here.

Vertical Furnace Model

- Full non-linear radiation and conduction model
- Two radiation bands (< 3.3 microns >= 3.3 microns)
- Temperature dependent silicon properties (IR transmission and thermal conductivity)
- Real-time wafer stack vertical position included
- Fast model suitable for real-time execution

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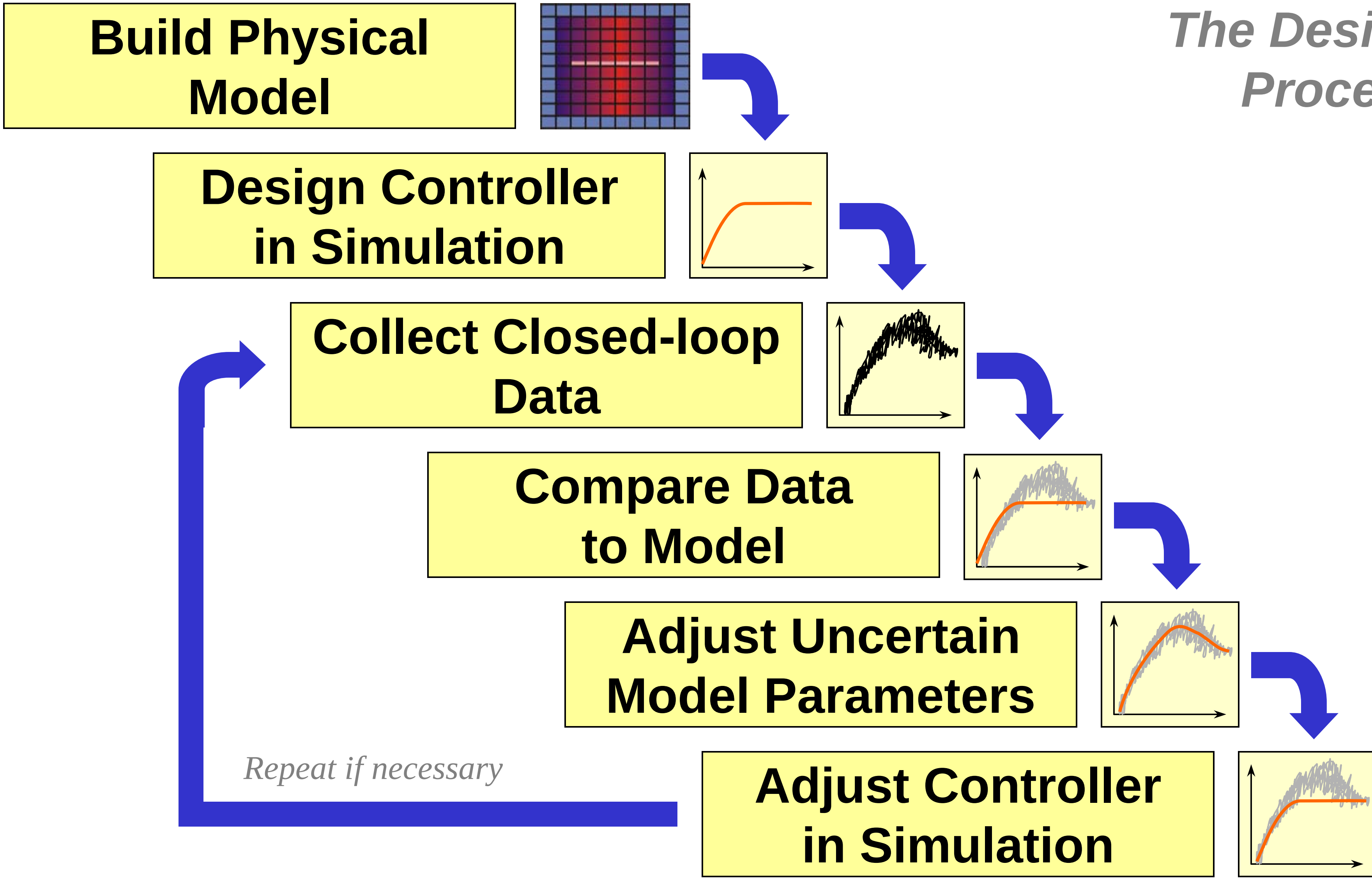
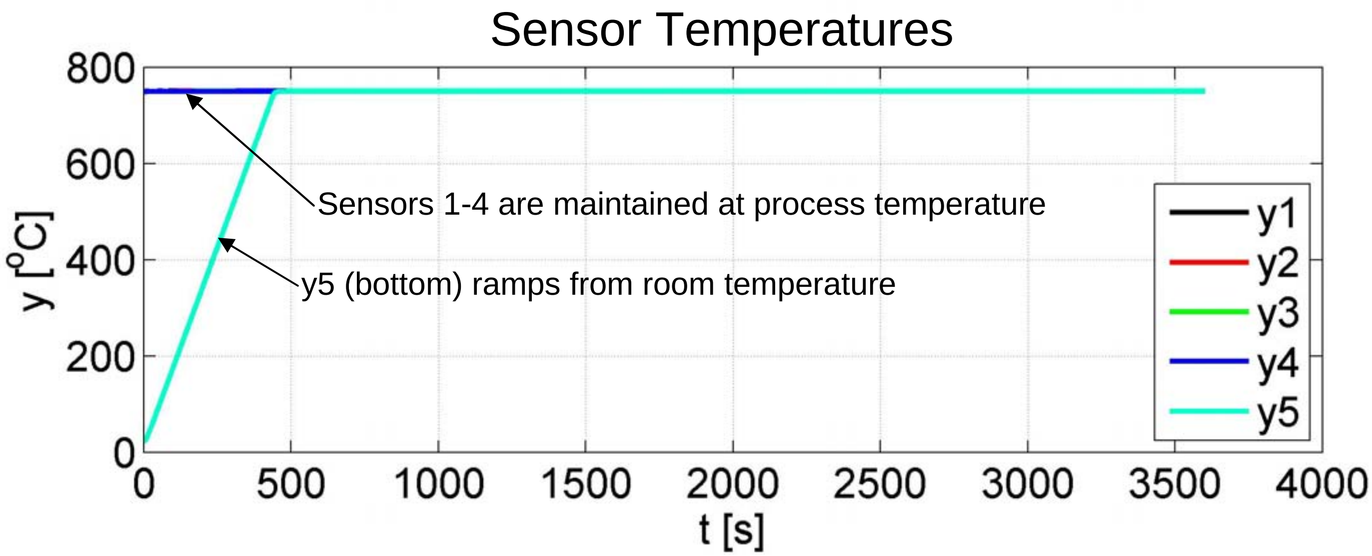
Model-Based Control Design

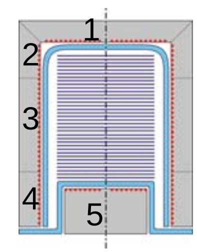
The Design Process

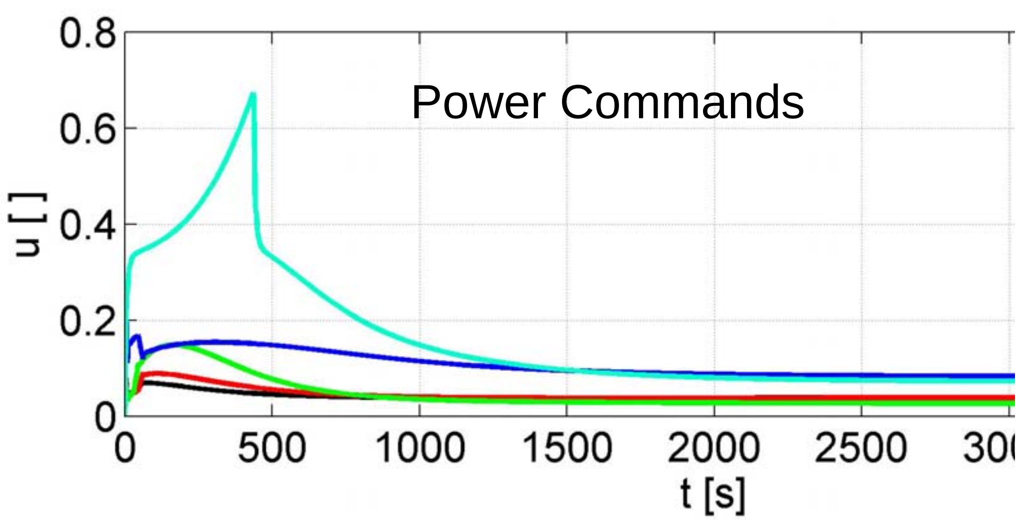


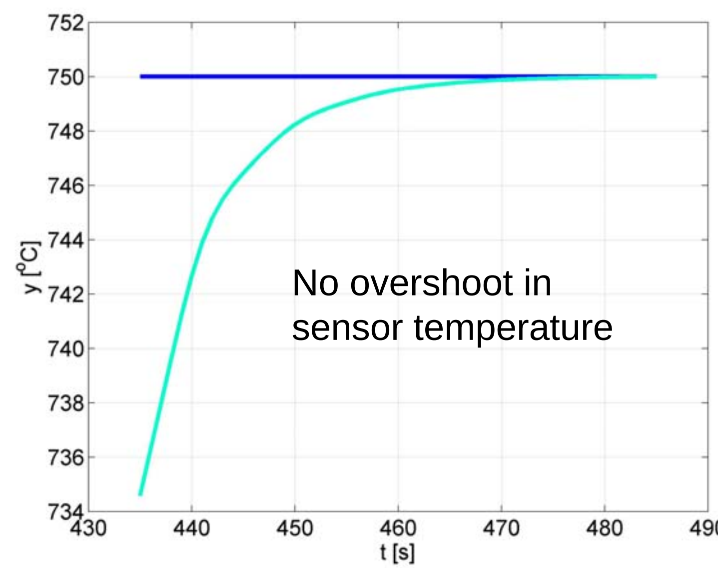
Closed-loop Simulation



Model-based multivariable feedback controller.







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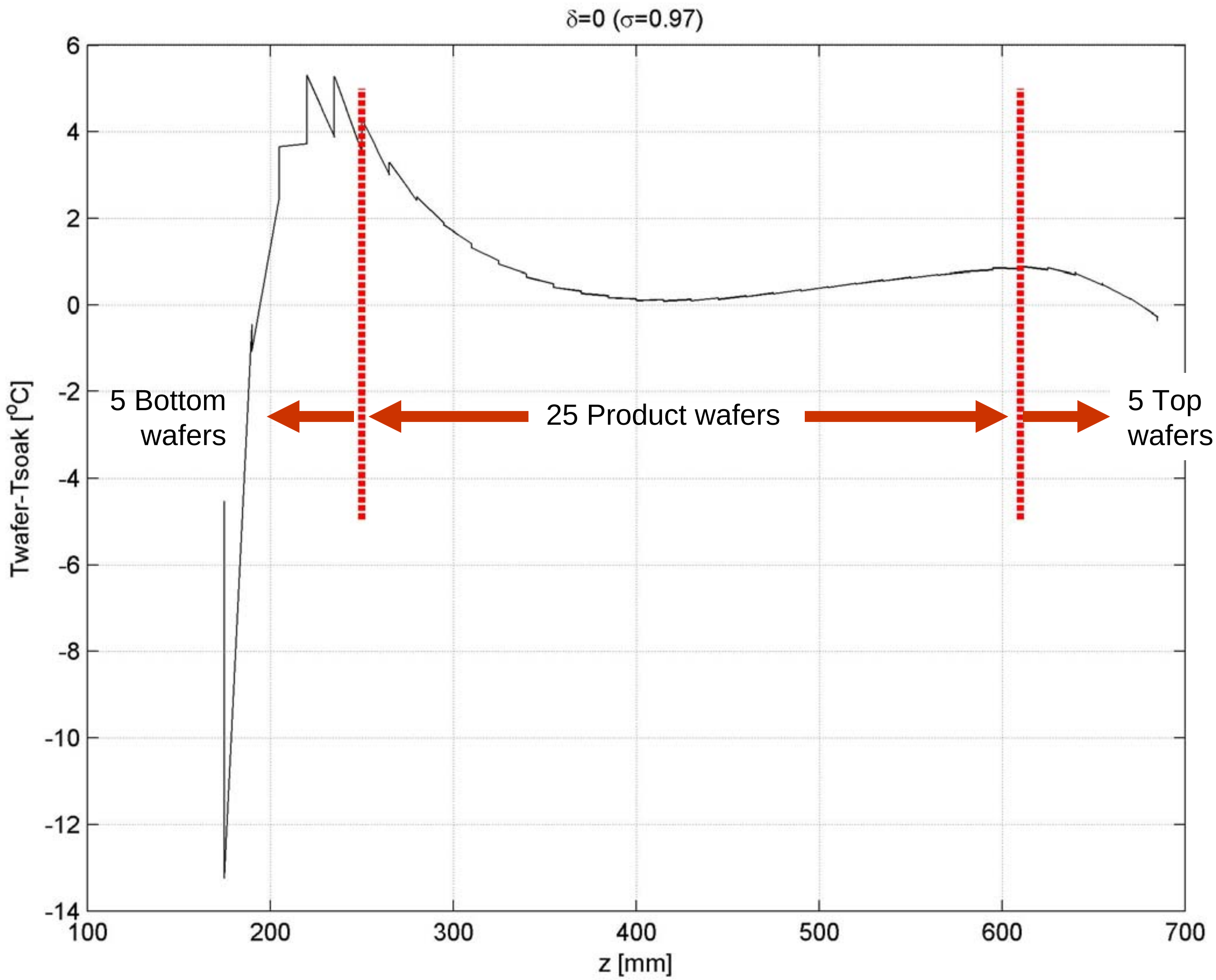
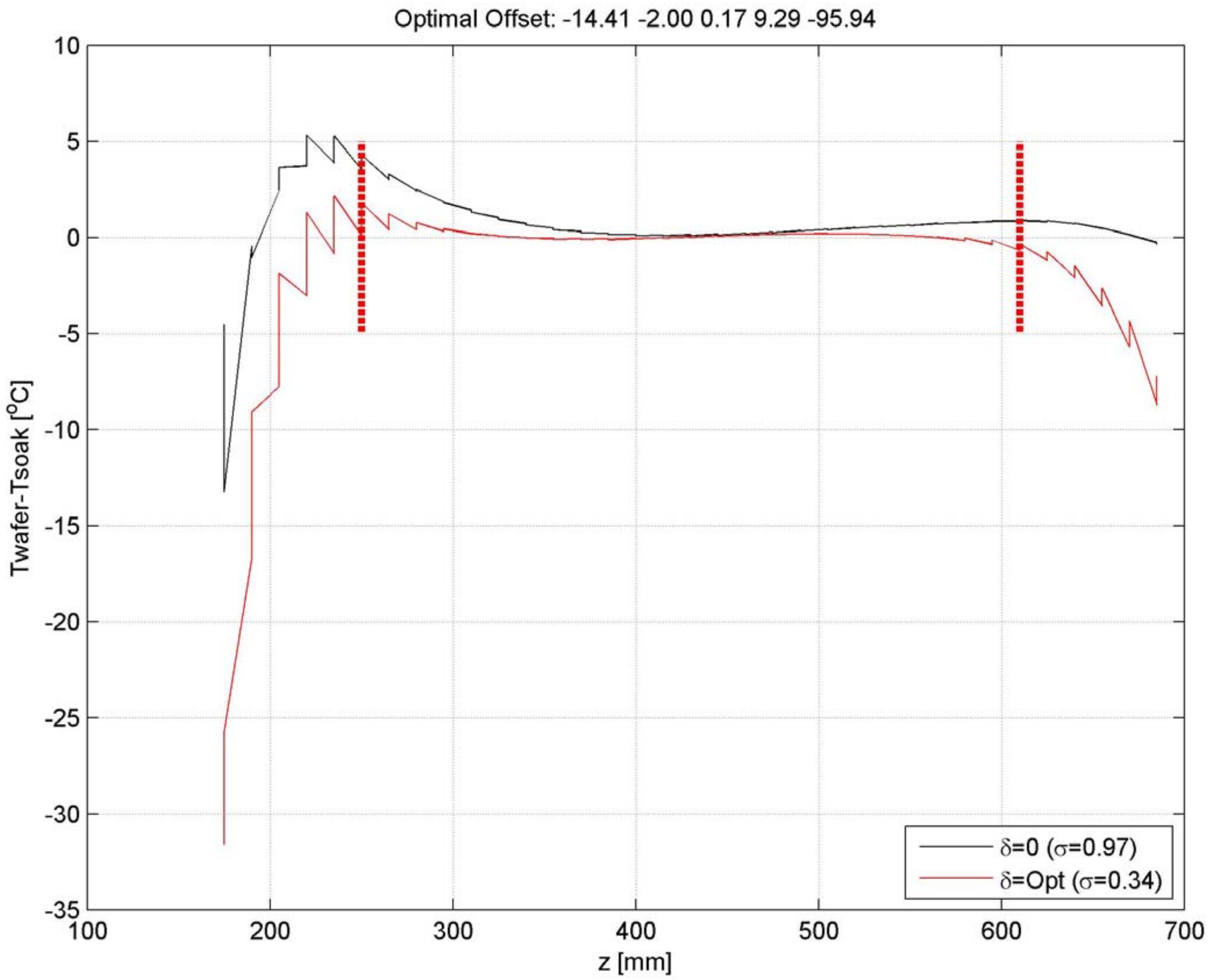
Baseline Wafer Uniformity, No Tuning



Wafer Temperature Uniformity: Optimal



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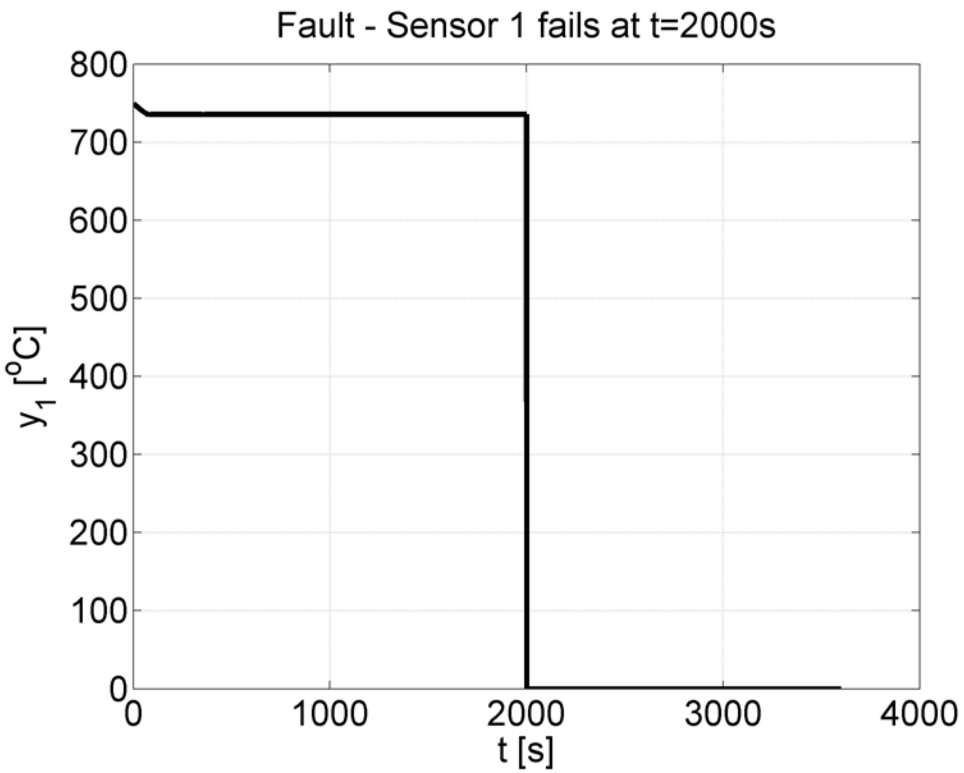
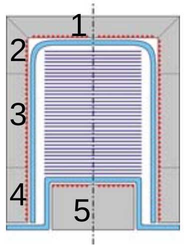
Sensor Failure

- What happens if a sensor fails?
  - *Could abort, but that might ruin a batch of wafers*
  - *Could hold last good value of power, but that might be bad*
  - *Use physics-based model to build a Model-based Estimator*

Sensor Failure

- Simulate a failure where sensor 1 drops out at t = 2000 s





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Estimator Design - Background

A linear system with states x, inputs u, and outputs y can be written as

$$\begin{aligned}\dot{x} &= Ax + Bu + w \\ y &= Cx + Du + \nu\end{aligned}$$

where w is system noise and ν is measurement noise. An estimator can be built that tracks the output y. This estimated output is $\hat{y}$ and depends on states $\hat{x}$ and can be written as

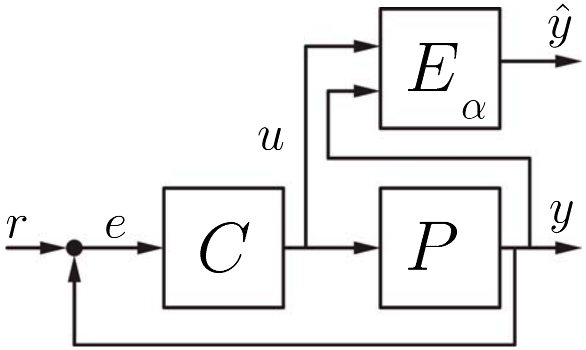
$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} &= C\hat{x} + Du\end{aligned}$$

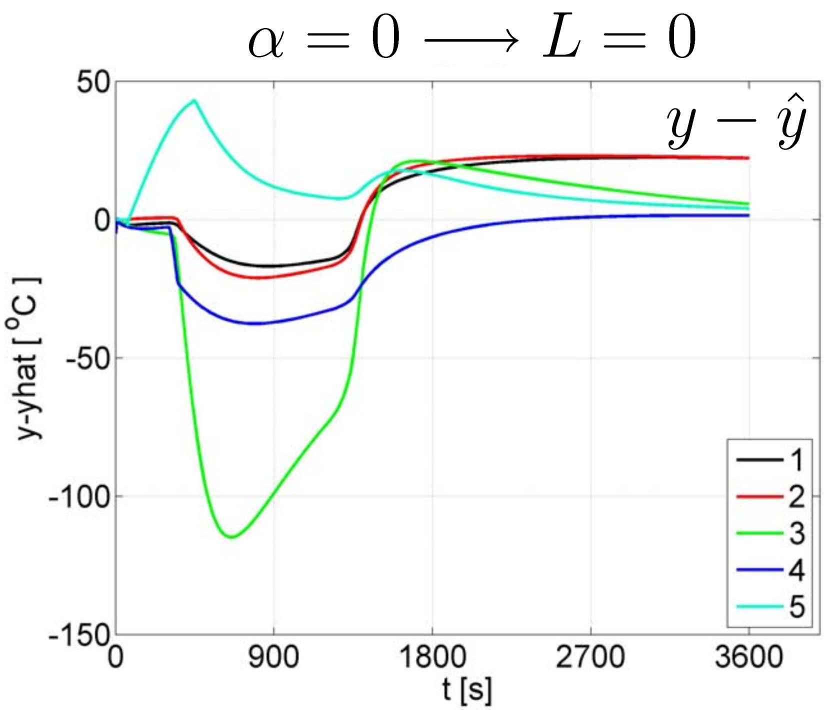
where $L = PC^T R^{-1}$ and P satisfies the Riccati equation

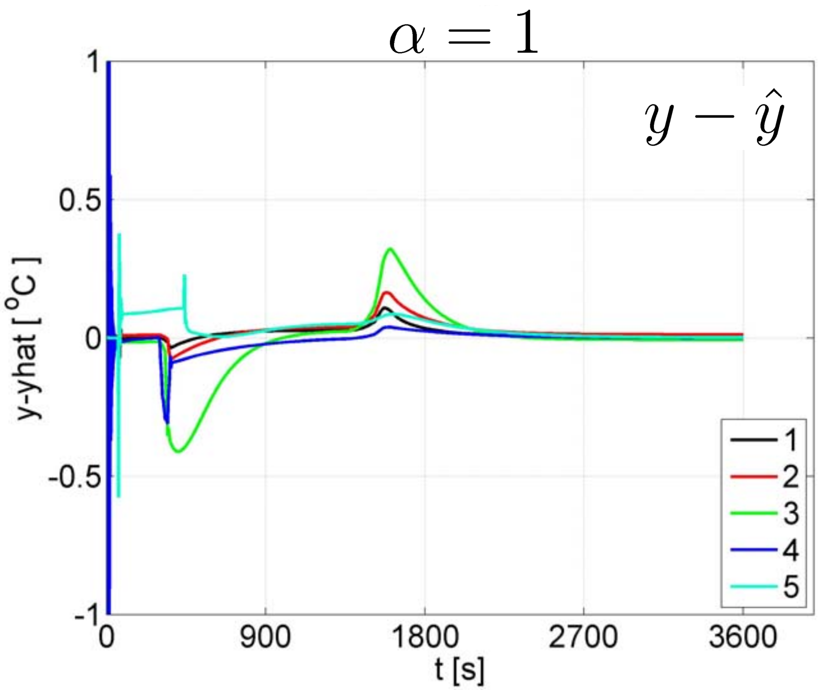
$$\dot{P} = AP + PA^T + BQB^T - PC^T R^{-1} CP$$

Here Q and R are weighting matrices we can tune to vary performance.

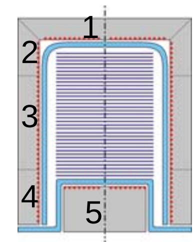
Estimator Design - Example







$$Q = \alpha Q_o$$



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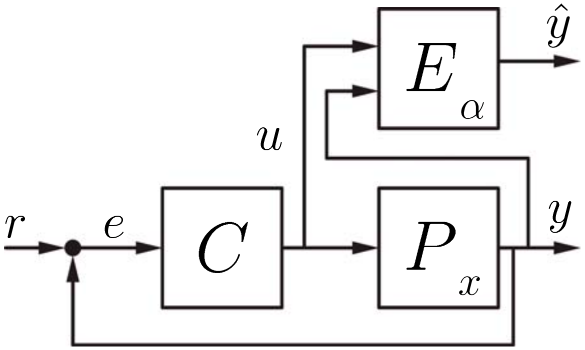
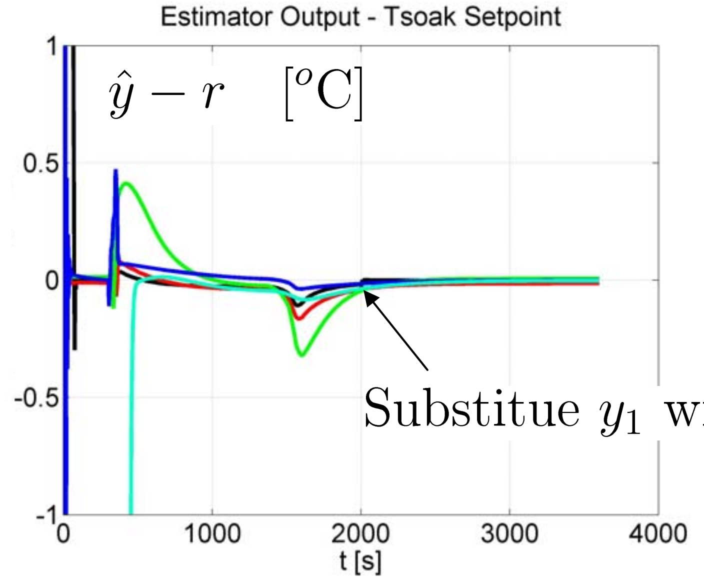
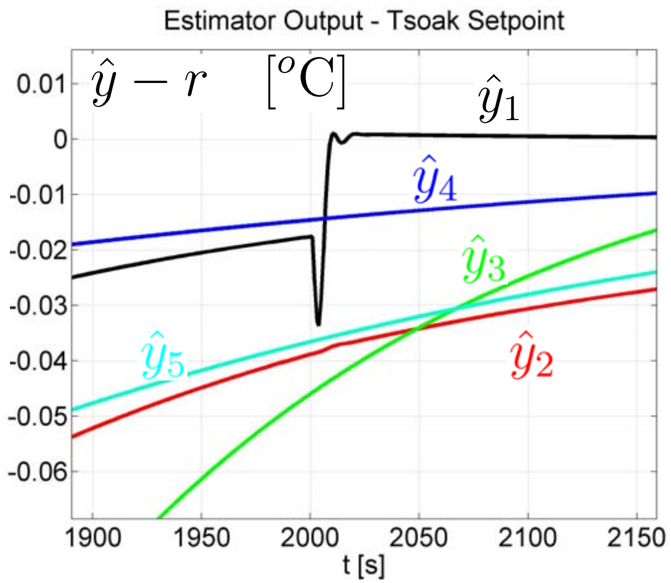
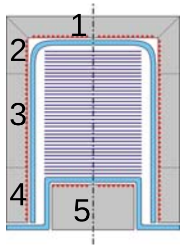
Failure Accommodation



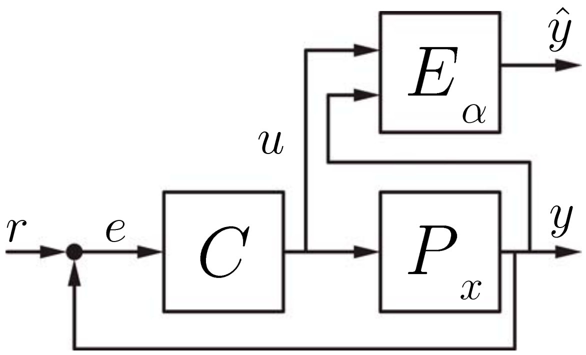


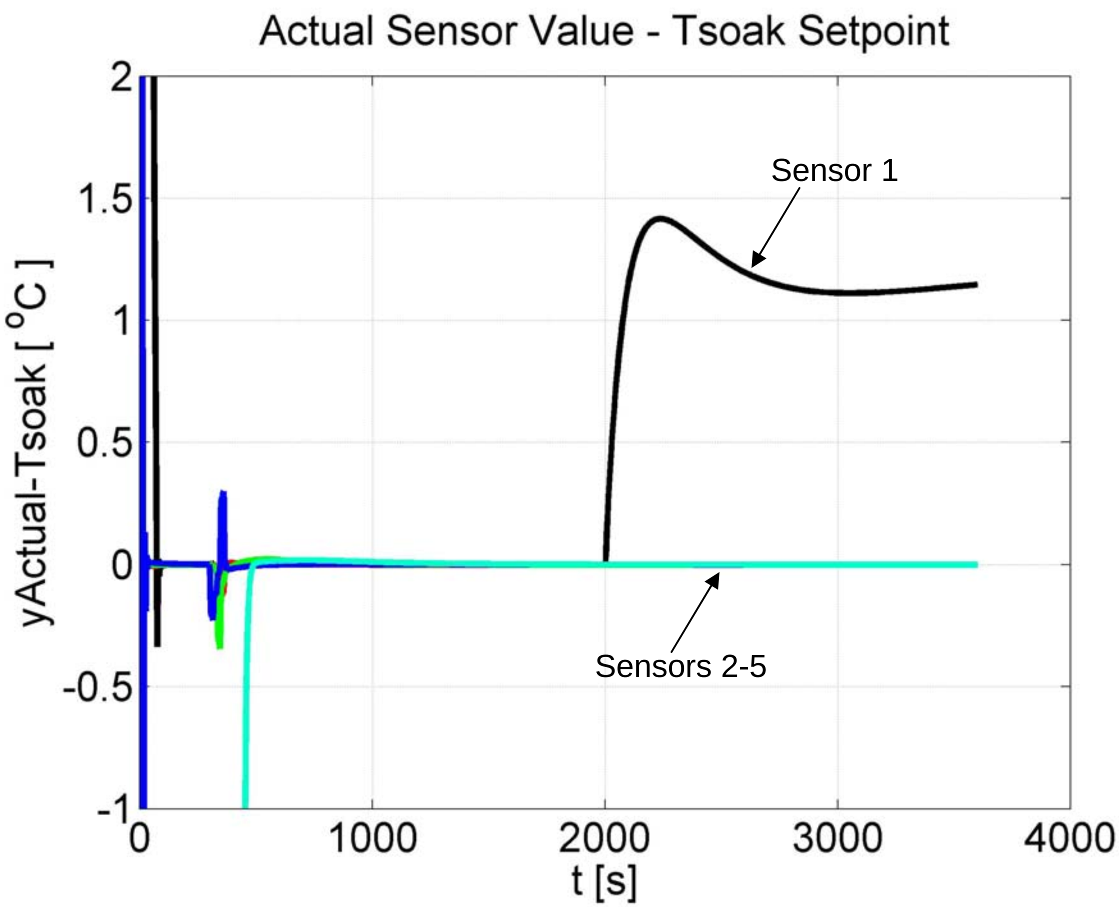


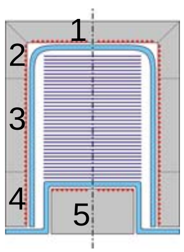
Zoom in on t = 2000 s



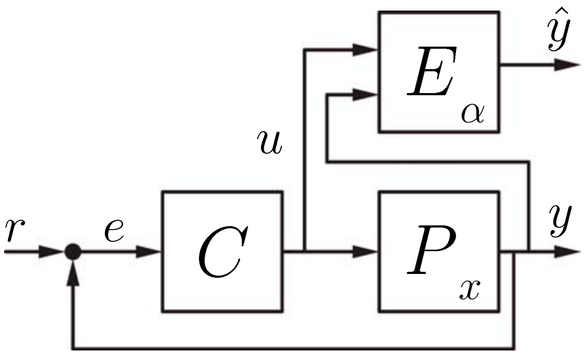
Failure Accommodation



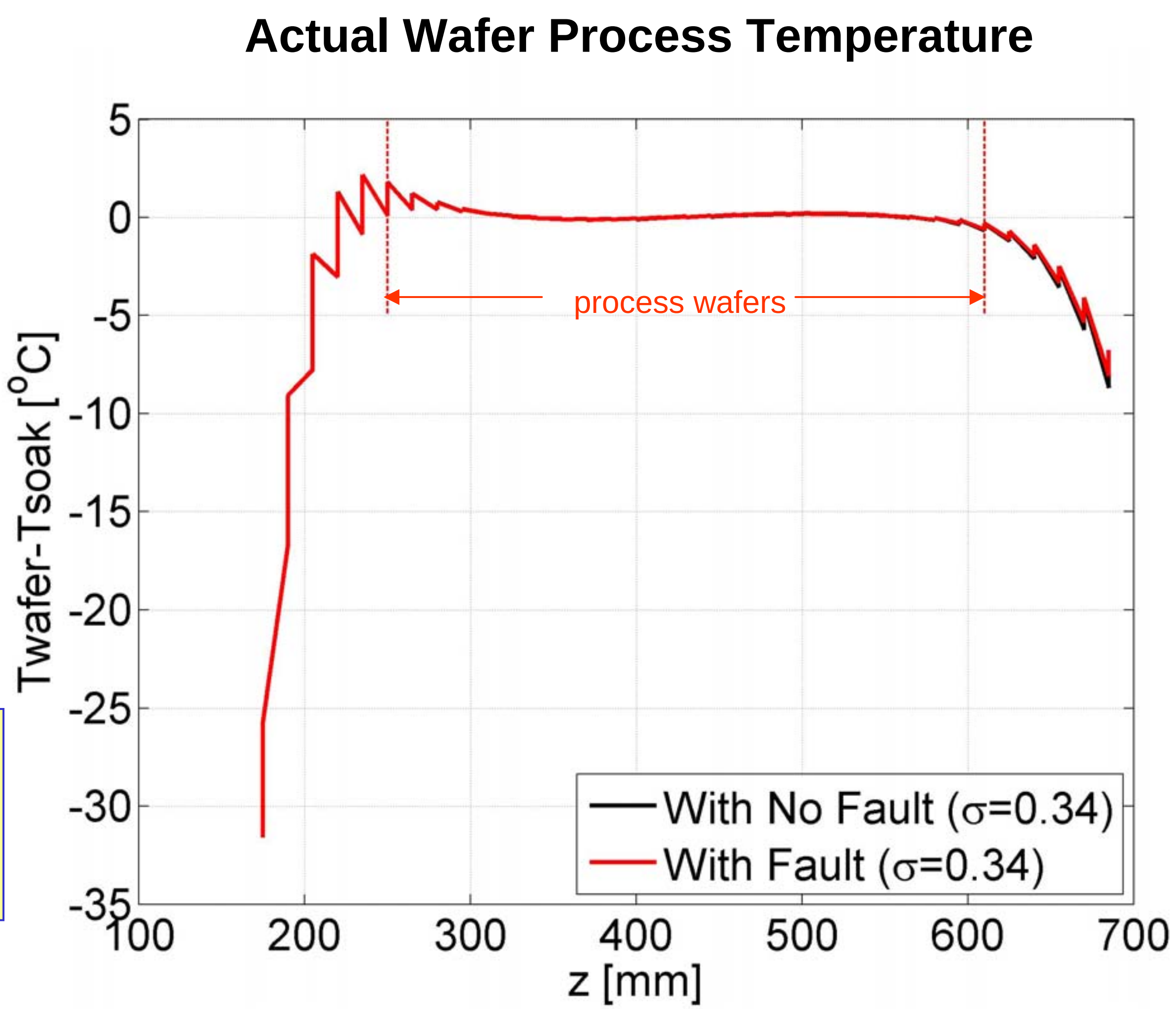




Failure Accommodation



Accommodation is very good for this situation. No change in σ.



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Summary

- **Developed detailed heat transfer model of furnace.**
  - ***Realistic and complex radiation properties***
  - ***Dynamic geometry (wafer stack position)***
  - ***Fast, real-time model***

- **Developed model-based multivariable feedback controller.**
  - ***Robust regulation and tracking***
  - ***No overshoot***
  - ***Good temperature uniformity***

- **Developed model based estimator**
  - ***Use as virtual sensor to predict unmeasured temperatures.***
  - ***Demonstrated use for sensor failure accommodation.***