U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

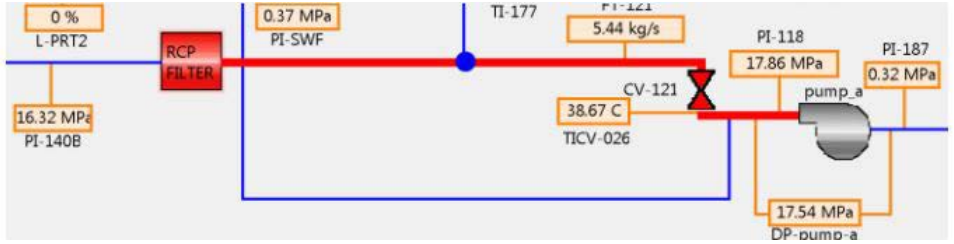
Process-Constrained Data Analytics for Sensor Assignment and Calibration

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 24 – 27, 2022

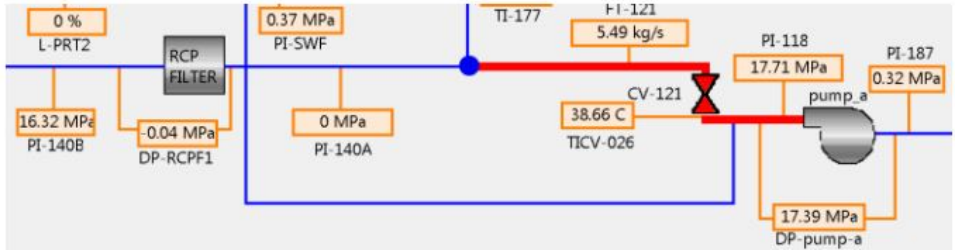
R. Vilim
Nuclear Science and Engineering Division
Argonne National Laboratory

Project Overview - Objectives

- **How to select a sensor set for equipment and sensor health monitoring**
  - Given a list of faults to be diagnosed, find the sensor set that will accomplish this goal at the least cost
- **Incorporate domain knowledge (physics-based digital twin) to provide for**
  - Virtual sensors to reduce number of physical sensors
  - More reliable and explainable diagnoses

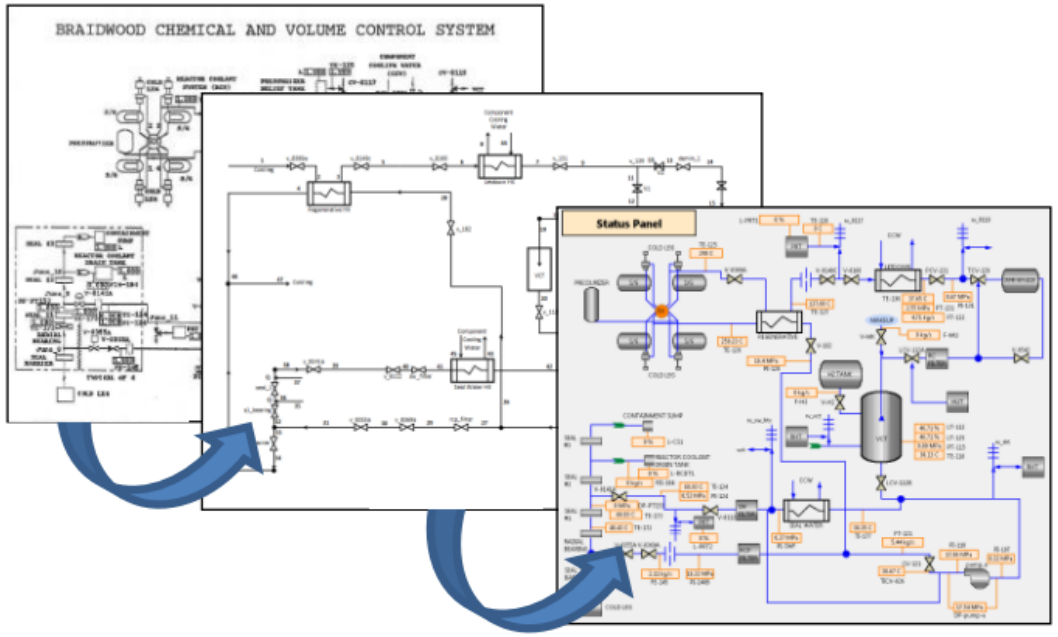


Increased fault spatial resolution obtained by addition of sensors



Project Overview - Approach

- **Diagnostic Algorithm - Digital Twin Based**
  - Use automated reasoning to look at difference between digital twin prediction and what sensors are reporting
  - Use digital twin to represent domain knowledge
    - How components communicate with each other
    - Process physics for each component
- **Sensor Assignment Algorithm**
  - Find the set of sensors that minimizes the cost of satisfying a set of diagnostic objectives
  - Cast as a mixed-integer programming (MIP) problem where a sensor in a specific location is 0 or 1

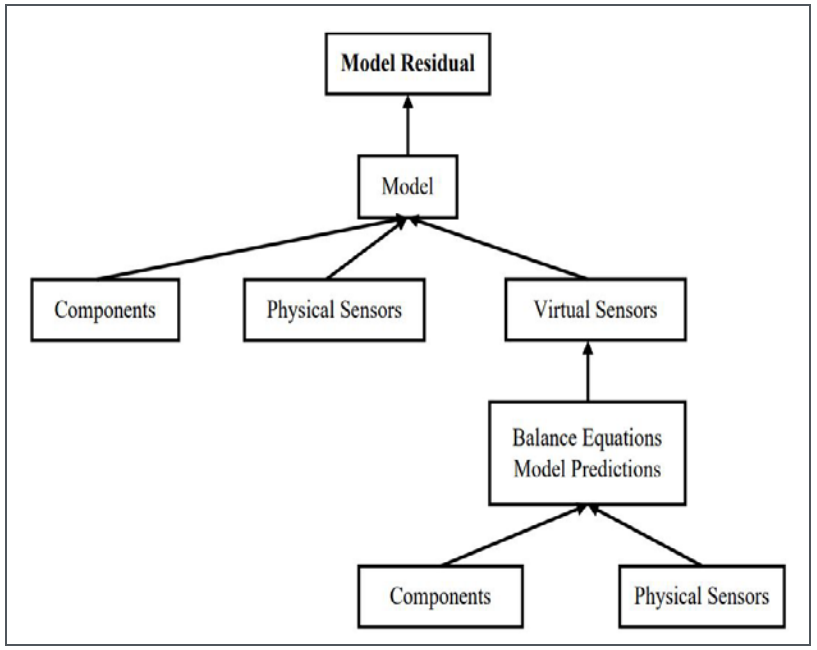


Creation of Physics-Based Digital Twin from P&ID

Project Overview - Schedule

FY19

Methods and Algorithm Development



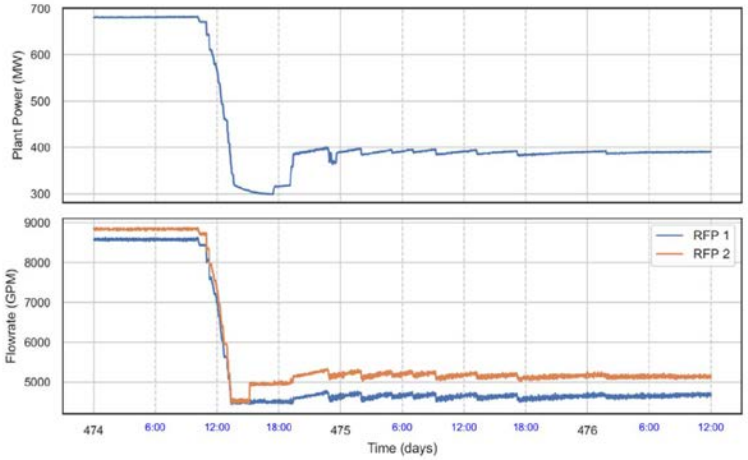
FY20

Analysis and Sensitivity Studies

Residuals	Component Faults			Sensor Faults				
	Motor	Bearings	Pump	P_m	I	n	Q	p_{in}/p_{out}
$r_{m,P}$	1	0	0	1	0	1	0	0
$r_{m,I}$	1	0	0	0	1	1	0	0
$r_{p,\Delta p}$	0	0	1	0	0	1	1	1
$r_{c,P}$	1	1	1	1	0	1	1	0
$r_{m,P2}$	1	0	0	1	1	0	0	0
$r_{c,P2}$	1	1	1	1	0	1	0	1

FY21

Validate with Utility Data



FY22

Iterate with industry on TRL

- Extensible software
- User graphic interface
- User manual
- Beta code release
- Demo sessions

Technology Impact - Making of a business case

CRITERIA

- **Specification of system engineering data limited to P&ID**
- **Differentiates between component and sensor faults**
- **Creates virtual sensors**
- **Immune to plant operating point change**
- **Rank orders likelihood of component faults by probability**
- **Formal statement of what is diagnosable and what is not**
- **Auto reconfigures on dropped sensor**
- **Solves for an “optimum” sensor set**

Digital-Twin Based Diagnosis	*Data-Driven* Based Diagnosis
✓	
✓	
✓	
✓	
✓	
✓	
✓	
✓	

Technology Impact – Industry Engagement

Application	System	NPP
Differentiating between component and sensor faults	FW Pump-Motor set	Monticello, Xcel
System-level diagnosis	PWR High-Pressure FW System	North Anna, Dominion
Incorporating Anomaly Detection Approaches	FW Pump-Motor set	Monticello, Xcel
System level sensor set analysis	BWR FW Heater Train	Peach Bottom, Constellation

FW pump-motor set

Probability ranking of impeller fault

```
                    DIAGNOSTIC RESULT
-------------------------------------------------------------
Reasoning method: Probabilistic
Faults, ranked by posterior probability:
-------------------------------------------------------------
|Rank|Fault Name                                |Probability|
-------------------------------------------------------------
|1   |Pump-rfp11                                |   0.81504 |
|2   |SensorFault-rfp11:vflow:in                |   0.15186 |
|3   |Bearings-rfp11                            |   0.15186 |
|4   |SensorFault-rfp11:press:in                |   0.11696 |
|5   |SensorFault-rfp11:press:out               |   0.11696 |
|6   |SensorFault-rfp11:rspeed:mid              |   0.00009 |
|7   |SensorFault-rfp11:power:mid               |   0.00002 |
|8   |SensorFault-rfp11:current:mid             |   0.00001 |
|9   |Motor-rfp11                               |   0.00000 |
```

Results and Accomplishments – Challenge #1

Engaging Industry – What they are asking for

- **A monitoring and diagnostic capability that has**
  - Greater specificity in terms of fault diagnosis
  - A requisite specificity of fault diagnosis and an associated identifiable sensor set
- **Advanced Reactor Developer**(paraphrased)
  - "Give me a capability that I can use to defer periodic maintenance on a system that currently requires it"
- **Nuclear Utility #1** (paraphrased)
  - "I want to expand diagnostic capability beyond our installed anomaly detection and thermal performance monitoring software"
- **Nuclear Utility #2** (paraphrased)
  - "I would like through automation to have the option of not having to find a replacement for an individual who choses to retire in five years"

Results and Accomplishments – Challenge #2

Progressing to a Full Capability

	Class of Application	Intended Use
1	Virtual Sensors	Survey/assess installed or proposed sensor set to understand how it might be modified to better inform.
2	Sensor Set Selection	Design a sensor set for M&D Center or for plant license extension.
3	PB Nominal Diagnoses	Off-line simulation-based look at diagnostic capabilities of installed sensor set or potential upgraded set.
4	Combined DD and PB Nominal Diagnoses	High-value version of Class 3 with respect to diagnoses rendered.
5	PB Probabilistic Diagnoses with Rank Ordering of faults	Real-time equipment condition
6	PB Probabilistic Inference of Fault Severity	Real-time equipment condition deep dive by engineered system specialist.
7	Combined DD and PB Probabilistic Rank Ordering	High-value version of Class 5 with respect to diagnoses rendered.

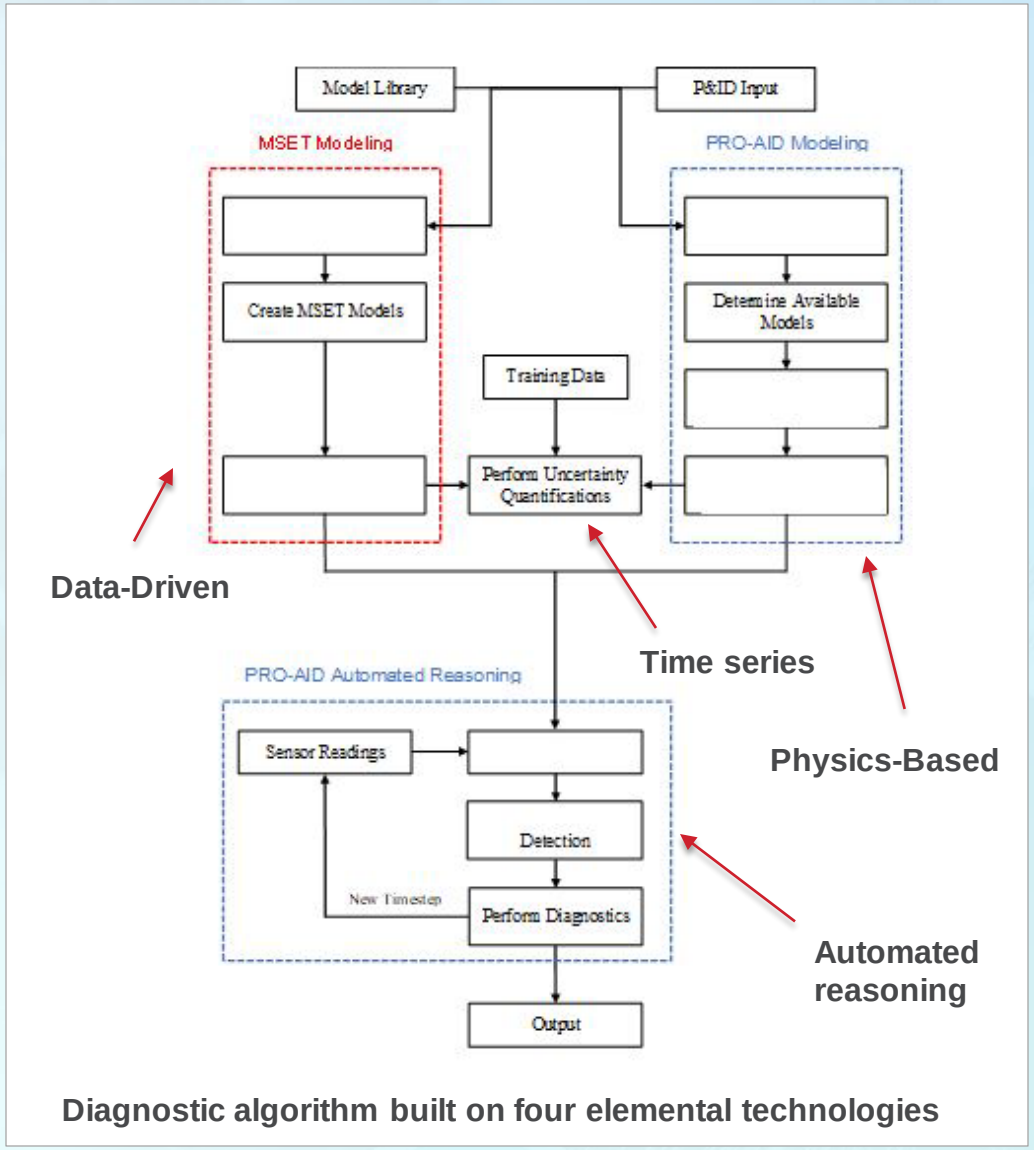
Realized capability

DD – Data Driven
PB – Physics Based

Results and Accomplishments – Challenge #3

Merging of Data-Driven and Physics-Based Approaches

- **Physics-Based Knowledge**
  - First principles physics-based models
- **Data Driven Knowledge**
  - Input-output mappings acquired by machine learning
- **Time Series**
  - Uncertainty captured by sequential analysis
- **Automated Reasoning**
  - Infer what is implied about the system from combined information of sensors and models representing physical laws

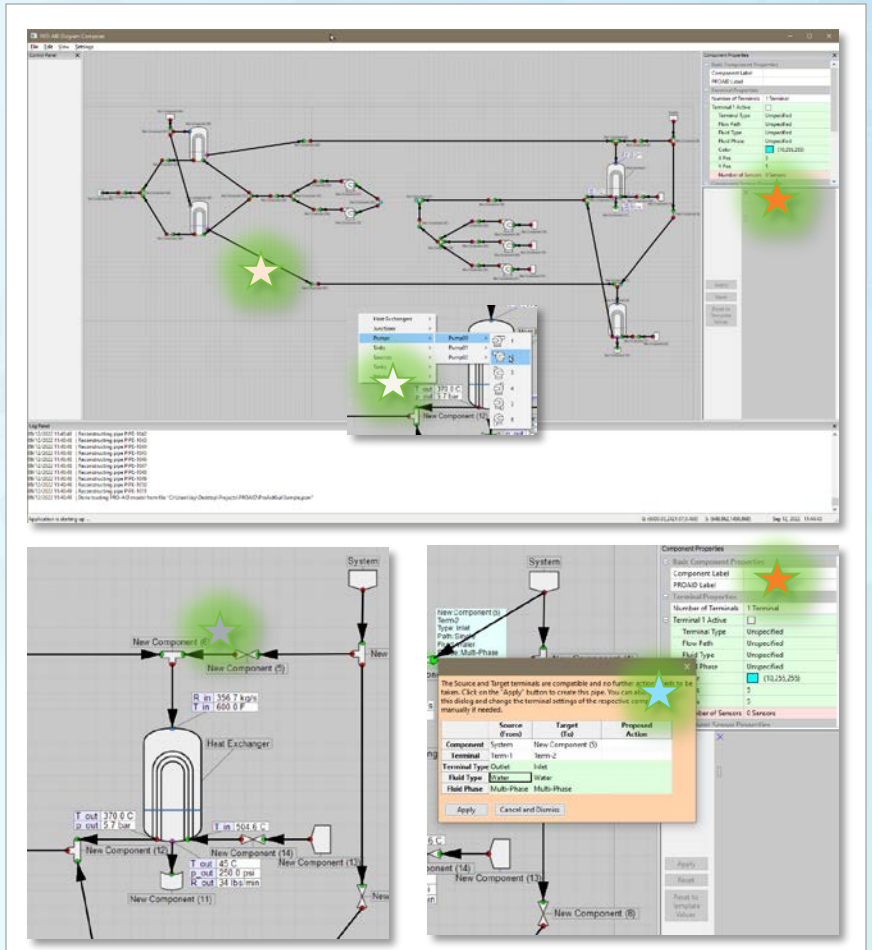


Diagnostic algorithm built on four elemental technologies

Results and Accomplishments – Challenge #4

Transitioning PRO-AID Code for Use by Non-Experts

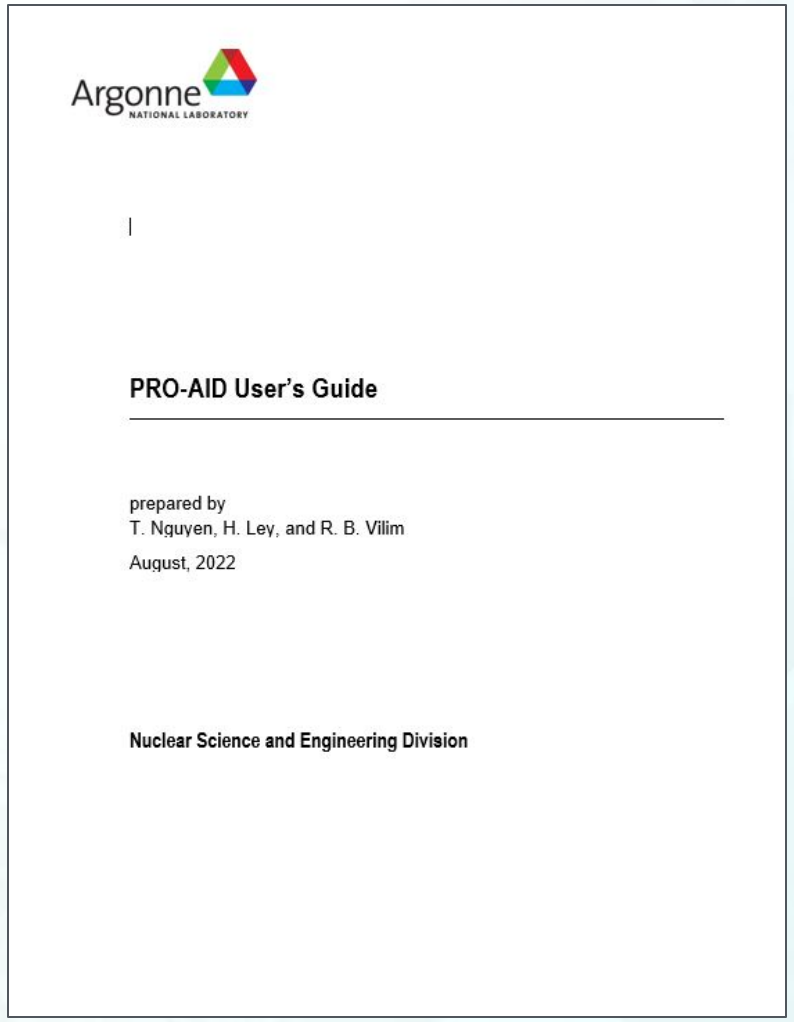
- **Graphical User Interface Development**
  - Current Focus: Building PIDs for PRO-AID
    - Creates the PID input files and allows for the detailed specifications for components and loop connections
  - Future Focus: Demonstration Environment
    - Operating on simulated data sources, provide a graphical representation of both the plant PID and the PRO-AID analysis



Graphical User Interface – PID Builder

Results and Accomplishments

PRO-AID User Guide and Version 1.0 Release



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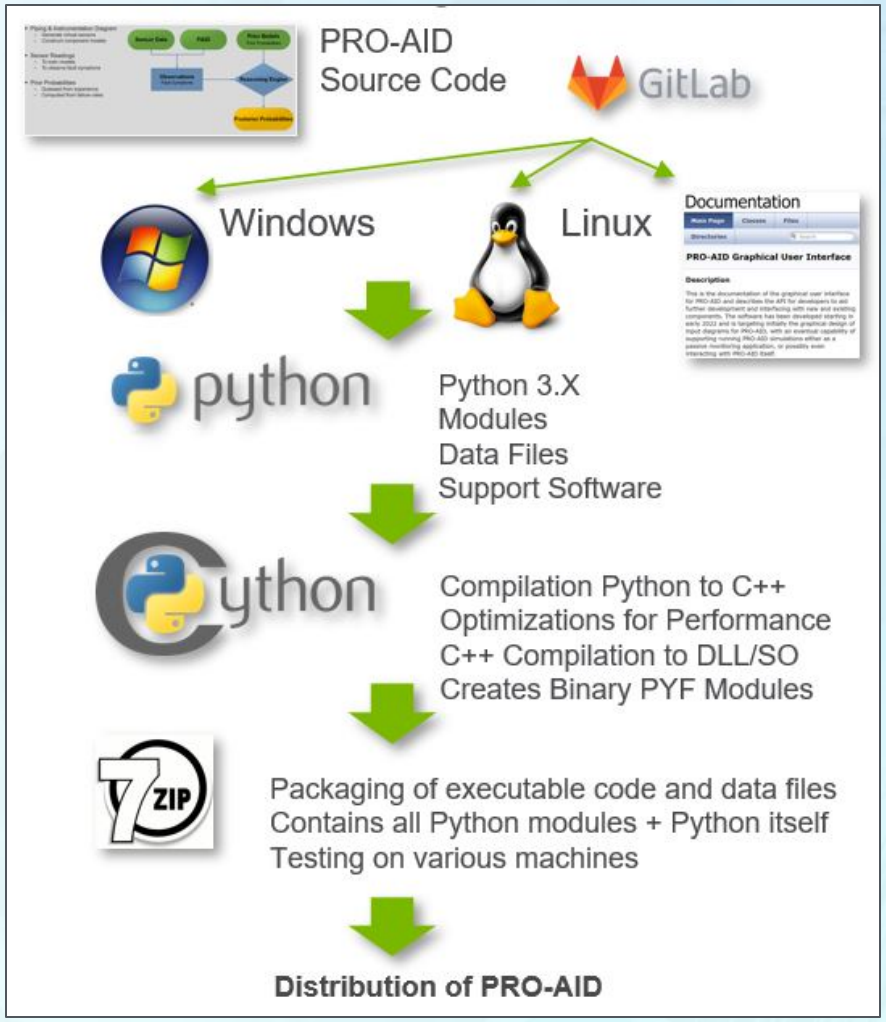
PRO-AID User's Guide

prepared by
T. Nguyen, H. Ley, and R. B. Vilim

August, 2022

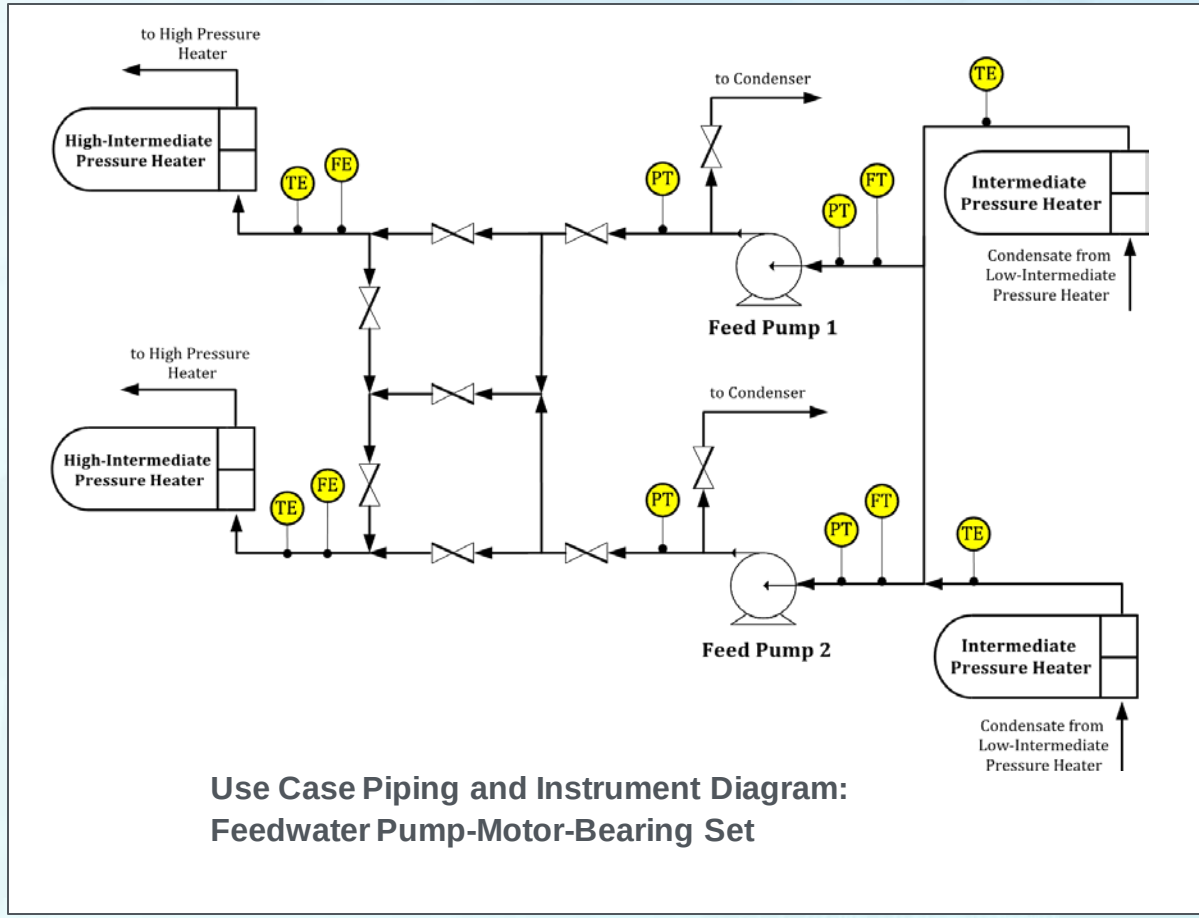
Nuclear Science and Engineering Division



Results and Accomplishments

Live PRO-AID Demos Hosted for Industry

- **Demo 1 – Examining Some User Input Options**
  - How to modify the frequency at which the code outputs results
  - How to adjust fault *prior* probabilities (i.e., the probability of a fault occurring based on historical data)
- **Demo 2 – Exploring the Dependence of what can be Diagnosed Given a Sensor Set**
  - How to drop a sensor from the data sets ANL provided (e.g., dropping the motor power sensor)
- **Demo 3 – Modifying Data Sets to Investigate Diagnoses for Different Faults**
  - How to inject a bias into one of the sensors in the data sets ANL provided (e.g., adding a bias to a pressure sensor)



Use Case Piping and Instrument Diagram: Feedwater Pump-Motor-Bearing Set

Concluding Remarks - Publications

Journal Papers

- Nguyen, T., and R.B. Vilim, "A Probabilistic Model-Based Diagnosis Framework for Fault Detection and System Monitoring in Nuclear Power Plants," Annals of Nuclear Energy, August 25, 2020.
- Nguyen, T., Roberto Ponciroli, R., Vilim, R., "A Physics-Based Parametric Regression Approach for Feedwater Pump System Diagnosis," accepted for publication, Annals of Nuclear Energy, August 2021.
- Nguyen, T., and R.B. Vilim, "A Digital-Twin Approach to System-Level Health Monitoring for Increased Diagnosis Specificity," under revision, Annals of Nuclear Energy, October 2021.

Conference Papers

- Vilim, R. "Explainable Diagnostics Achievable Using Process-Based Automated Reasoning," 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, virtual meeting, June 14-17, 2021.
- Vilim, R. "A Physics-Based Automated Reasoning Approach for Sensor Set Assignment," 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, virtual meeting, June 14-17, 2021.

Panel Sessions

- R. Vilim, R. Ponciroli, D. Akshay, T. Nguyen, "Autonomous Power Plant Operation in a Net-Zero World," panel session presentation, EPRI AI and Electric Power Summit, Rome, Italy, October 4-6, 2022.
- R. Vilim and T. Nguyen, "Inclusion of Domain Knowledge in Time-Series Monitoring of Process Equipment," invited technical session presentation, EPRI AI and Electric Power Summit, Rome, Italy, October 4-6, 2022.

Patent Applications

- T. Nguyen, R. Vilim, and R. Ponciroli, "Fault Diagnosis Framework for Standalone Component," filed U.S. Patent Office, December 2020.
- T. Nguyen, R. Vilim, and R. Ponciroli, "Fault Diagnosis Framework for Multi-Component System," filed U.S. Patent Office, December 2020.
- R. Vilim, T. Nguyen and H. Wang, "Sensor Assignment Optimization," filed U.S. Patent Office, December 2020.

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Thank You