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An Overview in the Development of a Multi-Sensor Data Science System for Monitoring a Solvent Extraction Process

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ABSTRACT

To enhance nuclear nonproliferation stewardship, Idaho National Laboratory is building the Beartooth nuclear fuel processing test bed. The Beartooth test bed will allow researchers the opportunity to study fuel separation operations that include the use of centrifugal contactors and solvent extraction equipment. In addition to solvent extraction operations, the test bed is designed to support data collections that will allow for the monitoring of process operations in real-time and implementation of machine learning algorithms. As part of this project, researchers will study data collected from a host of sensors that have not been typically used to monitor solvent extraction processes. Measurements include vibration, acoustic, colorimetric, and thermal among others. The goal of this research is to employ machine learning and data analytics to study the confluence of signals collected from both traditionally and nontraditionally used sensors for the discovery and identification of important process events. The identification of process events has the potential to provide information to process operators and indicate process anomalies. This paper presents an overview of planned sensors and experiments that will focus on signal discovery.

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

INTRODUCTION

As part of a nuclear fuel cycle research and development initiative, Idaho National Laboratory (INL), is developing the Beartooth test bed. The Beartooth test bed will support fuel cycle stewardship and provide researchers with infrastructure and hands-on experience to test new technologies and further their understanding of separation chemistry [1]. Beartooth infrastructure will reside in INL's Fuel Conditioning Facility, a facility designed for the separation, purification, and recovery of fissile elements from used nuclear fuel [2]. Beartooth infrastructure will include glove box lines, dissolution equipment, separations equipment including centrifugal contactors, and additional equipment that will allow for processing of special nuclear materials [1]. In addition, Beartooth will provide opportunities to scientists and engineers by allowing for the collection of process data in real-time and the promotion of machine learning through the discovery and identification of process signals that may aid in safeguards and nonproliferation efforts.

As part of the Beartooth initiative, researchers will utilize prototype equipment designed for nonradioactive materials to begin investigations prior to the completion of Beartooth. Additionally, researchers will equip centrifugal contactors and associated infrastructure with nontraditional sensors,

sensors not typically installed in a solvent extraction system, to monitor process operations. Researchers will apply machine learning and data analytic methods on data collected for signal discovery and characterization. Signals correlated to equipment usage and process operations may provide operators with insights into process activities including process anomalies. Research into process activities has the potential to impact fundamental understanding in separation chemistry. Furthermore, researchers will devise experiments to determine whether process anomalies can be measured, such as material diversion. Results from this research will be used to inform design elements in Beartooth and more broadly, has the potential to impact decision making that supports Safeguards by Design in industry-wide solvent extraction systems. This paper provides an overview of monitoring efforts on INL's prototype solvent extraction equipment with details on the sensors and equipment purchased as well as a summary of recent data collection campaigns.

MONITORING EQUIPMENT

Solvent extraction processes that use centrifugal contactors typically monitor flow rate, solution temperature, ambient temperature, and the motor's number of revolutions per minute (rpm). These activities are either set or tracked in the prototype contactor system utilized for the Beartooth initiative. In addition to tracking these traditional measurements, researchers have purchased nontraditional sensors to monitor vibrations, acoustics, seismic activity, solution density, solution viscosity, solution color, solution pH, solution conductivity, tank levels, infrared thermal imaging, and temperatures in various locations within the system. Table 1 lists the sensors that are planned for monitoring the prototype system. A balance for material diversion experiments is also listed. The sensors will be strategically placed within the solvent extraction system with locations dependent on the goals of the planned experiments. Most of the sensors listed in Table 1 have been fitted to meet installation requirements. To accommodate the recording of all the sensors, a data acquisition architecture was designed to handle data reading and writing at various frequencies. Software has also been created to provide a visual interpretation of measurements in real-time for many of the sensors.

Table 1. Monitoring sensors of interest for the Beartooth prototype.

Measurement or Activity	Sensor	Sensing Range
Vibration	PCB Piezotronics high sensitivity accelerometer	0.5 Hz-10 kHz
Vibration	PCB Piezotronics modal array accelerometer	0.5-3 kHz
Acoustics	GRAS Sound & Vibration ½" Rugged Free-Field microphone	3.15-20 kHz @ 2dB
Acoustics	GRAS Sound & Vibration ¼" Free-Field microphone	4-80 kHz @ 2dB
Acoustics	GEM Infrasound logger	0.05-25 Hz
Seismo-acoustic	Raspberry Shake and Boom	Infrasound 1-44 Hz Seismic 0.7-44 Hz
color	Atlas Scientific EZO-RGB Embedded Color Sensor	~425- ~750 nm wavelength
pH	Atlas Scientific pH 101P	0-14
Conductivity	Atlas Scientific Conductivity K 10	10 µS/cm-1 S/cm
Liquid tank level	Innovative Components Ultrasonic Level Sensor	1.75 inches – 3 feet

Viscosity & density	Rheonics Inc. inline process density & viscosity meter	Viscosity 1-3000 cP Density 0.4-1.5 g/cc
Accelerometer, magnetometer, temperature, acoustics, humidity, & luminosity	Various brands	various
Infrared imagery & temperature	Teledyne FLIR C5	Temperature 0-100 ˚C
Mass	A&D Apollo high-capacity precision balance	0.1 g – 22.2 kg

DATA COLLECTION CAMPAIGNS

Two data collection campaigns have recently been conducted using the prototype test bed: one using a single contactor and the other utilizing multiple contactors (up to 30 that make up the system). The goal of the single contactor campaign was to utilize a limited number of sensors and collect an initial set of data. The data was provided to data scientists for testing their machine learning tools and for gathering feedback on improvements that could be made with data formats. In addition, the data communication and data acquisition system were tested as well as sensor fittings to determine improvements preferred for future installations.

The goal of the multiple contactor campaign was to validate initial results from the single contactor campaign, examine changes to signals when multiple contactors are utilized, and examine new signals generated from using multiple contactors. Testing was performed on additional sensors that were installed for the multiple contactor campaign. Moreover, data was recorded at higher sampling rates to determine system limitations and future storage requirements. In both initial campaigns, aqueous and organic feeds from known separations were not required for the testing of sensors.

Single Contactor Data Collection Campaign

A single contactor was plumbed to deliver aqueous and organic solutions to flow-through beakers for sensor measurement. The aqueous solution consisted of three solutions with different concentrations of nitric acid: 0.01, 0.1, and 1 M. The 0.01 M solution was dyed with $10\,mg{\cdot}L^{-1}$ methylene blue to test the functionality of the color sensor. The organic feed consisted of 30% tributyl phosphate isopropyl. Both flow-through beakers allowed for the inclusion of pH, conductivity, and temperature sensors. The temperature probe was utilized to validate the measurements collected by the pH and conductivity sensors. Figure 1 shows a diagram of the sensors installed or utilized in the single contactor data collection campaign. In addition to sensors situated in the flow-through beakers, three multi-sensor units were installed: one affixed to the external cylindrical wall of the contactor motor, one affixed to the external cylindrical wall of the contactor vessel, and one affixed to the lower flat edge of the contactor vessel. Infrasound and seismo-acoustic sensors were placed on the floor beneath the contactor system. Finally, an infrared thermal camera was positioned in front of the contactor system with a field of view that included the single operating contactor.

For this campaign, operation events focused on contactor motor changes, heater changes, and changes in the volume of dye added into an initially clear aqueous solution. Although, comprehensive data analysis from the single contactor campaign is currently underway, preliminary results suggest the color, pH, conductivity, infrared, and multi-sensor units provide indicators of process events. Data from the infrasound and seismo-acoustic sensors has yet to be analyzed. Initial takeaways led to modifications in the color sensor vessel; a custom-built component that allowed for submersion into a solution. Data examined in real-time led to a design change that allowed for more solution to flow through the color vessel. The vessel material was also changed to provide more reflective properties that would increase the detection sensitivity. Data examined in real-time from the accelerometers in the multi-sensor units showed significant changes in the signal associated with large incremental operational changes made to the contactor motor. However, due to a low sampling rate, an alternate multi-sensor unit with a higher sampling rate was purchased for testing in future experiments. Furthermore, the infrared thermal camera showed higher temperatures, presented in Figure 2, associated with motor operation as well as solution flowing through system tubing.

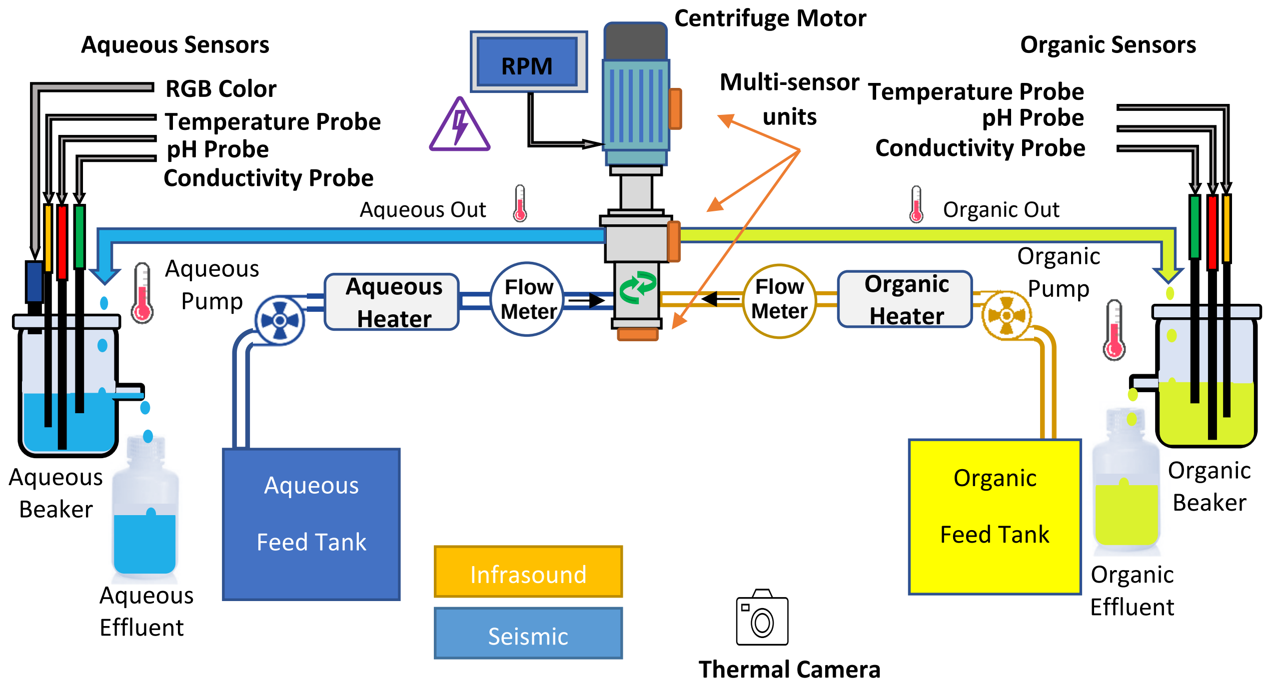

Figure 1. Diagram of sensors installed in single contactor data collection campaign.

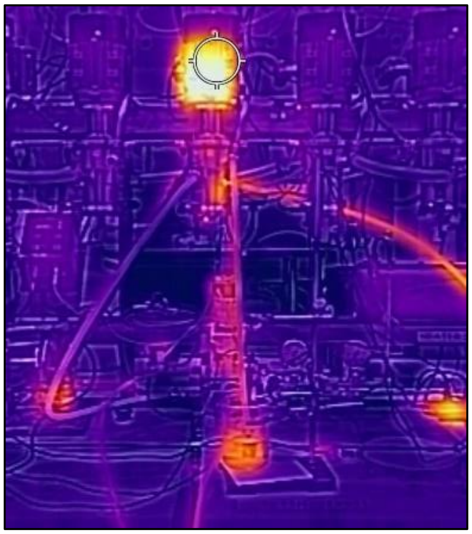

Figure 2. Infrared thermal image of single contactor operation.

<u>Multiple Contactor Data Collection Campaign</u>

In the multiple contactor data collection campaign, all sensors that were used in the single campaign were installed. In addition, two more infrasound sensors were positioned in the room. Several high-sensitivity and modal array accelerometers were positioned on or near the contactors as presented in Figure 3. The image on the left-hand side in Figure 3 shows a high-sensitivity accelerometer positioned on the top of a fan that is affixed directly over and on axil to the contactor motor. This accelerometer can measure high frequency signals including those emitted from the contactor motor. The image in the center shows a metal block attached to a structural bar where all contactors are attached. The arrows in the image point to single-axis accelerometers on the metal block. These accelerometers were positioned to measure vibrations emitted from the system as opposed to a single contactor. Figure 3 also includes a microphone used to record operational sounds. Operational changes conducted in the multiple 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.

Although a comprehensive examination of the data from the multiple contactor campaign is yet to be performed, visual inspections of the data acquired in real-time revealed visible changes in the vibration and acoustic signals as the motors were changed in 1 rpm increments. Real-time data also showed changes in measurements when the color, pH, and conductivity changed. A thorough examination of the data is required to determine if other operational variations, such as changes in flow rate, can be measured. A thorough examination of the data is also required to determine if visual changes in the signals, made in real-time, can be quantified with operational changes. Comprehensive data analysis is currently being conducted.

Figure 3. The image on the left shows an accelerometer axial to the contactor motor. The image in the center shows directional accelerometers deployed on contactor framework. The image on the right shows a microphone used to record operational sounds emitted from the contactor system.

FUTURE EXPERIMENTS

Future experiments using the system of contactors will be conducted over the next two years. These experiments include the addition of more sensors such as viscosity, density, and ultrasonic level sensors. Additional experiments that may be conducted include running the system of contactors in separation stages that includes extraction, scrub, and stripping sections; similar to the operational approaches utilized in a given separation. Furthermore, experiments are being designed to determine if implementing data science techniques on combined data from traditional and nontraditional sensors can provide methods of safeguarding against material diversion.

CONCLUSIONS

To support research and development into an evolving nuclear fuel cycle, INL is constructing the Beartooth test bed. Beartooth will provide training to scientists and opportunities to test emerging technologies. In support of Beartooth, researchers have deployed nontraditional sensors in a system of centrifugal contactors that are used for solvent extraction. Researchers will determine if machine learning methods applied to the confluence of signals can provide operators with process awareness including process anomalies. Signals measured include vibration, acoustics, color, pH, conductivity, and seismic. These signals were recorded along with signals measured from traditionally used sensors measuring flow rate, temperature, and rpm.

Two data collection campaigns were conducted where operational changes were instructed for the discovery of signals. The first campaign utilized a single contactor and a limited set of sensors with the goal of collecting an initial set of realistic data to provide to data scientists. The data allowed scientists to test machine learning tools and determine improvements to data formats. The campaign also allowed for the testing of installation fixtures, sensor functionality, and use of an initial version of a custom-built data acquisition system. A second data collection campaign was conducted where multiple centrifugal contactors and additional sensors were operated. This campaign tested sensor response to multiple contactor signals, improvements and additions to custom-built data acquisition software, and will allow for the comparison of signals emitted from a single contactor. Initial inspection of data from both campaigns indicates that signals from pH, conductivity, color, vibration, and acoustic sensors can be associated with equipment usage and process events. Research into signal discovery and characterization will continue for an additional two years.

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