Glass Defect Reduction in The Tin Bath – Using Sensors, Automation, and Artificial Intelligence to Improve Glass Quality & Manufacturing

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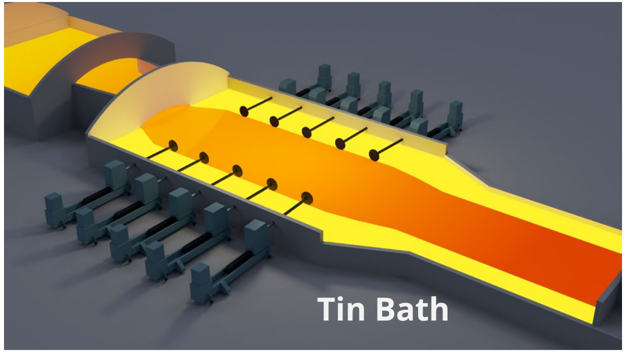
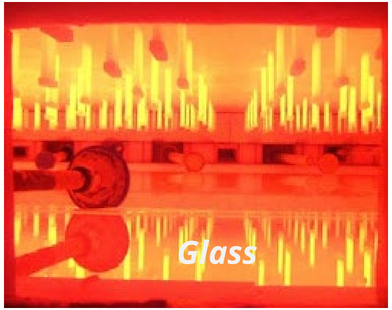
Agenda

- Overview/Background
- Tin-Based Defects
- Monitoring System and Sensor Setup
- AI/Machine Learning Algorithm
- Results
- Conclusions
- Future Work

Tin Bath Atmosphere Monitoring & Optimization

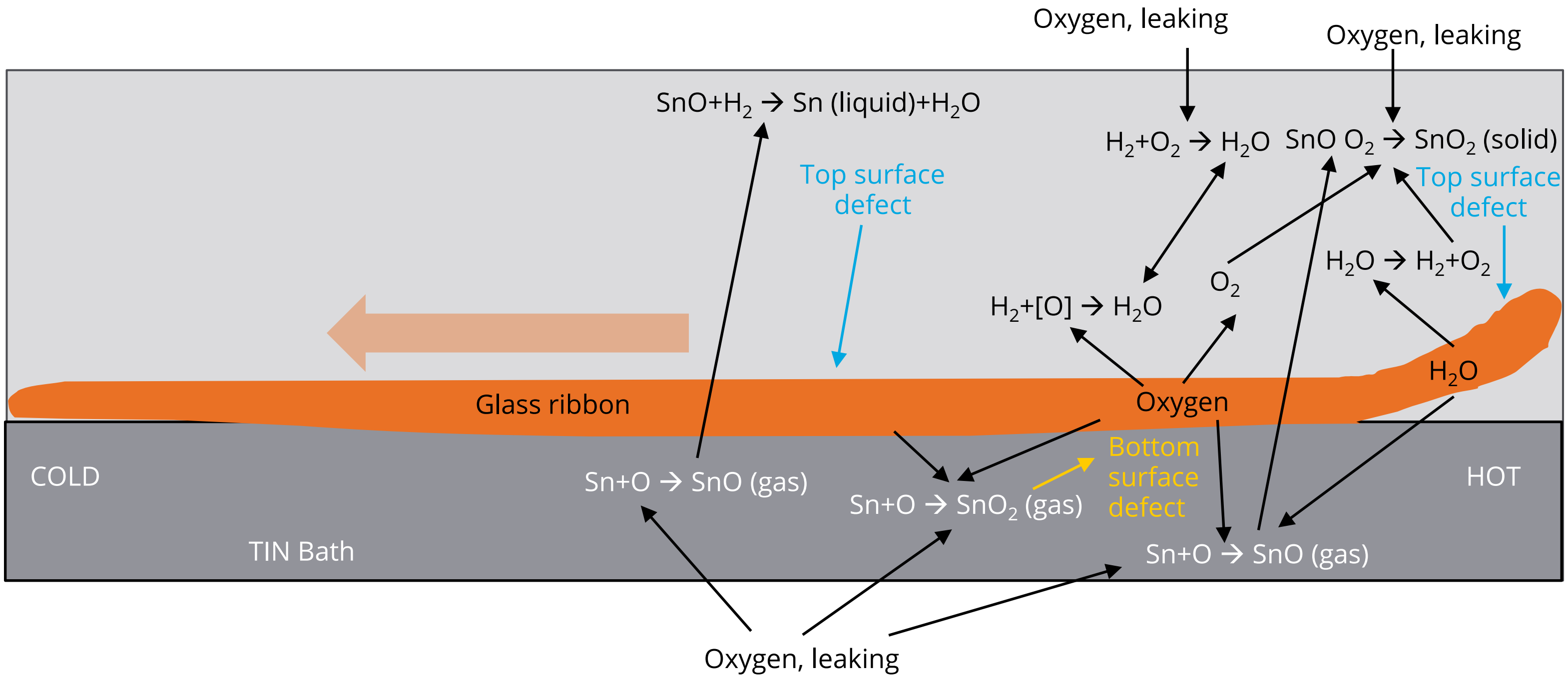


- Tin-based defects can account for up to 1% of lost glass yield due to tin contamination on the glass surface. For a 650 TPD furnace, that yield loss equates to 2,400 tons of lost glass per year, which is valued at approximately $800K USD
- Air Products has developed a new (patent pending) Tin Bath Atmosphere Monitoring & Optimization system to correlate atmospheric conditions with defects
  - Provides continuous measurements of dew point and H_2 concentration, as well as dissolved oxygen in the molten tin
- As the process parameters (including glass thickness and width) change, the system can optimize gas atmospheres to minimize tin defects using AI and machine learning
  - It is in essence a digital twin that can help operators make small control adjustments to minimize the number of tin-based defects formed within the bath
- The result is reduced tin-based defects as well as optimized N_2 and H_2 usage with the goal of minimizing overall H_2 usage



https://washingtonglass.blogspot.com/2010/12/float-glass-fun-facts.html

Tin Bath – Sources of Defects

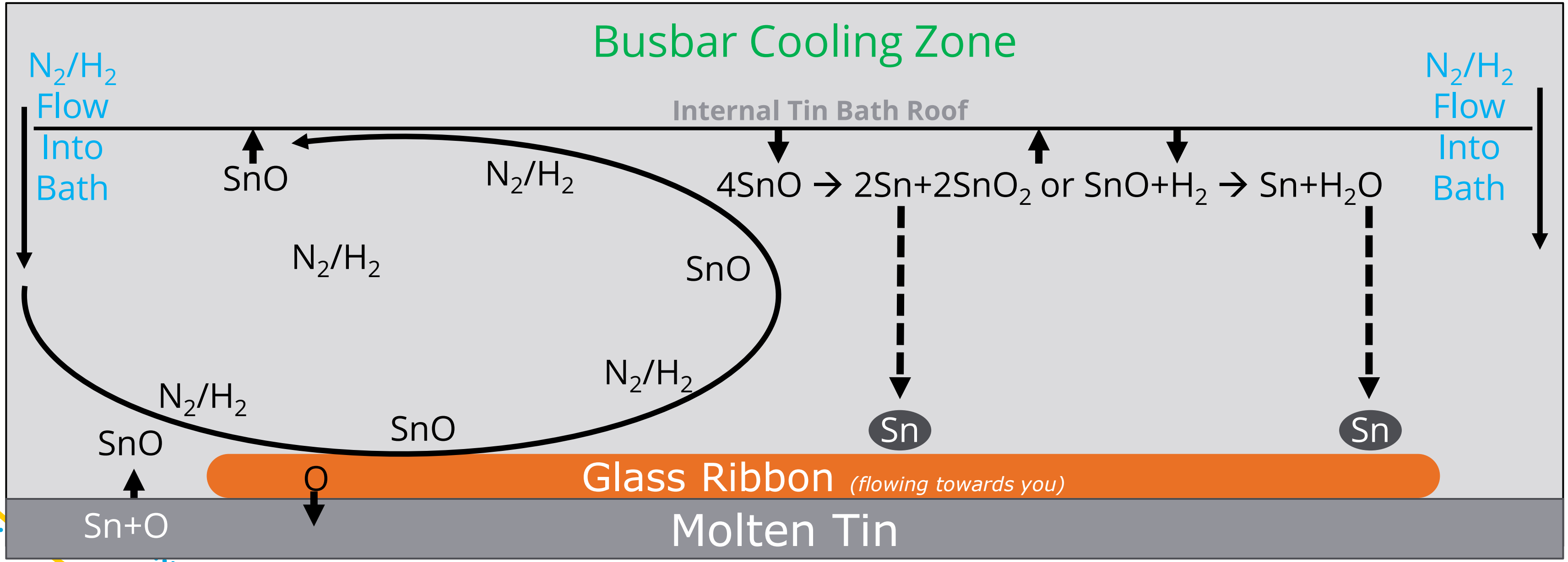


- Oxygen and H_2O can be dragged into the tin bath with the glass ribbon
- O_2 then reacts with molten tin creating tin oxide which can become a vapor, condense and agglomerate, and/or stick to the glass ribbon

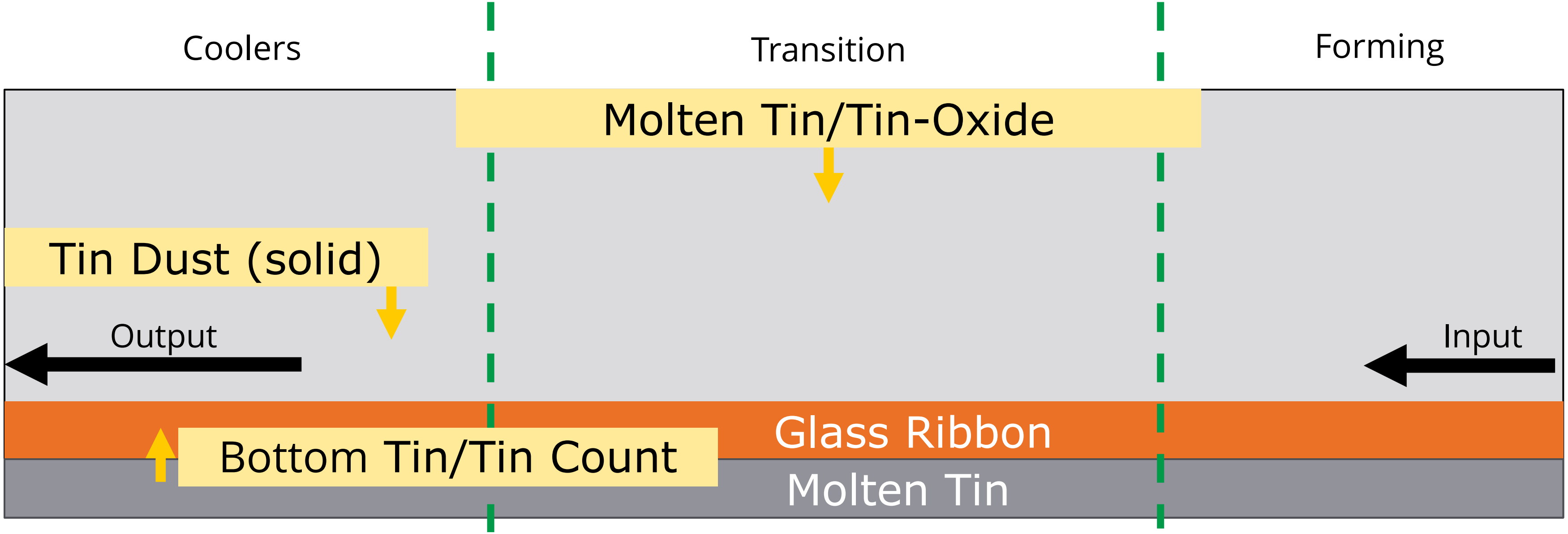
Tin Bath – Source of Defects

Tin Monoxide (SnO) to Liquid Tin (Sn) Cycle

The flow patterns of N_2/H_2 inside the tin bath can sweep tin-oxide vapor to roof where it can condense, react, then drip onto top surface of glass ribbon



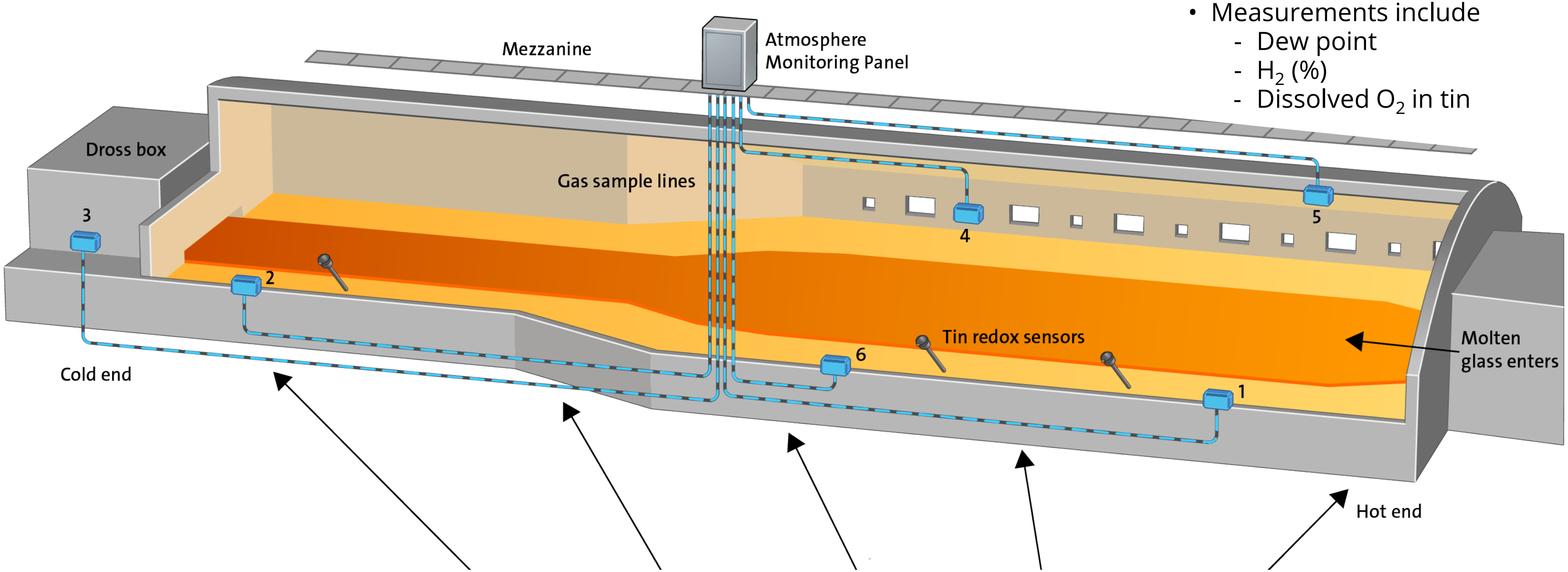
Defect Types By Approximate Location



- Top surface defects include molten tin and/or tin-oxide drips and/or larger dust-like agglomerations of tin-oxide
- Bottom surface defects include larger tin-oxide or thin tin layer often referred to as tin-count

Air Products Tin Bath Atmosphere Monitoring System*

- Continuous gas sampling
  - Locations vary by temperature
- Measurements include
  - Dew point
  - H_2 (%)
  - Dissolved O_2 in tin

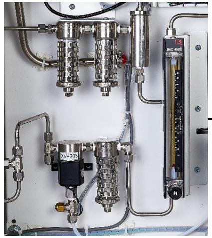


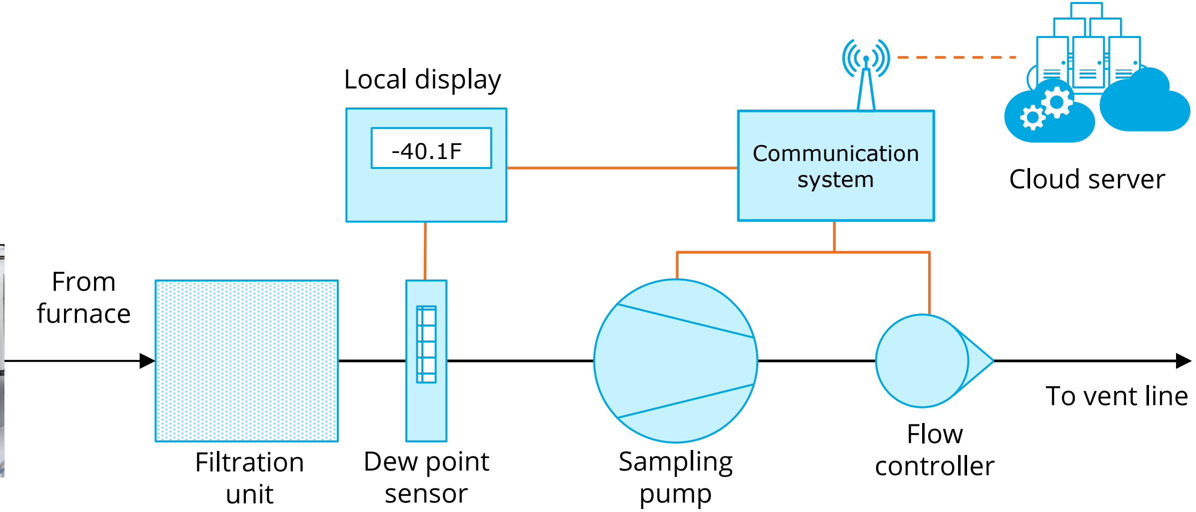
Zone	5	4	3	2	1
Tin temp (C)	600 - 650	775 - 790	800 - 875	925 - 975	1050 - 1100

* patent pending

Atmosphere Monitoring System – Dew Point Measurement

Atmosphere Monitoring Panel



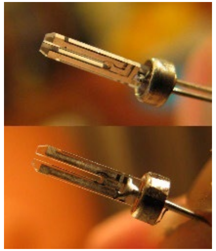


- Staged stainless steel filter system to protect sensors
- Sensor system at stable temperature
- Data management on cloud server

Air Products Novel PQT Sensor for H_2 Measurement

- Air Products' novel PQT Sensor can measure H_2 in a variety of gas mixtures including humidity
  - "P" – Pressure, "Q" -Molecular mass, "T" - Temperature
- **Core technology is Quartz Tuning Fork Oscillator**, to measure gas density
  - A pair of electrodes are attached to the narrow sides of each fork
  - When applying volts on the electrodes, the forks move in a 'clap-hands' way, in the same direction, because of the wiring
  - Connecting one wire (two electrodes) to the input, the other wire (also with two electrodes) to the output of an amplifier → feedback oscillator
- Additional features:
  - **Temperature sensor** to measure gas temperature
  - **Pressure sensor** to measure gas pressure
  - **Microprocessor** as the 'brain' of this sensor
  - **Wired/Wireless data output**

Air Products PQT Sensor for H_2



Tuning fork sensor can correlate changes in frequency with density changes

Air Products Public

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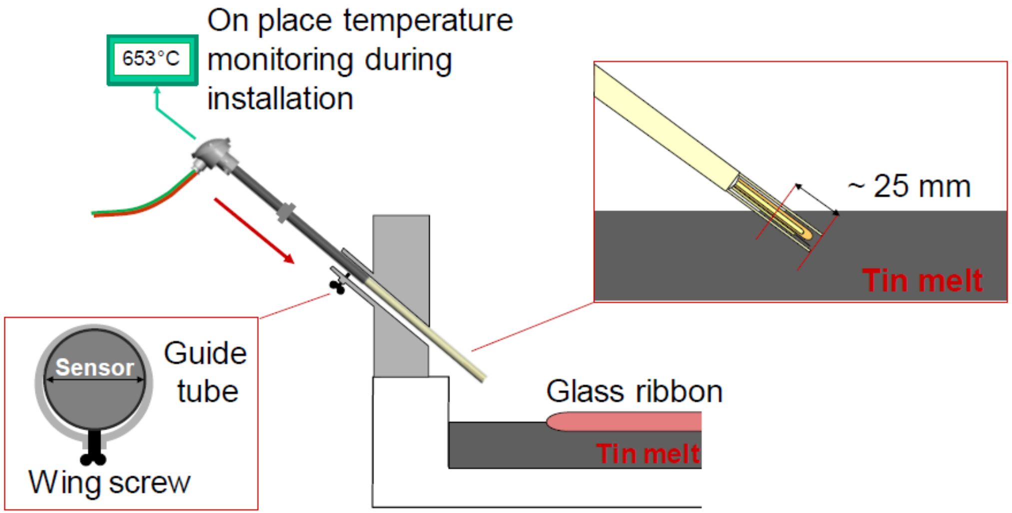
Atmosphere Monitoring System – ReadOx Probes

- Specialized probes from ReadOx were used to measure dissolved oxygen within the molten tin
- This data helps us to understand the level of oxygen absorption into the tin bath
- The ReadOx probes can be installed in place of a thermocouple



https://www.readox.com/product/tin-melt-oxygen-sensor/

Tin Bath Atmosphere Process Advisor
Digital Twin with Machine Learning

Digital Twin

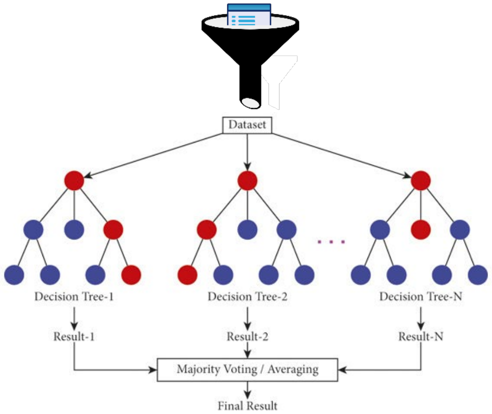
Data Preprocessing	Machine Learning	Auto Updating

Digital Experiments

Drive Towards Lowest Defects & Optimal H_2 Usage

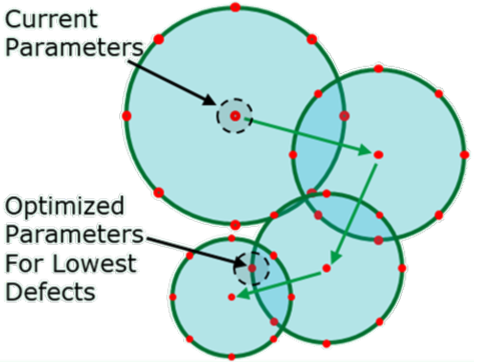
AP Smart View Plus HMI

Alert Operators To Required Changes



Random Forest Model

https://mlarchive.com/machine-learning/decision-trees-and-random-forest-all-you-need-to-know/



Search algorithm allows for faster model optimization

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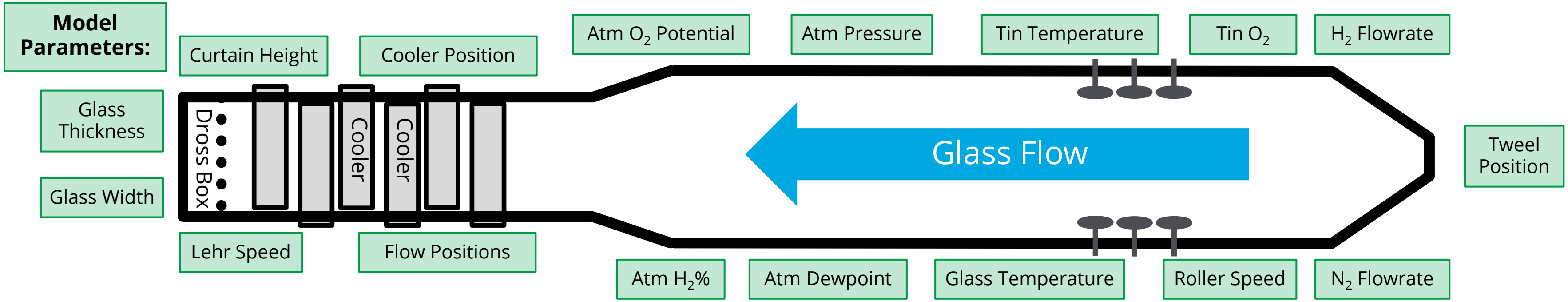
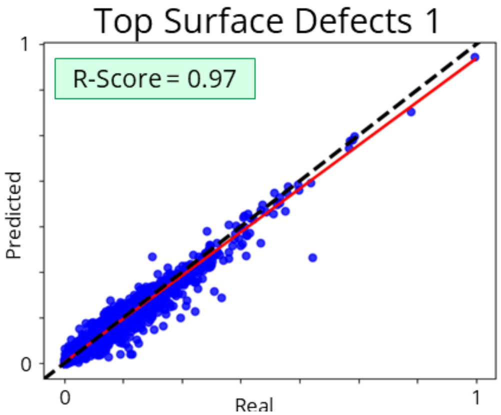
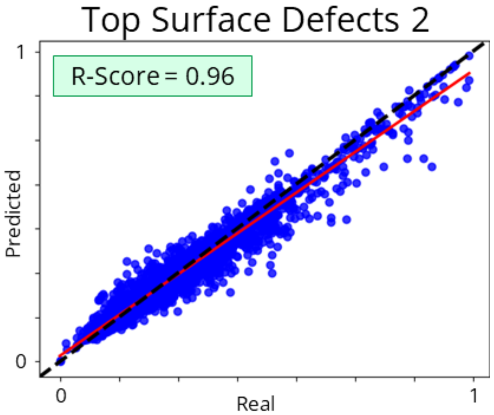
Tin Bath Digital Twin With Machine Learning

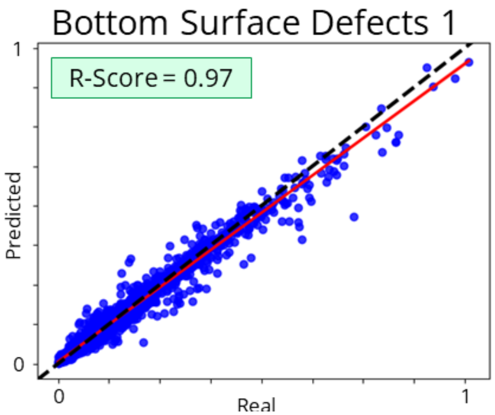
Black Box Model for Black Box Chemistry



Digital Twin Modeling Results – Strong Correlation observed!

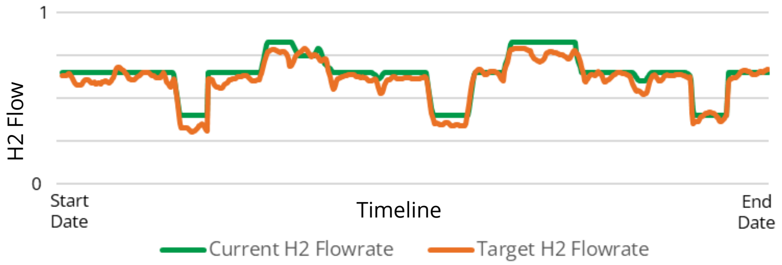




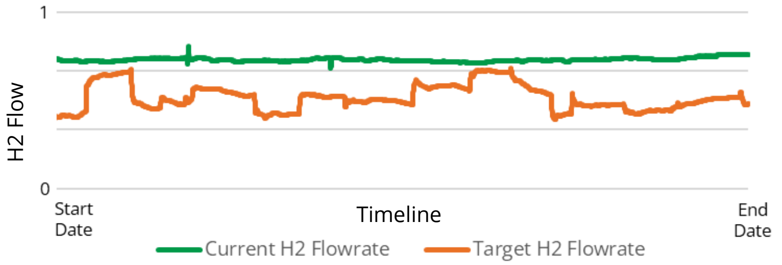


Tin Bath Optimization
Machine Learning Model Suggests Process Changes

- Air Products' machine learning (ML) model predicts when process changes need to occur (orange "target" line).
  - *This is based on a variety of factors, e.g., glass thickness or ribbon speed*
- When the model is followed, the result is a reduction in tin-based defects
- Currently our system is not a closed-loop that makes automatic adjustments. Operators must choose to respond and make the corresponding change
  - *Eventually closed loop automatic control will be an option, but while this system is new, we opted for a safer approach to allow the plant to have full control*
- Model predictions improve with time as a larger historical data set becomes available



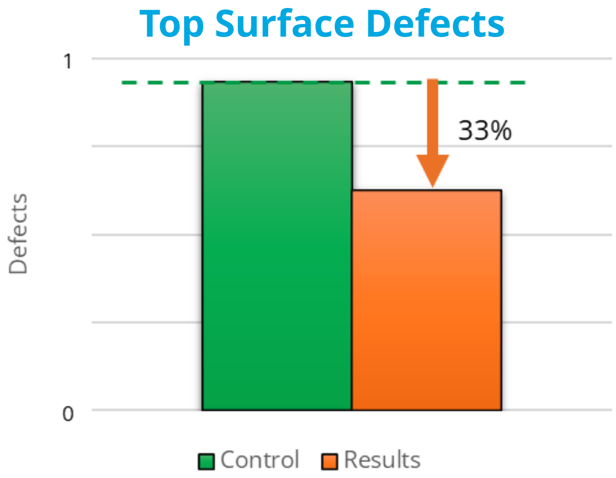
Customer following AI model-suggested operation



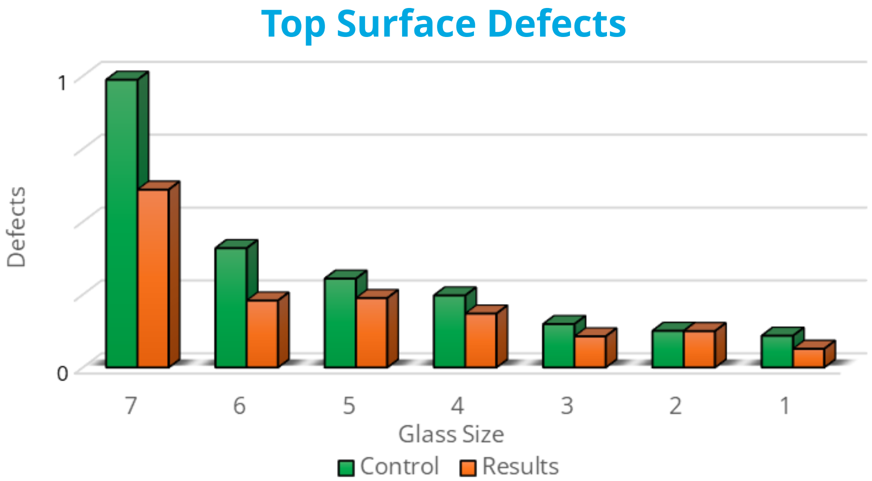
Customer operating tin bath in static mode

Results

Top Surface Defects were reduced by 33%

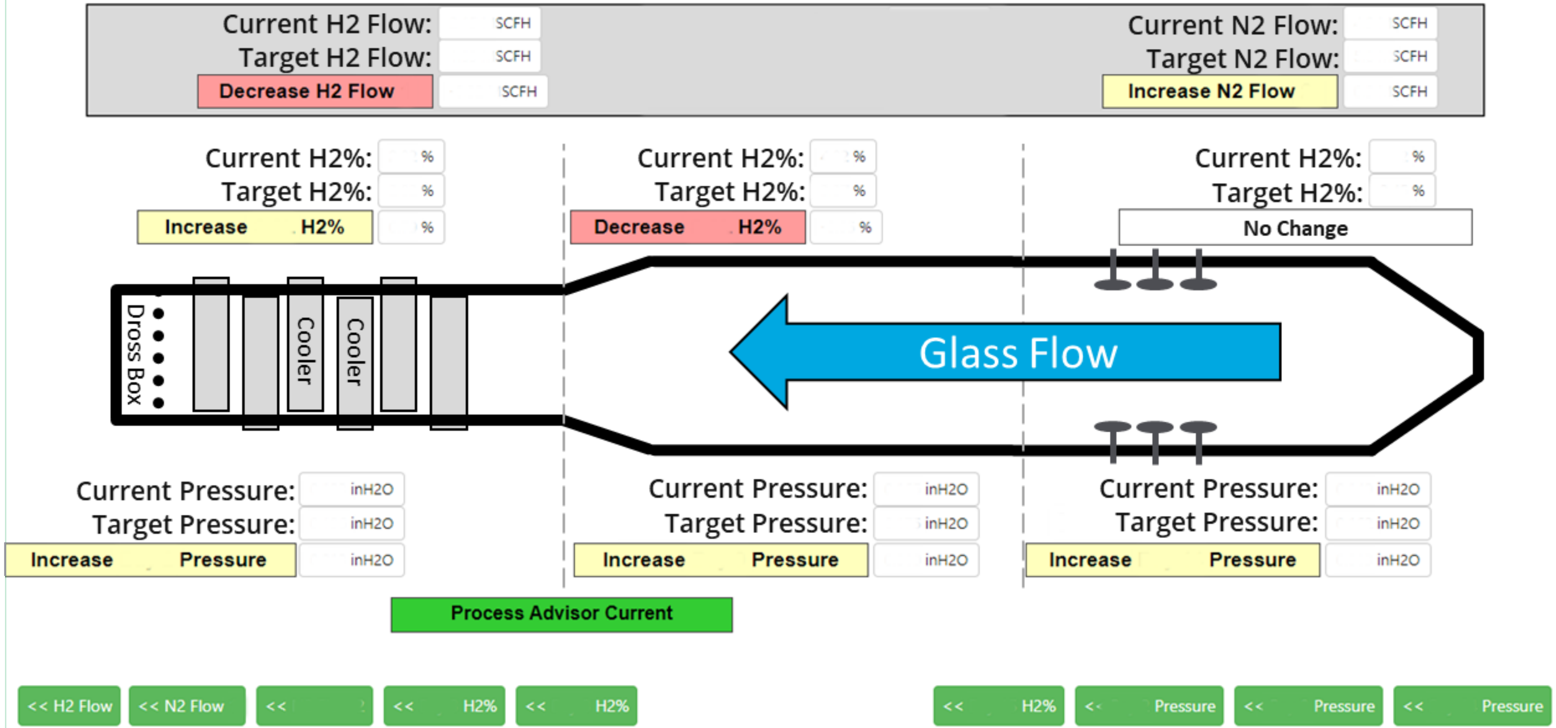


The largest reduction in defects was observed in glass thicknesses with the highest defect count



- For glass produced under control runs, process parameters were kept constant and thus top surface defects were higher
- For glass produced with ML model-suggested control, top surface defects were lower

Tin Bath Monitoring & Optimization – Process Advisor



Conclusions

- Air Products Tin Bath Atmosphere Monitoring & Optimization system is a novel system that provides operators with a means to control their Tin Bath more effectively, while reducing tin-based defects
- Continuous measurements of dew point, H_2 conc (%), and dissolved O_2 in molten tin provide operators with a real-time view of the status and health of the tin bath
- System uses state-of-the-art machine learning to predict defects and suggest changes to help mitigate defects. The system learns as conditions within the Tin Bath change over time
- A trial of the system achieved approximately ~30% reduction in tin-based defects and the increased glass yield has a value of nearly $200K USD per year!

Future Work

- A new installation will be online in Fall 2025 in a full oxy-fuel float glass furnace
- The system will continue to learn and improve as the training data set grows. We expect even greater defect reduction is possible
- Seeking to expand model to include sulfur species as other potential sources of defects

Thank you

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