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

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# Big data analytics solutions to improve nuclear power plant efficiency: Online monitoring, visualization, prognosis, and maintenance decision making

Advanced Sensors and Instrumentation Annual Webinar

November 6, 2019

Kaibo Liu
**UW-Madison**

# Project Overview

- Goal and Objective: Significantly advance the ability to assess equipment condition and predict the remaining useful life (RUL) to support optimal maintenance decision making in nuclear power plants
- Participants (2019):
  - Prof. Kaibo Liu (UW), Prof. Po-ling Loh (UW) and Prof. Todd Allen (U Michigan) have been working closely
  - Data coordination/sharing with industrial company (SC) and UW reactor
  - Three Ph.D. students (two females), MinHee Kim, Changyue Song and Elisa Ou have been funded by the project
- Schedule: 10/01/2018 to 09/30/2021

# Logical Path to Success

- Analyze the critical log events recorded by operators and historical CM signals collected from plant equipment
- Quickly detect and identify abnormal events in real time
- Develop novel data fusion models for visualizing degradation status evolution by fusing multiple signals
- Investigate real-time prognostic algorithm that allows continuous updates of RUL predictions based on online measurements
- Establish predictive maintenance strategy that aims to reduce maintenance cost and improve efficiency
- Test and validate our methods using both simulation and real-world data

# Research accomplishment:

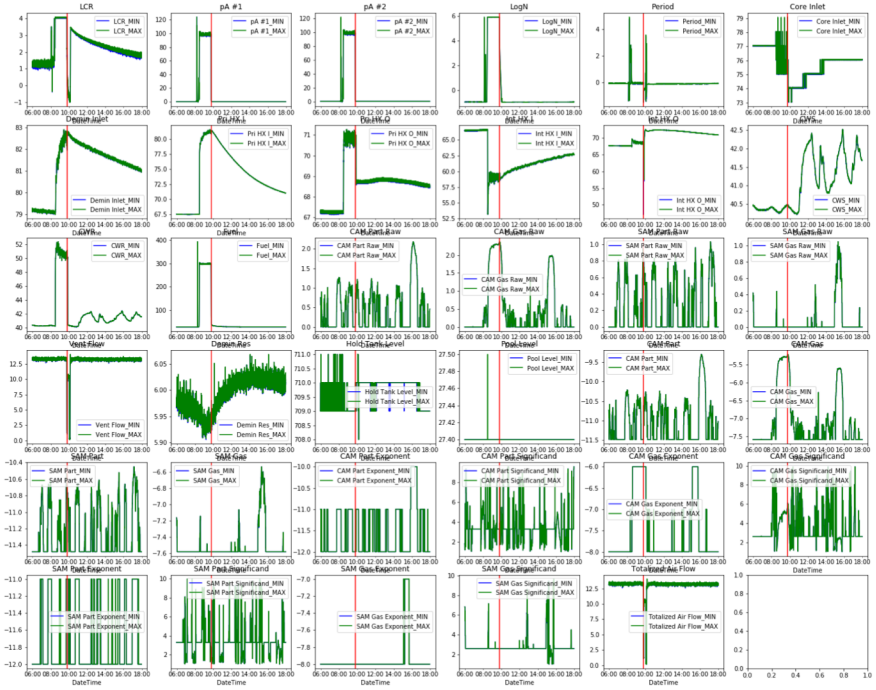
- Three publications on methodology development for abnormal event detection, diagnosis and prediction (all acknowledge the funding support of DOE)
  - Song, C., Liu, K., and Zhang, X. (2019), "A Generic Framework for Multisensor Degradation Modeling based on Supervised Classification and Failure Surface", *IISE Transactions*, in press (Feature article in ISE Magazine).
  - Kim, M., Song, C., and Liu, K. (2019), "A Generic Health Index Approach for Multisensor Degradation Modeling and Sensor Selection", *IEEE Transactions on Automation Science and Engineering*, in press (This paper is selected for presentation in the T-ASE invited session in the 2019 INFORMS conference).
  - Xian, X., Li, J., and Liu, K. (2019), "Causation-based Monitoring and Diagnosis for Multivariate Categorical Processes with Ordinal Information", *IEEE Transactions on Automation Science and Engineering*, 16, 2, 886-897.
- Data collection and preliminary analysis to the UW reactor and Southern Nuclear data
- The research team was invited and gave talks at conferences, universities and industrial events to introduce and quickly share the research outcomes, which helps to stimulate follow-up studies and collaborations

# UW Reactor Data Overview

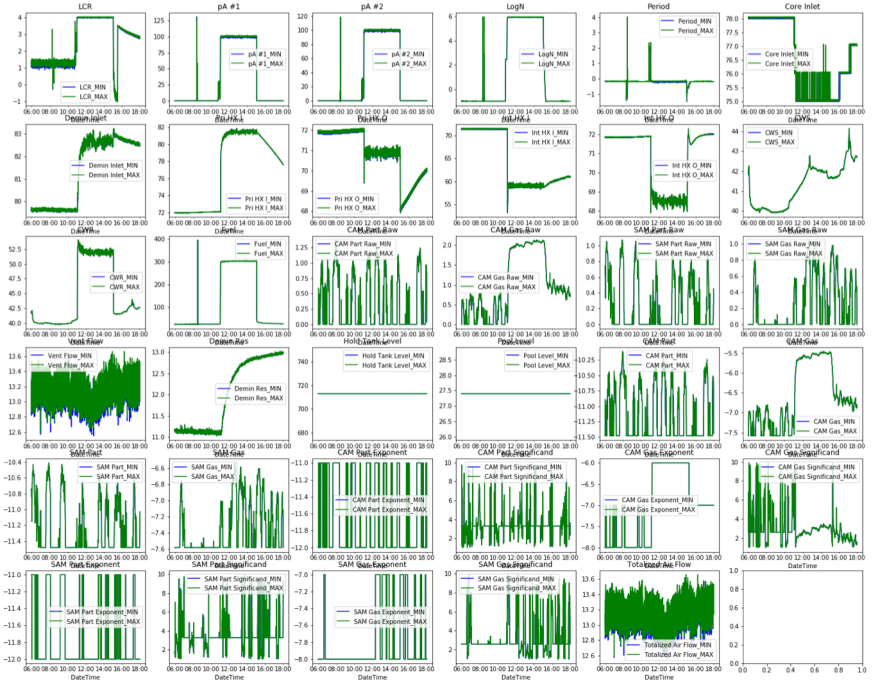
- Recorder Data
  - 40 days (36 days w/o scrams, 4 days with scrams)
  - 35 channels
  - Measurement interval: 1s
  - Possible task: Scram Detection
- Operation Logs
  - 5 types of reports
  - Handwritten
  - Possible task: Data Extraction from Handwritten Logs

# Recorder Data

- Example

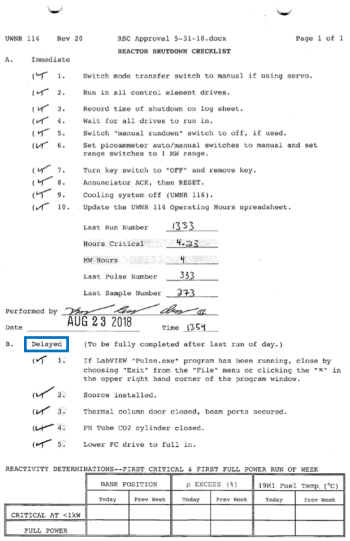


Day with Scram (red line = scram)



Day without Scram

# Data Extraction from Handwritten Logs



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REACTOR SHUTDOWN CHECKLIST

A. Immediate

1. Switch mode transfer switch to manual if using servo.
2. Run in all control element drives.
3. Record time of shutdown on log sheet.
4. Wait for all drives to run in.
5. Switch "manual rundown" switch to off, if used.
6. Set picoammeter auto/manual switches to manual and set range switches to 1 NW range.
7. Turn key switch to "OFF" and remove key.
8. Annunciator ACK, then RESET.
9. Cooling system off (UNNR 116).
10. Update the UNNR 114 Operating Hours spreadsheet.

Last Run Number 1333
Hours Critical 4.23
MW Hours 4
Last Pulse Number 333
Last Sample Number 273

Performed by
Date AUG 23 2018 Time 1354

B. Delayed (To be fully completed after last run of day.)

1. If LabVIEW "Pulse.exe" program has been running, close by choosing "Exit" from the "File" menu or clicking the "X" in the upper right hand corner of the program window.
2. Source installed.
3. Thermal column door closed, beam ports secured.
4. FN Tube CO2 cylinder closed.
5. Lower FC drive to full in.

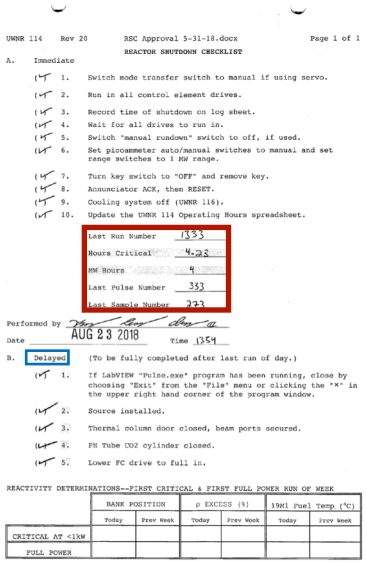
REACTIVITY DETERMINATIONS--FIRST CRITICAL & FIRST FULL POWER RUN OF WEEK

| | BANK POSITION | | ρ EXCESS (¢) | | 19M1 Fuel Temp. (°C) | |
|---|---|---|---|---|---|---|
| | Today | Prev Week | Today | Prev Week | Today | Prev Week |
| CRITICAL AT <1kW | | | | | | |
| FULL POWER | | | | | | |

**Template matching**

Delayed

Consider certain part of the image as an anchor point



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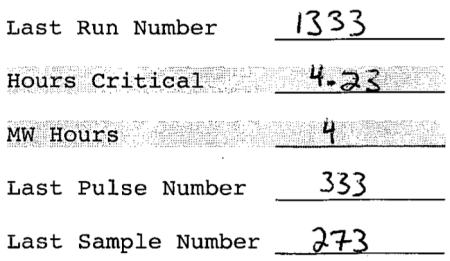
**Crop part**



Last Run Number 1333
Hours Critical 4.23
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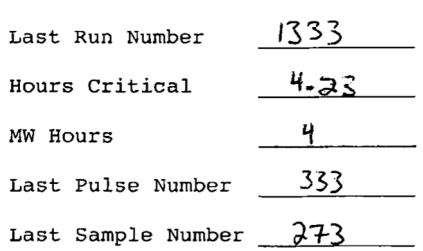
Last Sample Number 273

**Denoising**



Last Run Number 1333
Hours Critical 4.23
MW Hours 4
Last Pulse Number 333
Last Sample Number 273

**Handwritten recognition**

```
Full Text: Last Run Number
Hours Critical
1333
4.23
4
333
MW Hours
Last Pulse Number
Last Sample Number ___273
```

**Digital table**

| Log Sequence | 1 | 2 |
|---|---|---|
| Last Run Number | 1333 | |
| Hours Critical | 4.23 | |
| MW Hours | 4 | |
| Last Pulse Number | 333 | |
| Last Sample Number | 273 | |

# Limitations of UW reactor data

- Limited number of scrams
- Single reactor
- No clear sign of abnormal events (e.g. Student mistakes)
- Lack of detailed descriptions of abnormal events

# Southern Nuclear Data Overview

- Multiple Systems
- Multiple critical events per system

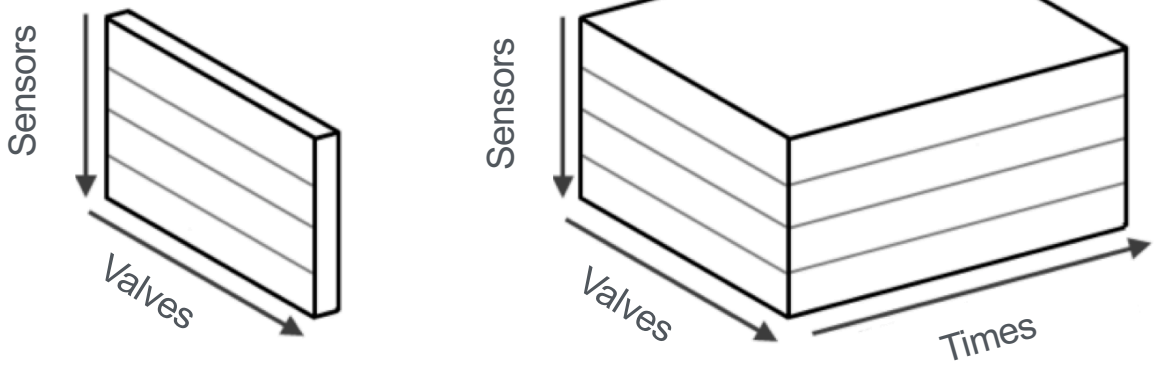
Current Focus

1. **Yokogawa Reader Dataset – Plant Hatch**
   - Multiple sensor signals collected from SRVs (safety relief valves)
2. **Vogtle Data**
   - Temperature and vibration data collected from bearings

Southern Nuclear

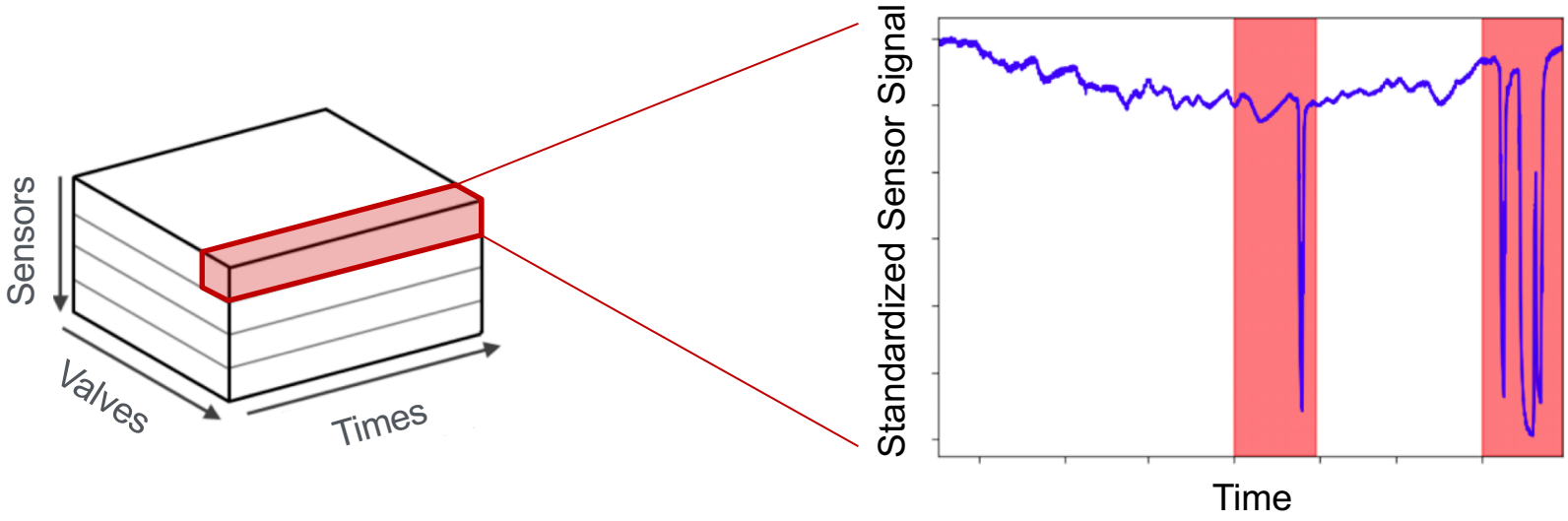
# Data overview – YOKO dataset

- Total 2 units
- Three dimensional
  - 11 Valves for each unit
  - 4 Sensors for each valve
  - Time-series (every 1s)



# Data overview – YOKO dataset

- Sudden drops
  - Exact time and date are not recorded
  - Detailed descriptions of causes are not provided




Example of sensor signal

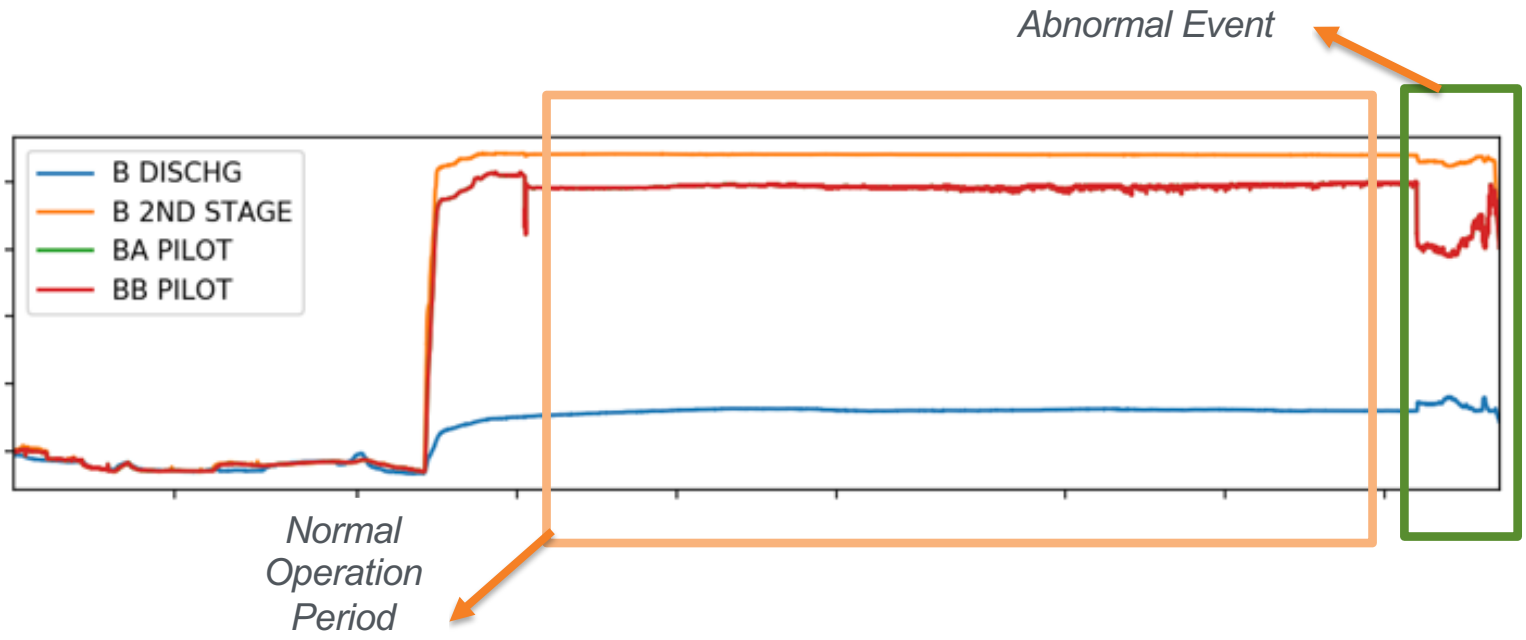
# Data overview – YOKO dataset

- **Research Need**
  - Predict when the abnormal event (sudden drop) will happen
  - Investigate what causes the event

- The causes could happen between 5hr up to 1 week previous to the sudden drops in signals (Domain Knowledge)

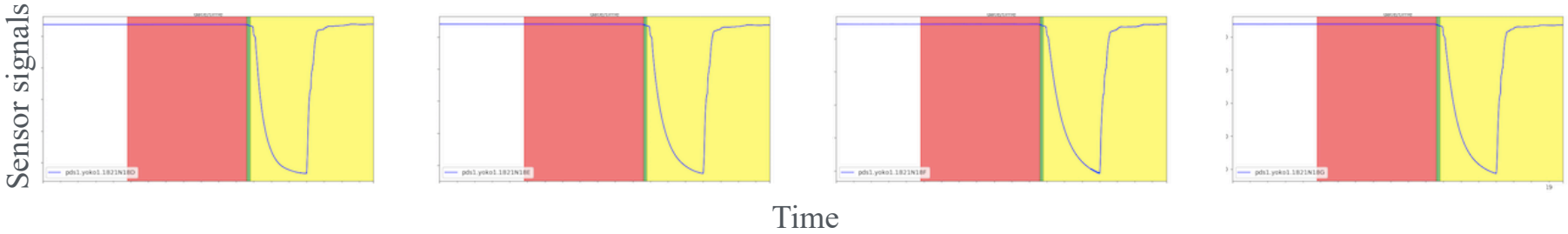
# Data analysis – Abnormal Event

- For most of the abnormal events, there is no clear and consistent pattern before the sudden drops.
- Predicting abnormal event using time period before is difficult.



# Data analysis – Detect Sudden drops

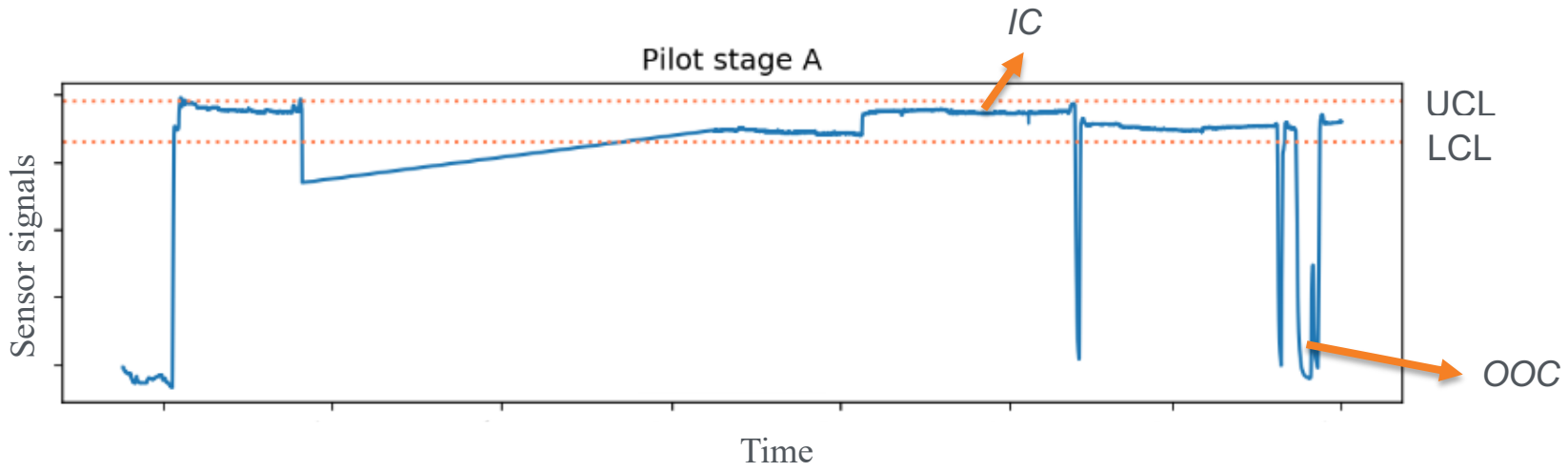
- Require deeper data analysis that investigates the complicated relations between different signals
  - Correlation Analysis
    - Correlation between valves
    - Correlation between sensors
  - Feature Extraction




Example of a detected sudden drop in four SRV sensor signals

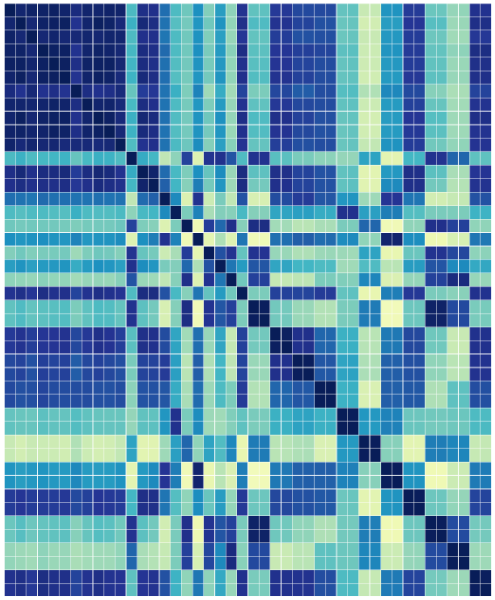
# Data analysis – IC & OOC Definition

- IC (in-control) : Time duration when all signals are within the IC
  - Each signal has predefined LCL (lower control limit) and UCL (upper control limit) values
- OOC (out-of-control) : Not IC

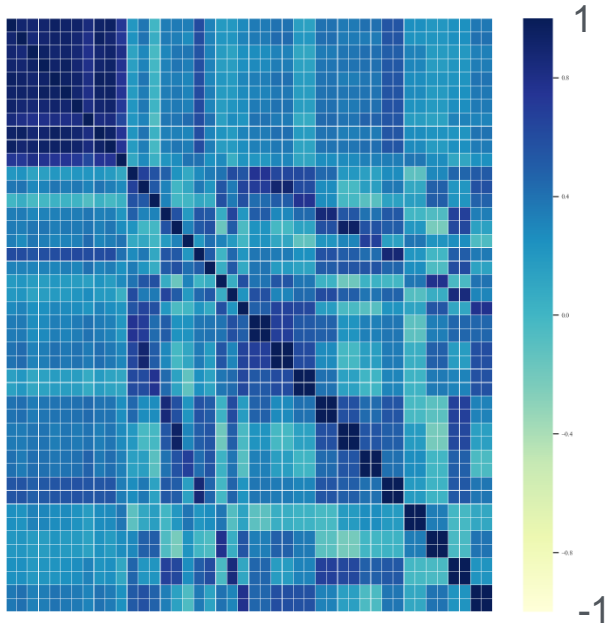


# Data analysis – Whole Correlation

- All 44 sensors are highly correlated
- Can spot several very strong correlations between specific sets of signals
- In general, signals in OOC show stronger correlation compared to those in IC



IC(In-control)




OOC(out-of-control)

# Education accomplishment:

- Awards
  - The PI (Liu) is the recipient of three prestigious early career awards, including the *2019 Outstanding Young Manufacturing Engineer Award by SME*, *the 2019 Feigenbaum Medal Award by ASQ*, and *the 2019 Dr. Hamed K. Eldin Outstanding Early Career IE in Academia Award by IISE*
  - The Ph.D. student, Changyue Song won the Mary G. and Joseph Natrella Scholarship awarded by the American Statistical Association (ASA) and won the Wisconsin Distinguished Graduate Fellowship (WDGF) for the year 2019-2020.
- Benefiting from the opportunities offered in this project, both the PI (Liu) and the Co-PI (Loh) have been promoted to associate professor with tenure in May 2019
- Co-PI (Allen) has retired from UW-Madison and has been named the Glenn F. and Gladys H. Knoll Department Chair of Nuclear Engineering and Radiological Sciences (NERS) at UM in Jan 2019

# Technology Impact

The developed methods and algorithms will

- significantly advance the state of the art in data-driven modeling, monitoring, diagnosis, prognostics, and maintenance
- contribute to the science base of the emerging data-rich challenges in nuclear plants
- support the DOE-NE research mission by enhancing equipment safety and utilization, lowering maintenance cost, improving operation readiness and efficiency, and ultimately help the U.S. gain a significant competitive advantage in nuclear power
- be carefully designed, conducted and documented for the future technology transfer and potential commercialization

# Conclusion

A great start in the first year (three publications, numerous awards, and close collaboration between the research team and industry collaborators, etc.)

The research developed in this project will fill a major gap in data science and Big Data analytics, and catalyze a transition from existing reactive/preventive service to an integrative predictive paradigm to improve nuclear plant efficiency and productivity

*Questions?*

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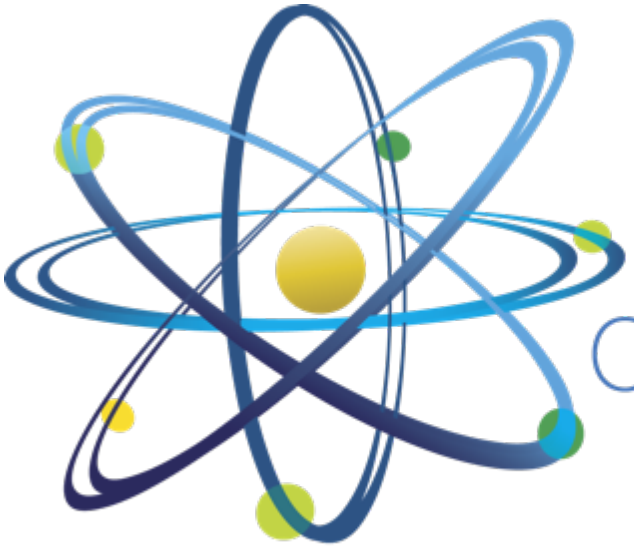

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