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Preliminary Results of a Multi-Sensor Data Science System for Monitoring a Solvent Extraction Process

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ABSTRACT
Idaho National Laboratory is building a test bed to allow researchers the opportunity to study nuclear fuel processing operations. This includes studying the solvent extraction process and the use of centrifugal contactors. The goal of this project is to develop a system that utilizes non-traditional measurement sources such as vibration, acoustics, current, color, flow, and temperature in conjunction with data-based, machine learning techniques that will allow for signal discovery. This multi-sensor data supports the development of safeguards by design, provides operator process awareness, and aids in the discovery of process anomalies. This paper highlights some of the preliminary results from initial data collection campaigns and shares some of the lessons learned.

Keywords: sensors, monitoring, solvent extraction, centrifugal contactors, nuclear nonproliferation, stewardship.

INTRODUCTION

In the nuclear industry solvent extraction has been extensively used for the recovery of uranium and plutonium from dissolved irradiated nuclear fuel. The separation of fission products from the remaining actinides leads to a dramatic reduction in the time towards manageable levels of radioactivity thus reducing the complexity of storing nuclear waste. These recovery and waste disposal efforts are an important part of the nuclear fuel cycle. Idaho National Laboratory (INL) is leading an effort to steward knowledge and information about important steps in the nuclear fuel cycle. As part of this initiative, INL is designing and constructing the Beartooth testbed which will include glovebox lines, dissolution equipment, and separations equipment. The testbed will provide infrastructure to scientists to test novel separation techniques and give early career researchers opportunities to have hands-on experiences and gain knowledge in separations science. In addition, Beartooth is uniquely designed to enable novel technologies including machine learning capabilities for the characterization of chemical process operations. One of the intentions of incorporating machine learning methods is to provide process operators with enhanced situational awareness for the optimization of separations.

MONITORING EQUIPMENT

Solvent extraction processes that use centrifugal contactors typically monitor flow rate, solution temperature, and ambient temperature. In addition, the motor's revolutions per minute (RPM) and the heater's temperature are set by the operator. These activities are tracked or manually recorded in a prototype contactor system arranged at INL's Bonneville County Technology Center and utilized for this project. In addition to tracking measurements from these traditionally used sensors, researchers have purchased sensors to monitor vibrations, acoustics, seismic activity, solution density, solution viscosity, solution color, solution pH, solution conductivity, liquid tank levels, infrared thermal imaging, and temperatures in various locations within the system. Details on the specific sensors and sensing ranges were presented at the 2022 Institute of Nuclear Materials Management Annual meeting [1]. The sensors have been strategically and temporarily installed within the solvent extraction system with locations dependent on the goals of the planned experiments. An example diagram is shown in Figure 1 which notionally identifies the sensors installed or utilized in the multi-contactor data collection campaign. Data management was accomplished using National Instrument's Technical Data Management Solution (TDMS). TDMS uses a structured hierarchy for storing data and a TDMS reader allows for searchability. The hierarchy includes three levels: file, group, and channel [2]. In addition to data collection, the software includes a graphical user interface (GUI), also developed in LabVIEW, where a visual representation of measurements is displayed in near real-time.

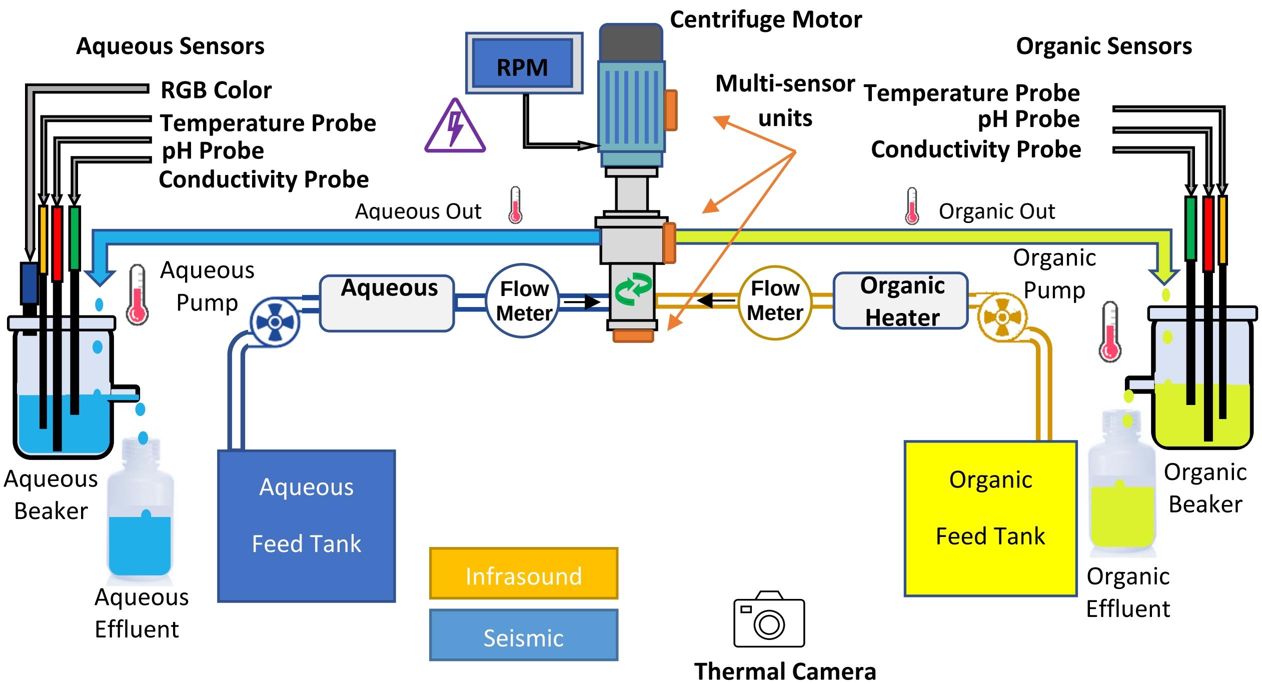

Figure 1. Diagram of sensors installed in single contactor data collection campaign.

DATA COLLECTION CAMPAIGN

The multi-contactor data collection campaign utilized all sensors shown in Figure **1** plus two more infrasound sensors, and several high-sensitivity and modal array accelerometers. Operational changes conducted in the multi-contactor campaign included small incremental RPM changes made to the contactor motors; the changes were made simultaneously with all motors or with individual contactor motors at varying times. Incremental changes of 1 rpm were made to study the sensitivity of the sensors. Additionally, researchers changed the flow rate of the organic solution and conducted pH and color changes to test sensors.

PRELIMINARY RESULTS

Acoustic signals show contactor motors turning on and off and changes in the motor's RPM. As described in the previous section, the process operator turned on the contactor motors one-by-one which is typical of activities conducted at the start of a separation. Signals, measured by a Raspberry Shake and Boom (RS&B) sensor, were present in coincidence with the contactor motors turning on one-by-one as identified in the acoustic spectrogram presented in Figure **2**. The time at which the contactors turned on and the number of motors turned on is also displayed in Figure **2**. Times were obtained from experimental and operator notes.

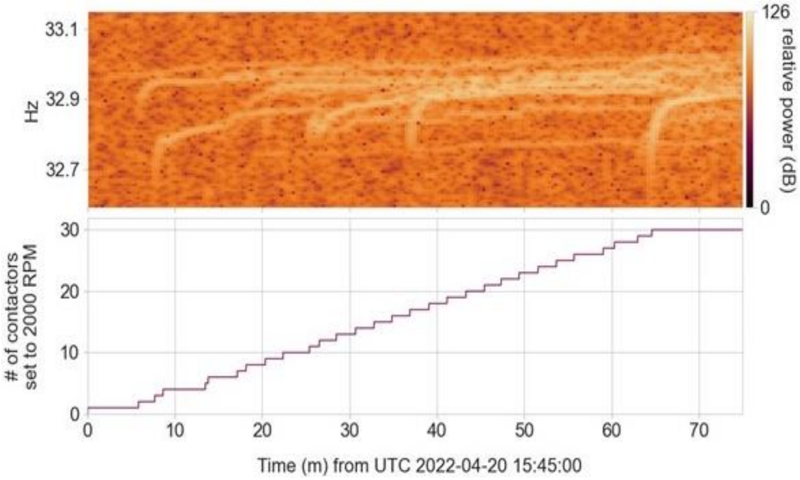

Figure 2. Short-time Fourier Transform spectrogram with acoustic signals measured from RS&B sensor (top panel) showing contactor start-up activity for motors turning on one after the other (bottom panel).

During the experiment, the RPM of the contactor motors were set to 2000, 2500, and 3000. The frequency in the acoustic signals present matched the change in motor RPM as shown in Figure 3. The time starting at approximately 290 minutes into the experiment to the end of time displayed shows acoustic power from a single contactor motor. A closer view of the time starting at approximately 231 minutes and until approximately 241 minutes into the experiment is displayed in Figure 4. The acoustic spectrogram shows acoustic power with the frequency increasing in coincidence with the contactor motor speeds increasing from 3000 to 3010 RPM in 1 RPM increments.

The sensiBLE 2.0 with accelerometer, magnetometer, humidity, temperature, pressure, microphone, infrared, and ultraviolet multi-sensing capabilities was tested as a low-cost alternative to higher fidelity sensors. Figure 5 shows the temperature and humidity recorded by a unit positioned on the flat bottom-side of a contactor vessel for measurements. Changes to temperature and humidity were observed during the experiment; however, the data appears to be highly granular with a low resolution. The low resolution of the sensor may make it difficult to distinguish between operating conditions that result in minor differences in temperature or humidity.

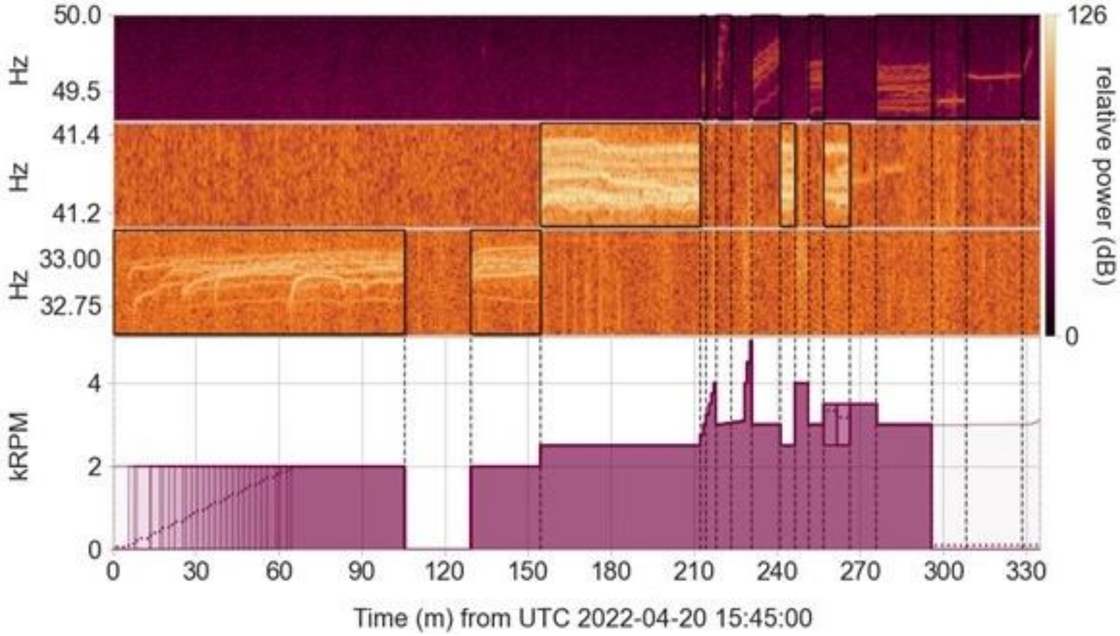

Figure 3. Short-time Fourier Transform acoustic spectrogram with signals measured from RS&B sensor showing power increases (upper panels) in coincidence with contactor motor RPM changes (lower panel).

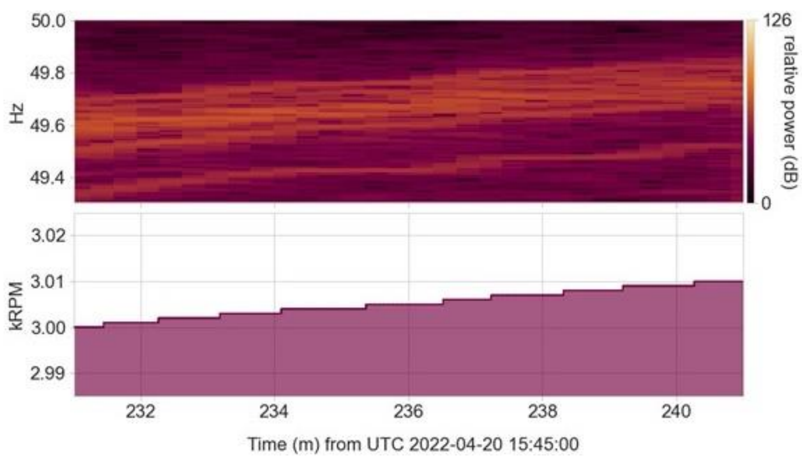

Figure 4. Short-time Fourier Transform spectrogram with acoustic signals measured from RS&B sensor (top panel) and centrifugal contactor activity (bottom panel) during a gradual increase, 1 RPM increments, in motor speed from 3000 to 3010 RPM.

An additional sensiBLE was installed at the cylindrical side of a contactor vessel for recording vibrations. The low sampling rate of the accelerometer in the sensiBLE excluded the possibility for frequency analysis in a relevant range, however, the raw data showed distinct changes in amplitude correlated with motor RPM operational changes as displayed in Figure 6. Furthermore, the sensiBLE experienced losses in data visible in Figure 6 at approximately 7 s, 15 s and 20 s into the experiment. In addition to data losses, the sensiBLE also experienced an issue with unequal sampling frequencies. Figure 7 shows the difference between time stamps of between 10 to 80 ms observed for adjacent points. This variability has the potential to affect acceleration results. For instance, the Fast Fourier Transform (FFT) assumes a constant sampling frequency as it shifts from the time domain to the frequency domain. Variability in the sampling frequency will lead to spectrum leakage (i.e., widening of peaks) that can obscure characteristic frequencies.

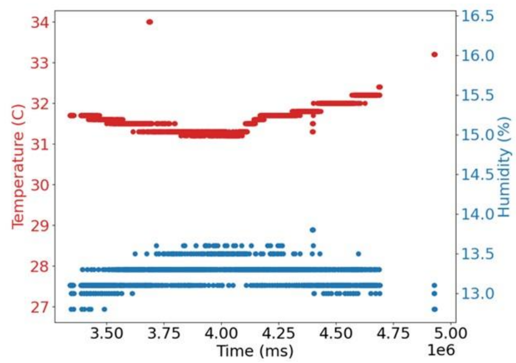

Figure 5. SensiBLE temperature and humidity measurements taken by unit positioned on the bottom of a single contactor vessel.

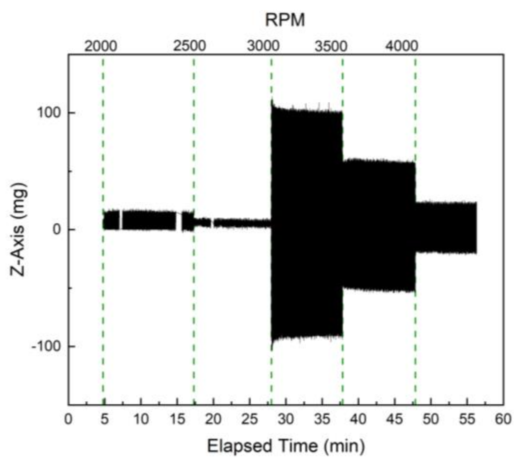

Figure 6. SensiBLE raw acceleration data measured from unit attached to a single contactor.

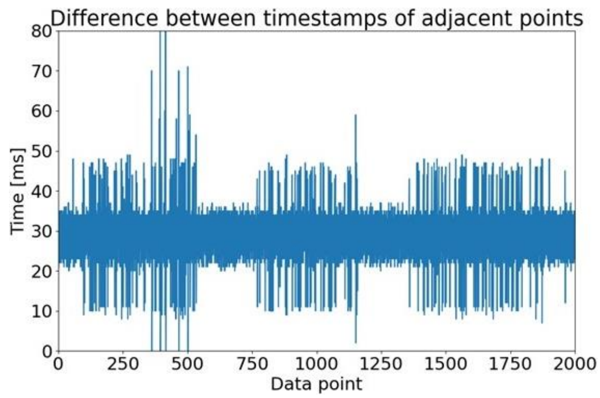

Figure 7. SensiBLE measures at an unequal sampling frequency. A uniform sampling frequency would have the same difference between time stamps.

CONCLUSIONS

Idaho National Laboratory is designing and constructing the Beartooth testbed in support of nuclear fuel cycle stewardship. The testbed will allow researchers the opportunity to study nuclear fuel processing operations. This includes studying solvent extraction processes that use centrifugal contactors. By design, Beartooth will also support the testing of novel technologies that have the potential to enhance separation methods and safeguarding of special nuclear materials. This includes monitoring a solvent extraction process with nontraditional sensors. Preliminary results show that nontraditional sensors have proven useful in determining operational changes with contactor motors, solution color, pH, and conductivity changes. Results also showed that significant challenges were found in the lower-cost multi-sensor units. These challenges led to the purchase of a different brand of sensor for future testing. Furthermore, future testing is also planned for additional sensors such as ultrasonic tank level sensors, solution viscosity, solution density, and laser doppler vibrometers. These analyses were possible by the collection of signals through a sophisticated system architecture that allows for the collection of data at high sampling rates from multiple sensors and the collection of data from multiple sensors at multiple sampling rates. Using commercially available equipment the team implemented the TDMS structured hierarchy for data management allowing for data collection with no known data losses. Although data storage requirements were met in the current year, the addition of sensors and continuous collection over a series of days would require streaming data and cloud storage solutions.

ACKNOWLEDGEMENTS

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2. J. D. Hix, J.T. Johnson, E. S. Cárdenas, L. A. Ocampo Giraldo, "Multi-Sensor Data Acquisition System for Monitoring Fuel Reprocess Systems," Proceedings of the 2022 American Nuclear Society Winter Meeting, November 2022.