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ASI Advanced Sensors and Instrumentation

ADVANCED CONTROLS

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

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Project Overview

Scope

- Investigate advanced monitoring and control capabilities enabled by a digital twin (DT)
- Demonstrate the use of a DT in the health monitoring of an engineered system and how it can inform a control task
- Demonstrate the use of a DT in the control of an engineered system and how in can provide for seamless transition across operating points and between operating modes
- Evaluate operational performance improvements achievable for the sodium purification system in the ANL METL facility

Project Overview

PI - ANL

- Rick Vilim

Participants - ANL

• Tim Nguyen	Diagnostic Algorithm and Uncertainty Analysis
• Alex Heifetz	Digital Twin and Control Algorithm
• Roberto Ponciroli	Process Engineering
• Hubert Ley	Networking, Databases, Computer Communication
• Tom Elmer	Visualization and Human Factors
• Derek Kultgen	METL Facility Operations

Participants – Purdue University (student)

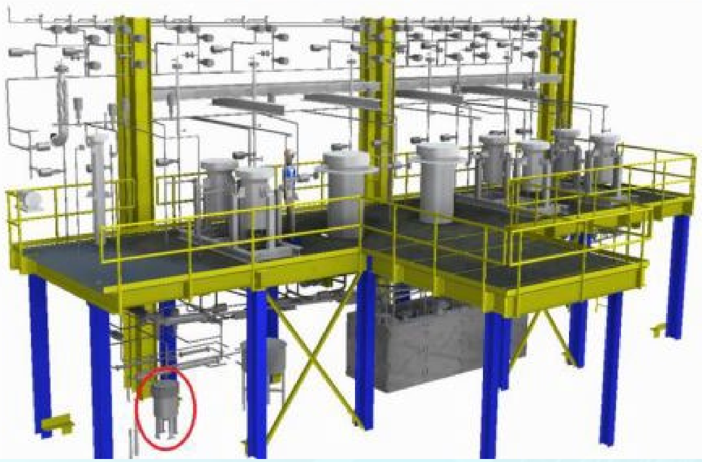
• Rita Appiah	Control Algorithm

Project Overview

ANL METL Facility as a Test and Demonstration Platform

- Mechanisms Engineering Test Loop (METL) facility
  - An intermediate-scale facility for testing instrumentation and components in a prototypical liquid-metal reactor environment
- Supports testing of monitoring and control methods for sodium reactor systems
  - Semi-scale electrical heated reactor primary system
  - Secondary heat removal system
  - Sodium purification system
  - 300 heater zones
  - +1000 sensors
  - Digital control system

The METL facility at Argonne National Laboratory.

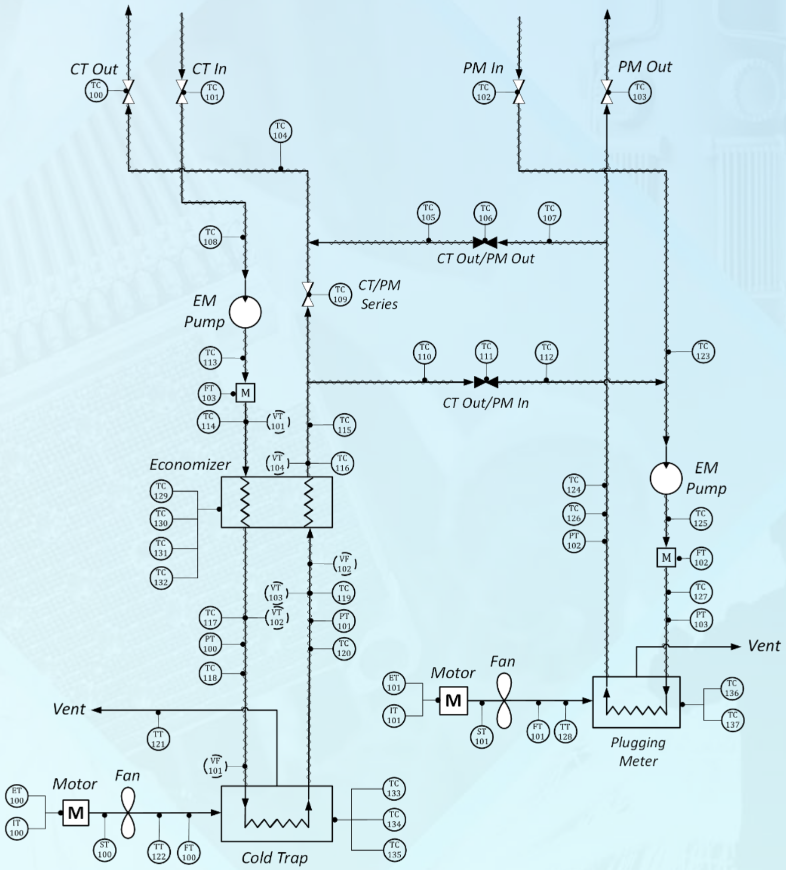


3D model of the liquid sodium loop and four test vessels. The cold trap is circled.

Project Overview

Monitoring and Control in the METL Sodium Purification System

- Control coolant chemistry to limit impurity concentrations
  - In-leakage of oxygen and water result in production of sodium oxide and sodium hydroxide impurities, which precipitate out as solids
- Impurity concentration is controlled by a system consisting of two parallel flow paths
  - A plugging meter that measures the level of sodium compound impurities
  - A cold trap that filters out these impurities



PRO-AID Sodium Purification System P&ID

Project Overview

METL Sodium Purification System Operating Modes

- Purification Mode - Only the cold trap is used to precipitate impurities
- Measuring Mode - Only the plugging meter is used to monitor the impurity levels within the flowing sodium.
- Purification/Measuring Mode - Both the cold trap and the plugging meter are connected to the main loop in parallel to simultaneously clean and monitor the bulk sodium.
- Test Mode - Both the cold trap and the plugging meter are connected in series to determine the effectiveness of the cold trap at different temperatures and flow rates.

Side and front views of the cold trap and blower.

Technology Impact

Advance Condition Monitoring using Digital Twin

- Realize fault diagnostic capabilities in engineered systems not achievable through anomaly detection algorithms
- Achieve more efficient staffing through automation of labor-intensive tasks
- Target remote utility's monitoring and diagnostic center
  - One person – Multiple systems and units
- In late stage CRADA discussions with major power systems vendor

PROAID

Improve Operational Performance using Digital Twin

- Provide for seamless updating of control algorithm with operating point change and process degradation
- Enable control across multiple production assets (e.g. nuclear/storage systems) where human would be challenged

Results and Accomplishments

Development of Digital Twin (DT) Models

Mass balance of Oxygen Precipitation:

$$\frac{dm}{dt} = \frac{d(\rho V)}{dt} = \sum_{i=inlet} \dot{m}_i - \sum_{j=outlet} \dot{m}_j$$

Oxygen concentration as:

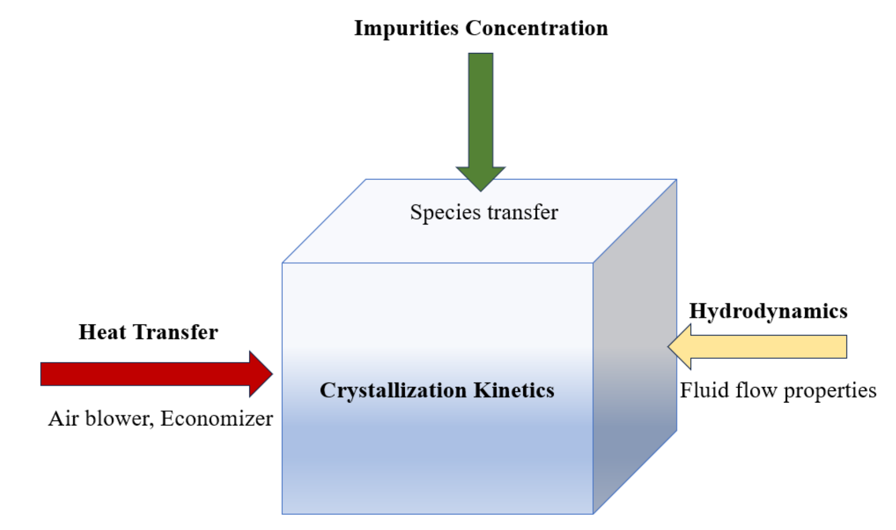
$$\frac{dC_{O_2}}{dt} = r_{O_2} V \left(\sum_{i=inlet} C_{O_{2i}} q_i - \sum_{j=outlet} C_{O_{2j}} q_j \right)$$

Reaction Rate:

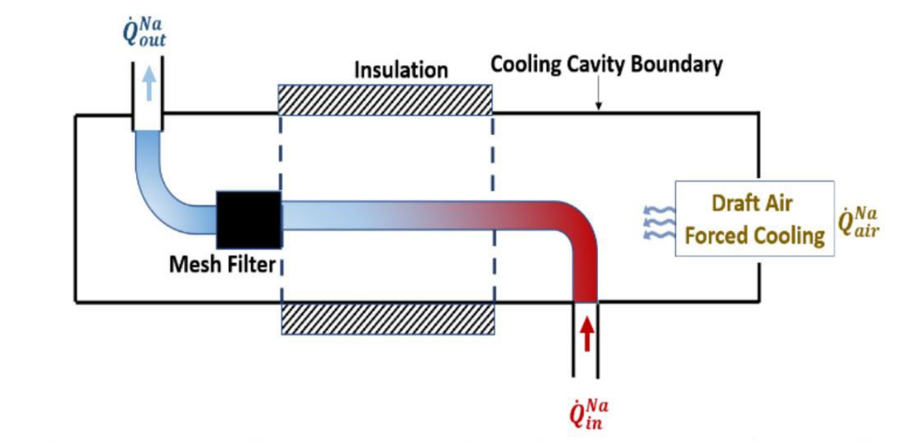
$$r_{O_2} = k_o C_{O_2} exp\left(\frac{-E}{RT}\right)$$

Total Cold trap temperature as:

$$\underbrace{\frac{d[\rho C_p V(T_r)]}{dt}}_{\text{Rate of energy accumulation}} = \left(\underbrace{\sum_{i=inlet} \dot{m}_i C_p (T_{ho} - T_r)}_{\text{Rate of energy input}} - \underbrace{\sum_{j=outlet} \dot{m}_j C_p (T_{co} - T_r)}_{\text{Rate of energy output}} \right) + \underbrace{\Delta Q}_{\text{Rate of heat added/loss by heating}}$$



Phenomena Modeled for Cold Trap

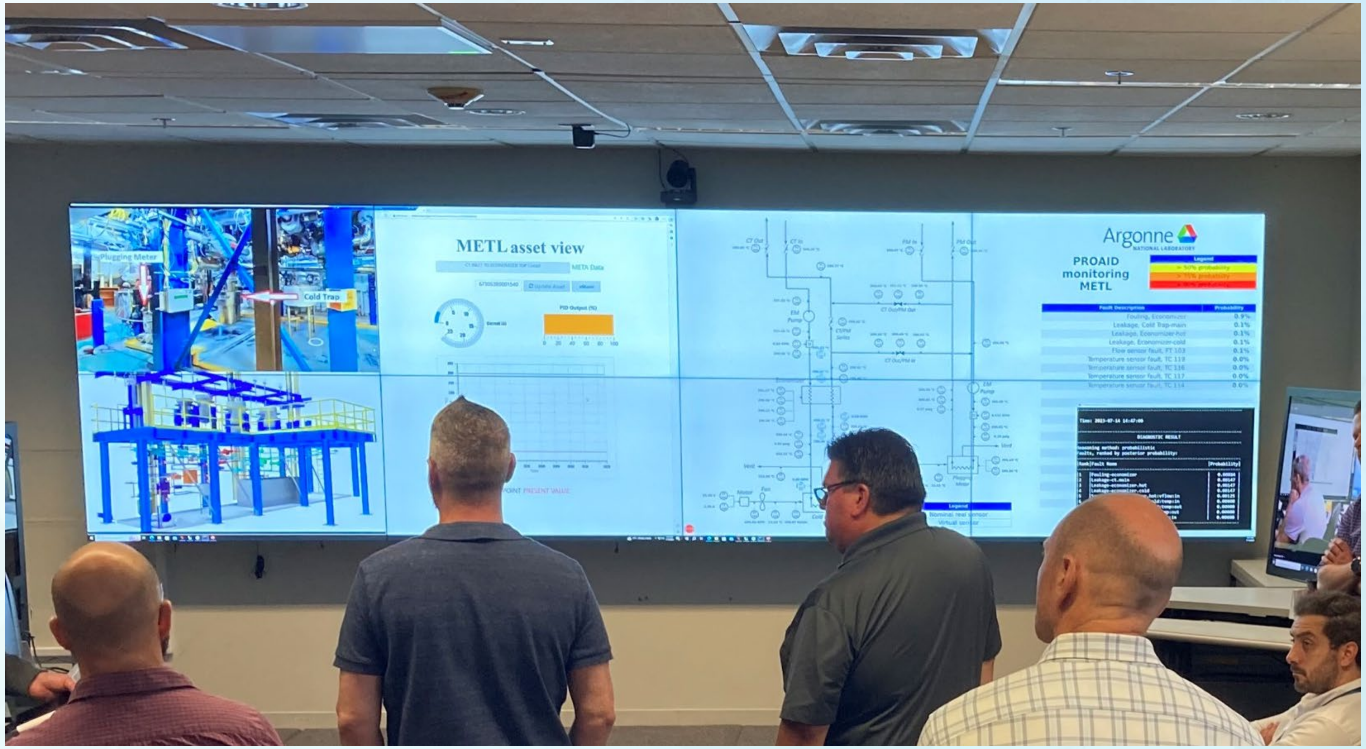


Cold Trap Heat Transfer Schematic

Results and Accomplishments

Application of DT to Advanced Monitoring

- Created visuals for display of monitoring results on large remotely located video wall
- Established remote data connection to METL server
- NLP algorithm unravels automated reasoning process used in PRO-AID to arrive at an explanation of the diagnosis
- Ran the PRO-AID monitoring software in real time processing METL data with display of diagnosis results



Results and Accomplishments

Application of DT to Advanced Monitoring

- Performed live diagnosis of thermocouple and blower faults injected into METL cold trap system
- Demonstrated natural language processing (NLP) query of PRO-AID code for explanation of how diagnosis was arrived at

PRO-AID Diagnostic Result Rendered in Explainable Form by NLP

```
agent.fault_query()
[Output]
The fault signature `F6' corresponds to the fault
`SensorFault-economizer.hot:temp:out'.

In this case, the active residuals were r1, r2, r3, r5,
and r6.

These residuals were activated due to the fault `F6'.
The sensors they rely on are available on further query.
```

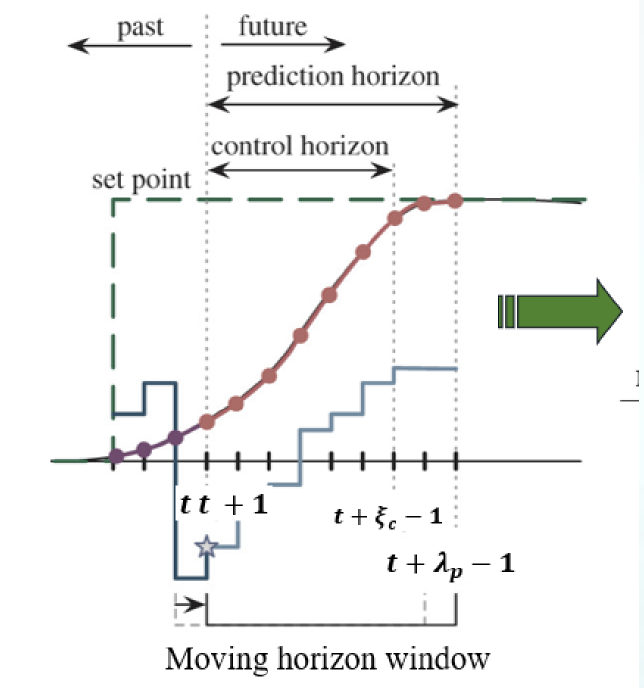
Operator may inquire further

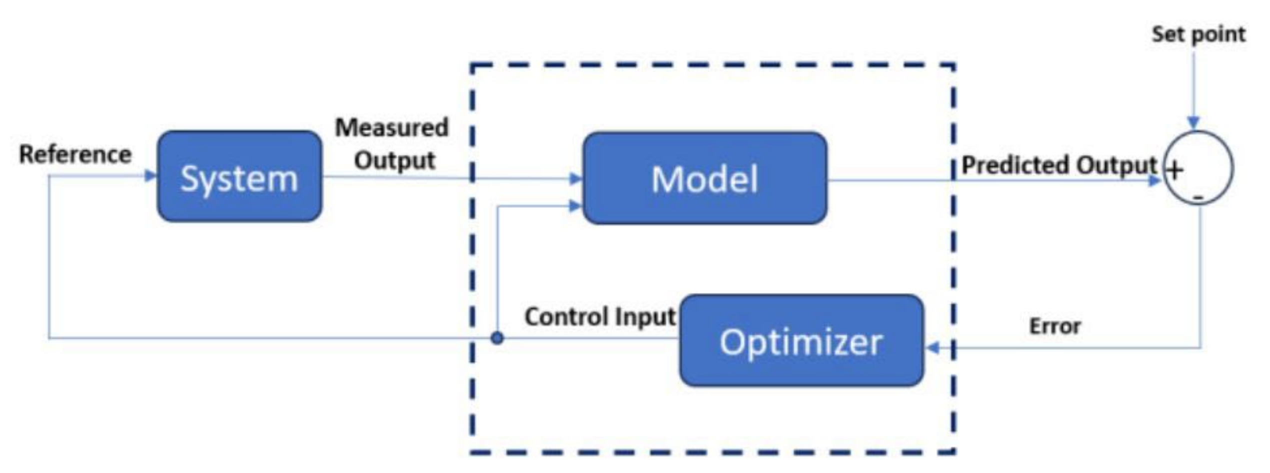
```
agent.custom_query('Explain why the other faults were
exonerated.')
[Output]
The other faults were exonerated because they did not
match the fault signature of the active residuals.

Looking at the dependencies, we can see that the other
faults (F1, F2, F3, F4, F5, F7, F8, F9) are not associated
 with all the active residuals.

In other words, the observed system behavior (as
represented by the active residuals) could not be
explained by these faults, and hence they were ruled out.
```

Results and Accomplishments

Application of DT to Advanced Control

- Developed Model Predictive Control algorithm





Min J $(\lambda, \xi, u) =$

$$\omega_i \sum_{i=1}^{\lambda} [T_r(t+1) - T_{pred}(t+i)]^2 + \omega_u \sum_{i=1}^{\xi} [\Delta T_{exp}(t+i-1)]^2$$

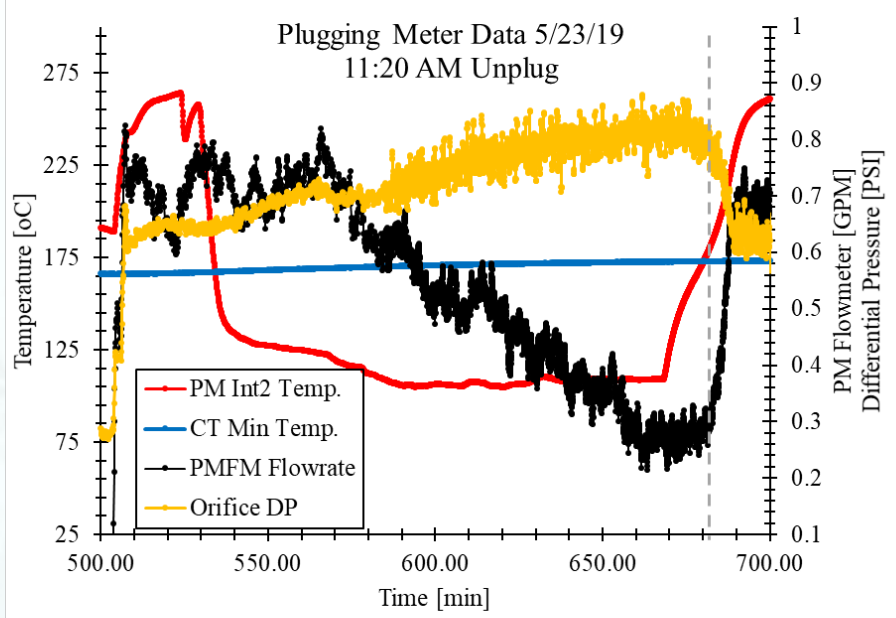
Subject to the constraints:

$$\lambda \leq \xi$$
$$|\Delta T_{exp}| \leq \Delta T_{exp_{max}}$$
$$T_{exp_{min}} \leq T_{exp}(t) \leq T_{exp_{max}}$$
$$T_{pred_{min}} \leq T_{pred} \leq T_{pred_{max}}$$

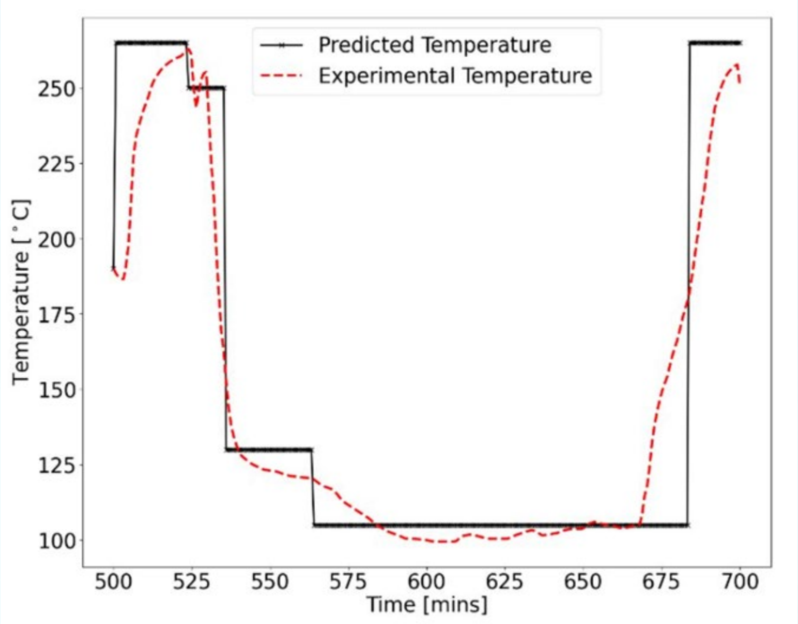
Results and Accomplishments

Application of DT to Advanced Control

- In a simulation the plugging meter setpoint was set to that for manual operation of plugging meter
- Reasonable control is realized (plot on right)



Process variable data used to validate digital twin for plugging meter



Plugging meter temperature predicted with digital twin control versus experimental data

Concluding Remarks

- **Publications (FY23)**
  - R. Appiah, A. Heifetz, D. Kultgen, L. Tsoukalas, R. Vilim, ”Model of Liquid Sodium Purification and Diagnostic System for Advanced Control Applications,” ANS Summer Meeting, 2023
  - T. Nguyen and R., “Direct Bayesian Inference for Quantitative Model-Based Fault Detection and Diagnosis,” Annals of Nuclear Energy, 194, December 15, 2023
  - T. Nguyen, A. Dave, R. Ponciroli and R. Vilim, “Design and Prototyping of Diagnostic Methods to Support Autonomous Operation of Advanced Reactors,” 13th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, Knoxville, TN US, July 15, 2023 - July 20, 2023.

- **Patents (FY23)**
  - T. Nguyen, R. Vilim and R. Ponciroli, “Fault Diagnosis Framework for Monitoring a Multi-Component Thermal Hydraulic System,” Patent No. US 11-740-157, US Patent Office, August 29, 2023.

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Thank You