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Stewarding the United States' Nonproliferation Competencies in Aqueous Processing

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The United States' National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation has recently initiated a new program, the Nonproliferation Stewardship Program (NSP). NSP's objective is to ensure that the nation's competencies in nonproliferation are maintained by cultivating a robust and enduring workforce of experts to meet present and future needs. A key component of NSP involves the use of modern test beds that provide hands-on experiences to develop expertise. One line of effort within this program addresses technical expertise in aqueous processing of spent nuclear fuel and associated nonproliferation applications under a project called Athena. As part of the Athena project, a new test bed called Beartooth is being developed and utilized where Plutonium Uranium Reduction Extraction (PUREX)-type unit operations in a glovebox environment can be conducted using Special Nuclear Material (SNM). Beartooth is designed to be flexible regarding flowsheet implementation, thereby allowing a variety of chemical separation processes relevant to the nuclear fuel cycle to be studied.

This paper will provide a high-level overview of the NSP as well as the Athena project (which includes Idaho National Laboratory, Pacific Northwest National Laboratory, Savannah River National Laboratory, and Argonne National Laboratory). The Beartooth testbed will be described in context of the Athena science and technology plan, application of advanced sensors, digital engineering, digital twin, and explainable machine learning.

Introduction

There is a critical need to sustain and grow nonproliferation expertise within the current and future workforce to support the peaceful use of nuclear energy in a low carbon economy. Just as the technology landscape is evolving with innovations such as micro and small modular reactors (SMRs), use of high assay low enriched uranium fuel (HALEU), and non-light water reactor designs, nonproliferation expertise must also adapt in both fundamental understanding of new technologies and advanced monitoring and analysis approaches. NNSA's Nonproliferation Stewardship Program (NSP) is addressing this need through intentional investment in science & technology environments and associated test bed infrastructure. As captured in the National Academies report [1], NSP will play a significant role in stewarding monitoring, detection, and verification expertise for both declared and undeclared facilities. NSP's goal of ensuring foundational technical nonproliferation competencies sustainment and growth is being realized by establishing modern science and technology environments through investment in infrastructure and hands on experimental activities. Program execution is based on a quadrennial cycle of establishing mission needs, evaluating associated competencies, and identifying gaps. Initial assessment of the state of workforce and infrastructure needed to meet mission needs identified two primary gaps- mass-based enrichment (uranium line of effort) and aqueous processing of irradiated fuel (plutonium line of effort). Other competency areas where there are significant capability gaps or high mission impacts include laser-based enrichment, pyroprocessing, and advanced reactors.

Athena Project

Under the plutonium line of effort is a project called Athena that is focused on aqueous processing of spent nuclear fuel, being executed by Pacific Northwest National Laboratory, Idaho National Laboratory, Savannah River National Laboratory, and Argonne National Laboratory. The Athena project is utilizing and developing a number of test beds designed to sustain and grow aqueous processing and associated nonproliferation expertise in laboratory, glovebox, and hot cell environments. In addition to basic unit operations representing the PUREX process, variations of PUREX, such as UREX, THOREX, and GANEX among others, will be able to be studied [2-7]. Table 1 shows some key characteristics of PUREX and variations designed for specific nuclear fuel cycle applications, including advanced reactors utilizing uranium, plutonium, and thorium fuels.

Table 1. PUREX process variations worldwide

Process	**Purified Effluents**	**Primary Extractant**	**Reductants, Salting Agents, etc.**	**Nations Researching or Employing**
PUREX	U, Pu	TBP	Fe(II), hydroxylamine, hydrazine	Numerous
UREX	U, Tc	TBP	AHA	US
Co-Decon	U+Pu+Np, U, Tc	TBP	AHA, hydrazine/U^{4+}	US
COEX	U+Pu, U, Am+RE	TBP	Hydroxylamine, U^{4+}	France
NUEX	U+Pu+Np, U, Tc	TBP	AHA	US, France, UK
NEXT	U+Pu+Np, Am+Cm	TBP		Japan
PARC	U, Pu, Np, Tc	TBP	Butyraldehyde	Japan
GANEX	U, U+Pu+Np+Am, Mo, Ru, Tc, Lns	DEHiBA, DMDOHEMA/HDEHP, HEDTA/citric acid, TEDGA/oxalic acid		France
TRPO	U, Pu, Np, Am+RE	TRPO	$(NH_4)_2CO_3$	China
APRO	U, Pu, Np	TBP	DMHAN/MH	China
THOREX	Th, U-233	TBP	HNO_3, $Al(NO_3)_3$	US, India

The overall science and technology approach includes process demonstrations at varying scales and feed materials, material and process monitoring and characterization, associated modeling and simulation, and data science. Advances made under the Athena project will provide a foundation for deploying the next generation of reactors with confidence and advance proliferation detection capabilities. In many cases, advanced reactors go beyond the current light water reactor experience, including new fuels (enrichments, composition, and forms), non-water coolants, and size (small modular and micro reactors), and will require additional nonproliferation tools and expertise [8]. The Athena project will advance nonproliferation capabilities to address challenges and opportunities associated with these new technologies.

Three flag ship test beds will be developed under the Athena project: hot cell-based processing at PNNL (Plutonium Recovery and Conversion System or PuRCS) and SRNL (Actinide Science and Engineering Test bed or ASET) as well as the shielded glovebox-based Beartooth test bed at INL. A general philosophy of implementing 'modern' test beds is being pursued where advanced monitoring and analysis capabilities are built in 'by design.' Digital twins are being implemented along with advanced data analytics employing machine learning. Stewardship activities are occurring throughout the lifecycle of each test bed representing design, fabrication, and operation, where senior staff mentor early and mid-career personnel.

Beartooth Test Bed

The Beartooth test bed is a new glovebox-based processing capability at INL's Material and Fuels Complex, capable of handling enriched uranium, plutonium, thorium, and minor actinides. The shielded nature of the glovebox configuration allows handling of fission products up to a dose of several R/hr (at contact). Beartooth is designed to have flexibility with respect to specific unit operations to allow a variety of PUREX-based flowsheets to be studied. Traditional and advanced monitoring capabilities are being integrated into the test bed as well as digital engineering aspects such as a digital twin capability and advanced data analytics. Figure 1 shows the general layout of the Beartooth test bed.

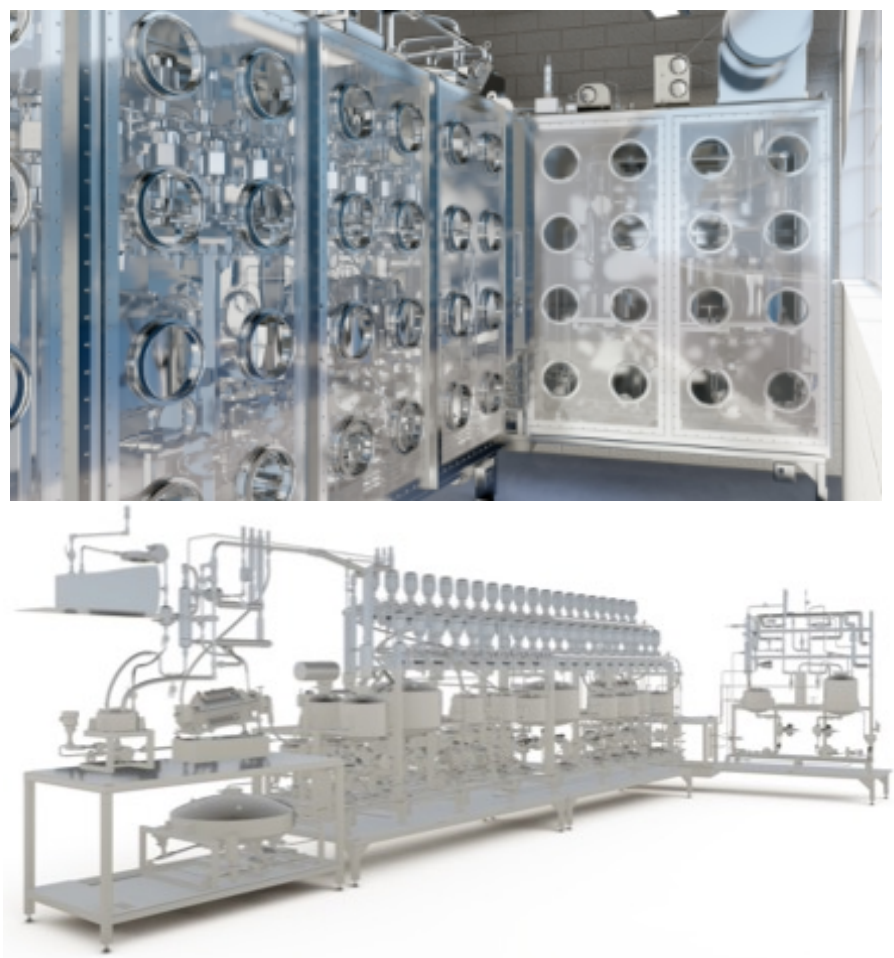

Figure 1. Design renderings of the Beartooth test bed at INL, top- process equipment with glovebox and bottom – without the glovebox structure.

The Beartooth test bed will be capable of dissolution (5-7 kg heavy metal batch size), chemical separations employing 40 stages of CINC V02 centrifugal contactors, and conversion/solidification via modified direct denitration. Components will be made from both Hastellow C276 and 316L stainless for chemical compatibility. Mass-limited criticality controls will be in place for maximum processing flexibility. Supporting analytical equipment and laboratory space will be located in an adjacent room. The test bed is being designed for monitoring flexibility including off gas, traditional and non-traditional process monitoring, and nuclear material tracking. Safeguards and security by design precepts are being employed in conjunction with development of the digital twin, including complex signature discovery via explainable machine learning. Cyber security research and development will also be enabled including the ability to change out the control system.

Development of the Beartooth test bed digital twin has proceeded in lockstep with the glovebox design activities and has been part of the formal design review process. Design drawings are imported directly into the digital twin framework and accessible using a HoloLens mixed reality headset. Several design modifications have been made using this approach, avoiding costly post-fabrication fixes. Figure 2 shows the digital twin framework including direct connectivity to test bed data, chemical systems modeling, and machine learning.

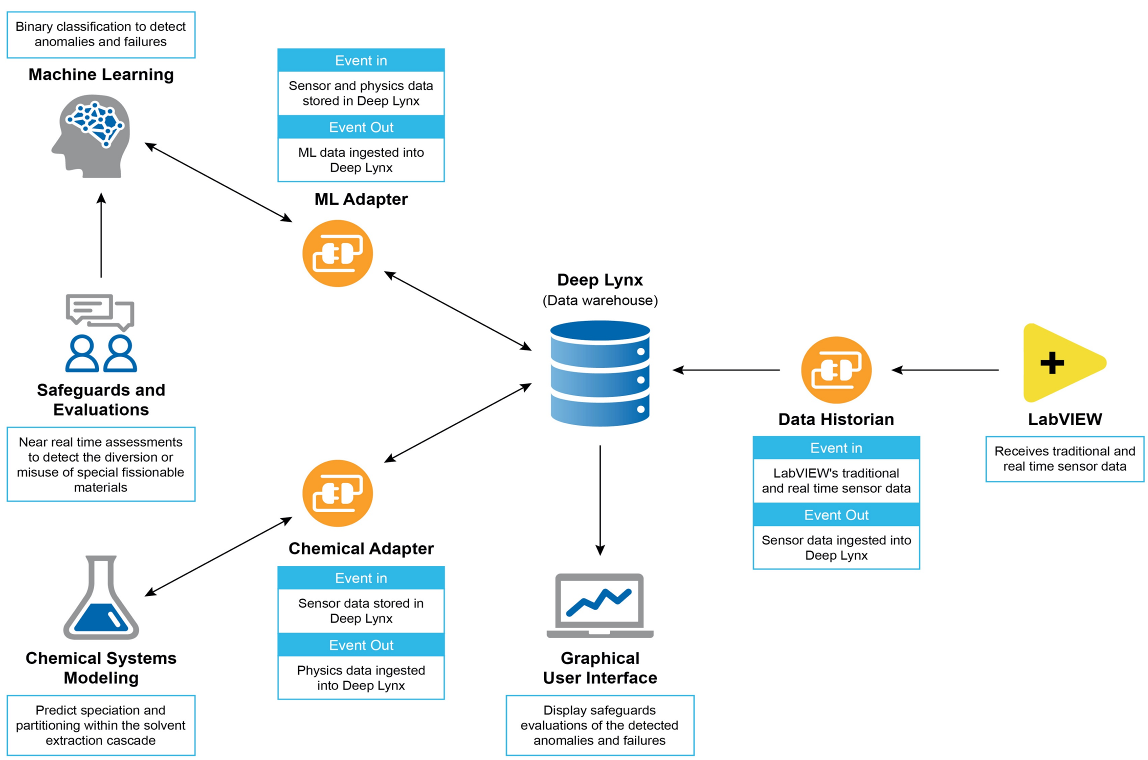

Figure 2. Digital Twin framework.

In addition to standard process monitoring capabilities such as flow rate, temperature, and contactor revolutions per minute, we are exploring advanced sensors such as vibration, acoustics, color, pH, density and thermal imaging. Experiments are being conducted in support of the Beartooth configuration design in a non-rad test bed with data being analyzed using explainable machine learning. These types of data can be useful to the operator as well as the safeguards inspector, highlighting process upsets prior to equipment failure as well as developing trend lines for inspector evaluation prior to significant nuclear material loss [9]. It is anticipated that these types of data can be integrated with traditional safeguards and nuclear material accountancy data to provide more robust awareness of facility operations, thereby increasing the confidence of peaceful use.

Summary

Stewardship of aqueous processing nonproliferation competencies under the NSP Athena project will help to enable advanced nuclear reactor deployment with confidence and enhance proliferation detection through the development of an enduring pipeline of nonproliferation experts and modern test beds. The Beartooth test bed being instituted at INL and will provide flexible flowsheet operations and development of advanced monitoring, detection, and verification capabilities.

Acknowledgements

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