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*Changing the World's Energy Future*

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# DEVELOPMENT OF A MULTI-SENSOR DATA SCIENCE SYSTEM USED FOR SIGNATURE DEVELOPMENT ON SOLVENT EXTRACTION PROCESSES IN SUPPORT OF SAFEGUARDS – AN OVERVIEW

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## Abstract

A new nuclear fuel cycle test bed is being built at Idaho National Laboratory to support the purification of special nuclear material recovered from used fuel. The test bed provides an opportunity to research process flow and the application of computational tools in solvent extraction processes. A deeper understanding of process and equipment behavior coupled with real time data collection can indicate whether a process failure is accidental or purposeful. The goal of this project is to develop a system that utilizes non-traditional measurement sources such as vibration, acoustics, current, light, flow, and temperature in conjunction with data-based, machine learning techniques that will allow for signal discovery. This multi-sensor data can support the development of safeguards by design and security by design measures for such a facility. Additionally, it can aid in early detection and identification of removed materials indicating diversion, which is essential for initiating material recovery and actor identification. This overview encompasses the current research and testing of sensors to develop a spectrum of process signatures. To be followed by planned experiments aimed to characterize said signatures and study potential feature extraction techniques to identify a fault in the system (i.e. flow diversion).

## 1. INTRODUCTION

Idaho National Laboratory is developing the Beartooth test bed in support of nuclear fuel cycle stewardship. 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]. By design, Beartooth will also support the testing of novel technologies that have the potential to enhance separation methods and the safeguarding of special nuclear materials. To facilitate that commitment, this project explores multi-sensor monitoring, on a solvent extraction process that uses centrifugal contactors, for signal discovery. Data science and signal processing techniques will be used to determine if process signals can characterize process conditions and improve an operator's situational awareness. This research has the potential to improve on recovery quantities of target metals, indicate process faults, and aid in near real-time decision making. Results from this research will be used to inform design elements in Beartooth and more broadly, has the potential to impact Safeguards by Design in industry-wide solvent extraction systems, process improvements and nuclear material accountancy.

## 2. CURRENT RESEARCH

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. The focus in the first

year of the project has been to research and test non-traditional sensors for installation in a system of centrifugal contactors used in solvent extraction processes. Sensors that measure vibration, acoustics, colour, pH, conductivity, and seismic activity were included in the research. A list of the sensors used in this testing is shown in Table 1 with sensing ranges. Sensor signals were recorded along with traditionally measured operational signals such as flow rate, temperature, motor rpm, and motor current draw.

The preliminary campaign utilized a single contactor, shown in Fig. 1, 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 preliminary campaign also allowed for the testing of installation fixtures, sensor functionality, and use of an initial version of a custom-built data acquisition system.

TABLE 1. List of sensors used in preliminary testing

Measurement or Activity	Sensor	Sensing Range
Acoustics	GEM Infrasound logger	0.05-25 Hz
Seismo-acoustic	Raspberry Shake and Boom	Infrasound 1-44 Hz Seismic 0.7-44 Hz
colour	Atlas Scientific EZO-RGB Embedded Colour Sensor	~425- ~750 nm wavelength
pH	Atlas Scientific pH 101P	0-14
Conductivity	Atlas Scientific Conductivity K 10	10 $\mu$ S/cm-1 S/cm
Accelerometer, magnetometer, temperature, acoustics, humidity, & luminosity	Various brands	various
Infrared imagery & temperature	Teledyne FLIR C5	Temperature 0-100 °C

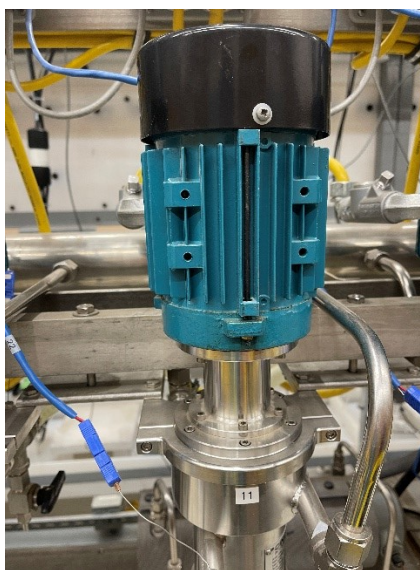


FIG 1. Photograph of the single centrifugal contactor used in preliminary testing.

## 2.1. Preliminary data campaign

A single contactor was plumbed to deliver aqueous and organic solutions to separate flow-through beakers for sensor measurement. The aqueous solution was dyed with methylene blue to test the functionality of a colour sensor that was positioned in the flow-through beaker. Both flow-through beakers allowed for the inclusion of pH, conductivity, and temperature sensors. Fig. 2 shows a diagram of the sensors installed in the preliminary data collection campaign. 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.

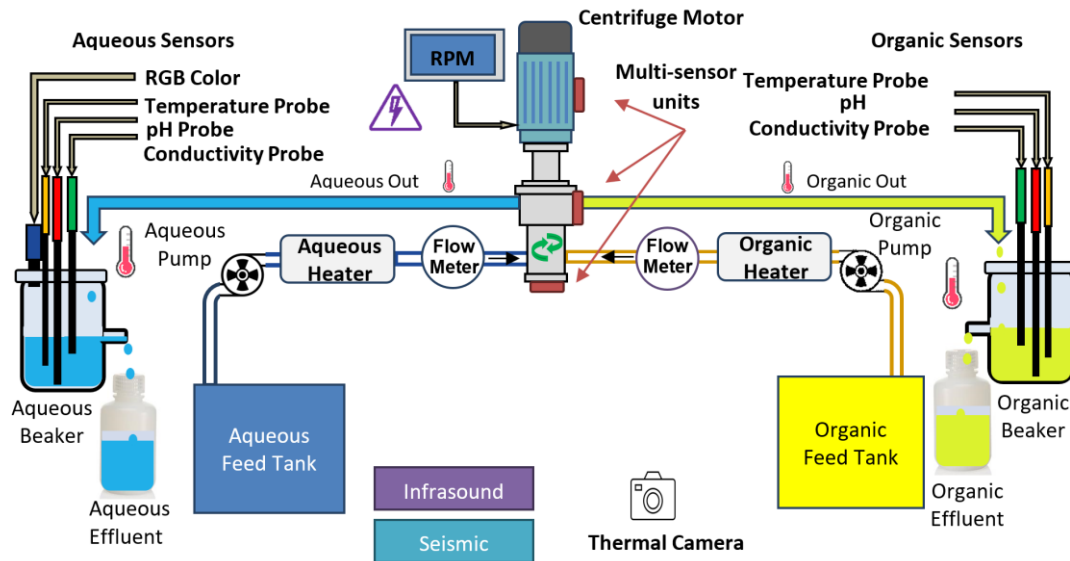


FIG 2. Diagram of sensors installed in single contactor data campaign [3].

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  $10\text{mgL}^{-1}$  methylene blue to test the functionality of the colour 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 [3].

## 2.2. Data acquisition

To accommodate the recording of all the sensors, a data acquisition architecture was designed to handle data reading and writing at various frequencies. The first data acquisition system (DAS) was created using LabVIEW to capture data from colour, vibration, pH, and conductivity sensors. This system is shown in Fig. 3 with a set of centrifugal contactors of which only one was used. A new iteration of the DAS has been created to expand on the number and types of sensors. The new sound and vibration data acquisition system (SVDAS) can record up to 12 accelerometers and/or microphone sensors simultaneously. SVDAS uses National Instruments (NI) hardware to digitize the signals as well as provide power to the sensors. The new SVDAS is used to stream sensor data to a file without any dropout or loss of information. The SVDAS hardware is modular making it scalable so that more sensors can be added.

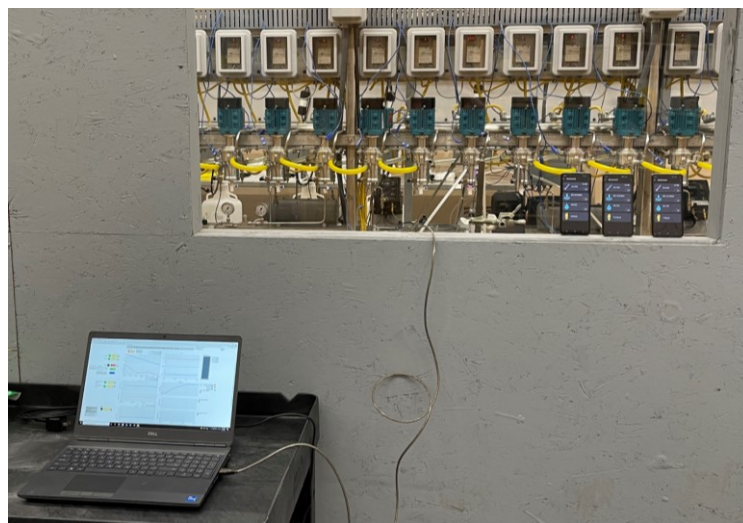


FIG 3. A photo of the original data acquisition system and a set of contactors.

### 3. DISCUSSION

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 colour, pH, conductivity, infrared, and multi-sensor units provide indicators of process events. Data from the infrasound and seismo-acoustic sensors is currently underway. Initial takeaways led to modifications in the colour sensor vessel; a custom-built component that allowed for submersion into a solution. Data examined in real-time has led to a design change that allowed for more solution to flow through the colour vessel. The vessel material was also changed to provide more reflective properties that would increase the detection sensitivity. Furthermore, results from the infrared thermal camera showed higher temperatures associated with motor operation as well as solution flowing through system tubing. Data 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.

The data was provided to data scientists for testing machine learning tools and for gathering feedback on improvements that could be made with data formats. In addition, data communication and data acquisition were tested which led to the improved SVDAS. A second campaign is currently underway to test the new SVDAS and the addition of accelerometers, microphones, and vibration sensors.

### 4. 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; like the operational approaches utilized in each separation. Furthermore, experiments are being designed to determine if implementing data science techniques on combined data from traditional and non-traditional sensors can provide methods of safeguarding against material diversion.

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