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Title: Process Monitoring for the Next Generation Safeguards Initiative (NGSI)

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Process Monitoring for the Next Generation Safeguards Initiative (NGSI)

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Abstract

For large throughput nuclear facilities, such as commercial reprocessing plants, it is difficult to satisfy the IAEA safeguards accountancy goal for detection of diversion. Process monitoring (PM) is used in safeguards as an additional measure to nuclear material accountancy (NMA). Process monitoring consists of utilizing process control measurements to detect abnormal plant operation. Process control measurements are those used by the operator to control the chemical and/or physical processes. Examples of process control measurements in reprocessing plants include (1) feed and product flow rates by measuring the change in tank volume versus time, (2) concentration measurement of nonnuclear material reagents, and (3) process temperatures. Significant challenges for the future use of process monitoring include greater access to the plant operator's process control data (enhanced PM), leveraging the development of new process control instrumentation and/or development of new independent IAEA instrumentation to be used for advanced process monitoring, and reducing inspector time required to evaluate process monitoring data since process monitoring for the future will likely include additional operator data. Enhanced process monitoring can be implemented near-term in existing facilities and advanced process monitoring can be implemented in the long-term in new facilities.

Acknowledgements

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Introduction to Process Monitoring (PM)

- For large throughput nuclear facilities, such as commercial reprocessing plants, it is difficult to satisfy the IAEA safeguards accountancy goal for detection of diversion.
- Process monitoring (PM) is used in safeguards as an additional measure to nuclear material accountancy (NMA).
- Process monitoring consists of utilizing process control measurements to detect abnormal plant operation. Process control measurements are those used by the operator to control the chemical and/or physical processes. Examples include;
  - Feed and product flow rates by measuring the change in tank volume versus time,
  - Concentration measurement of nonnuclear material reagents,
  - Process temperatures.

Examples of Existing Process Monitoring (PM) for a Variety of Nuclear Facilities

- Gas Centrifuge Enrichment Plants (GCEPs)
  - Load cells for continuous monitoring of feed, product and tails cylinder weight [Carchon, et al., 2011 and Howell, et al., 2010]
  - Enrichment monitors for the cascade header pipes [Ianakiev, et al., 2010]
- Nuclear reactors
  - NDA for spent fuel [Tobin, et al., 2011]
  - Advanced Thermal-Hydraulic Power Monitor (ATPM) for coolant flow and temperature drop [Aparo and Whichello, 2003].
- Spent Fuel Reprocessing Facilities
  - Solution monitoring [Burr and Wangen, 1996]
  - Neutron balance technique [Tobin, et al., 2011]
- MOX Fuel Fabrication Facilities
  - Neutron monitoring of nuclear material movement within and/or between glove boxes [Shimizu, et al., 2006, and Xerri, et al., 2002]

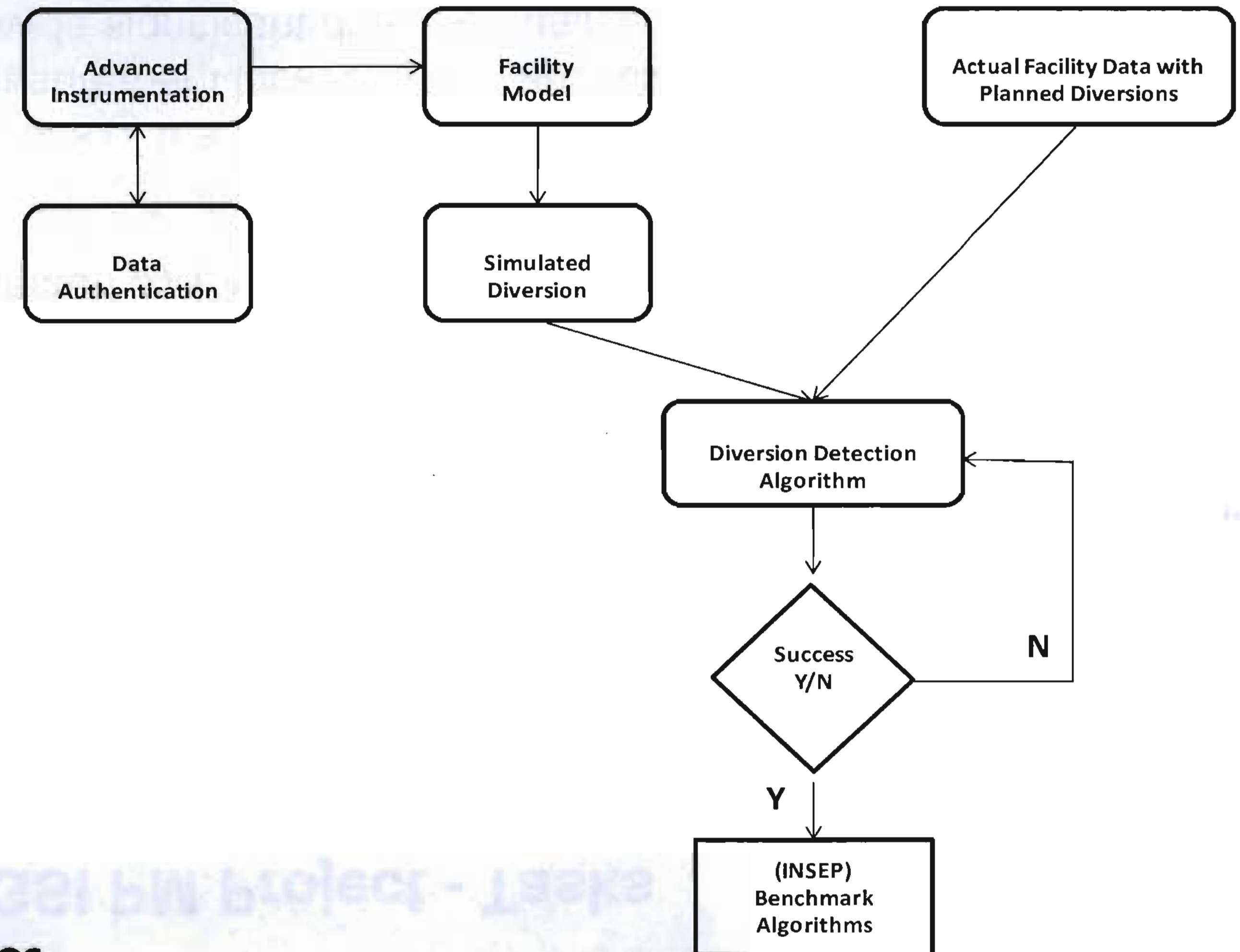
Future Process Monitoring Implementation - Objectives

- Significant challenges for the future use of process monitoring include:
  - Greater access to the plant operator's process control data (***enhanced PM***),
  - Leveraging the development of new process control instrumentation and/or development of new independent IAEA instrumentation to be used for ***advanced process monitoring***,
  - Reducing inspector time required to evaluate process monitoring data since process monitoring for the future will likely include additional operator data.
- **Enhanced** process monitoring can be implemented near-term in existing facilities and **advanced** process monitoring can be implemented in the long-term in new facilities.

The NGSI PM Project – Objectives

- Demonstrate the added value for safeguarding a facility with PM, in addition to nuclear material accountancy (NMA) alone.
- The United States National Nuclear Security Administration (NNSA) has initiated a process monitoring project through its Next Generation Safeguards Initiative (NGSI) to contribute to both near-term and long-term implementation objectives.
  - In the near-term, the analysis tools being developed by this project will be used to identify existing process control data in operating reprocessing facilities not currently shared with the IAEA that could significantly enhance current process monitoring efforts,
  - In the long-term, the analysis tools being developed by this task could be used to identify new process control instrumentation and/or new independent IAEA instrumentation to be used for advanced process monitoring in new facilities.

The NGSI PM Project - Overview



The NGSI PM Project - Tasks

- Facility Model and Simulated Diversion
  - In order to test the DDAs either actual plant data with a known diversion or simulated plant data with a diversion is required.
- Diversion Detection Algorithm
  - With knowledge of the reprocessing plant process control instrumentation and the expected distribution of nuclear material within the plant following the diversion (as determined by the plant simulation), the detection algorithm was used to provide an estimate of the likelihood that the diversion can be detected by PM.
- Advanced Instrumentation and Data Authentication
  - Results of the Diversion Detection Algorithm can be used to identify measurement locations and associated advanced instrumentation that can provide significant detection gains over existing process control data.

The NGSI PM Project – Tasks (continued)

- Actual Facility Data with Planned Diversions
  - Actual facility data that includes deliberate diversions for safeguards testing was collected during cold testing at the Barnwell facility in the United States during the early 1980s. Other facilities with real-data considered by the NGSI PM team include the Chemical Plant Facility at INL, the Integrated Equipment Test Facility at Oak Ridge National Laboratory (ORNL), Hanford operations at PNNL, and the canyon operations at the Savannah River Site (SRS).
- Benchmark Algorithms
  - Recent joint discussions between the U.S. and JAEA related to the International Nuclear Safeguards Engagement Program (INSEP) have identified a safeguards topic for joint collaboration, "Benchmarking Process Monitoring Models for Reprocessing in support of Joint Safeguards Modeling & Simulation". Benchmarking will be used in a fashion similar to that done by the U.S. Nuclear Regulatory Commission (NRC) for thermal-hydraulic codes, where actual reactor loss-of-coolant data is limited, and therefore the results of independent codes based on synthetic scenarios are compared (i.e. benchmarked) for validation.

The NGSI PM Project - Accomplishments

- Results to date for the NGSI PM project include
  - Development of a partial reprocessing plant model to generate process data representative of diversion
  - Identification of a diversion path to study, that involves incomplete dissolution by reducing the nitric acid concentration and/or reducing the solution temperature
  - Review of actual facility data that includes deliberate diversions for safeguards testing
  - Development of advanced instrumentation for process monitoring such as the Raman/UV-vis-NIR spectroscopic monitor and the Multi-Isotope Process (MIP) monitor
  - Planning for benchmarking the NGSI PM methodology with independent JAEA efforts

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Process Monitoring for the Next Generation Safeguards Initiative (NGSI)

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ABSTRACT

For large throughput nuclear facilities, such as commercial reprocessing plants, it is difficult to satisfy the IAEA safeguards accountancy goal for detection of diversion. Process monitoring (PM) is used in safeguards as an additional measure to nuclear material accountancy (NMA). Process monitoring consists of utilizing process control measurements to detect abnormal plant operation. Process control measurements are those used by the operator to control the chemical and/or physical processes. Examples of process control measurements in reprocessing plants include (1) feed and product flow rates by measuring the change in tank volume versus time, (2) concentration measurement of nonnuclear material reagents, and (3) process temperatures. Significant challenges for the future use of process monitoring include greater access to the plant operator's process control data (enhanced PM), leveraging the development of new process control instrumentation and/or development of new independent IAEA instrumentation to be used for advanced process monitoring, and reducing inspector time required to evaluate process monitoring data since process monitoring for the future will likely include additional operator data. Enhanced process monitoring can be implemented near-term in existing facilities and advanced process monitoring can be implemented in the long-term in new facilities.

The United States National Nuclear Security Administration (NNSA) has initiated a process monitoring project through its Next Generation Safeguards Initiative (NGSI) to contribute to both near-term and long-term implementation objectives. In the near-term, the analysis tools being developed by this project will be used to identify existing process control data in operating reprocessing facilities not currently shared with the IAEA that could significantly enhance current process monitoring efforts. In the long-term, the analysis tools being developed by this task could be used to identify new process control instrumentation and/or new independent IAEA instrumentation to be used for advanced process monitoring in new facilities. The NGI PM project is closely coupled with the NGSI Safeguards by Design project because, PM will be critical for future safeguards designs due to the difficulty in improving NMA for large throughput nuclear facilities, and early consideration of PM in the overall facility design activity will be necessary to avoid proprietary data concerns and provide for adequate data authentication.

1. INTRODUCTION

The purpose of this project is to demonstrate the added value for safeguarding a spent fuel reprocessing facility with process monitoring (PM), in addition to nuclear material accountancy (NMA) alone. In order to achieve this objective, the development of potential diversion paths, detection algorithms for PM, and advanced PM instrumentation are being developed for spent fuel reprocessing facilities.

The authors of this paper have not been able to identify an IAEA sanctioned definition for process monitoring. The "IAEA Safeguards Glossary" does not define process monitoring as a distinct safeguards measure. However, members of the international safeguards community have defined process monitoring as the IAEA's use of the operator's process control data to detect abnormal plant operation that could be indicative of nuclear material diversion (Burr, et al., 2007). In this context, IAEA process monitoring is not nuclear material accountancy but rather an additional safeguards measure above and beyond material accountancy to enhance overall safeguards. On the other hand, the U.S. Nuclear Regulatory Commission (NRC) definition for process monitoring does include nuclear material accountancy (10 CFR 74.53). This conflicting definition for process monitoring, concerning international safeguards and domestic (i.e. NRC) material control and accountancy (MC&A), is mentioned here only to clarify that the focus of this paper is IAEA process monitoring.

Process monitoring can be used in many types of nuclear facilities such as uranium enrichment, nuclear reactors, spent fuel reprocessing and mixed oxide (MOX) fuel fabrication. Process monitoring for uranium enrichment by Gas Centrifuge Enrichment Plants (GCEPs) includes (1) the use of load cells for continuous monitoring of feed, product and tails cylinder weight [Carchon, et al., 2011 and Howell, et al., 2010] and (2) enrichment monitors for the cascade header pipes [Ianakiev, et al., 2010]. IAEA verification of NMA is based on destructive assay (DA) of a withdrawn sample or non-destructive assay (NDA) of a cylinder for enrichment, and cylinder weighing before and after the feed and withdrawal stations. Verification is not comprehensive for every cylinder but rather based on a predetermined statistical plan. Carchon, et al., "present a few different possibilities of exploitation of the data that can be obtained by acquiring in continuous mode the weights of the cylinders in the feed and withdrawal stations". Howell, et al., discuss the use of a Mailbox-centered records collection system to limit inspector access to raw load cell data. Ianakiev, et al., suggest an enrichment monitor that "shifts the focus from qualitative (Go/No-Go) monitoring of the low-pressure header pipe to quantitative enrichment measurements of the high-pressure unit header pipe". Because of their continuous operation, load cells and enrichment monitors have been used to measure trends and abrupt changes that may indicate abnormal or undeclared operations. As their development progresses and use expands, load cells and enrichment monitors could potentially be combined for NMA, but that would not exclude their use for process monitoring.

Process monitoring for nuclear reactors includes the use of (1) NDA for spent fuel [Tobin, et al., 2011] and (2) the Advanced Thermal-Hydraulic Power Monitor (ATPM) for coolant flow and temperature drop [Aparo and Whichello, 2003]. Tobin and others have begun to evaluate a suite of technologies with potential application for NDA of the spent fuel. NDA measurement may enable the detection of missing pins. Aparo describes the ATPM as a continuous measurement for coolant flow and temperature drop that can be used to monitor trends and abrupt changes that indicate abnormal or undeclared operations.

Process monitoring for spent fuel reprocessing facilities includes the use of (1) solution monitoring [Burr and Wangen, 1996] and (2) the neutron balance technique [Tobin, et al., 2011]. Burr and Wangen define solution monitoring as "essentially continuous monitoring of solution level, density, and temperature in all tanks in the process that contain, or could contain, safeguards-significant quantities of nuclear material." They add that for safeguards purposes these measurements should be authenticated and independently verified. With solution monitoring it is possible to observe relevant liquid transfers, where the transfers should correspond to expected operations. The neutron balance technique is described by Tobin et al. as the complete tracking of all neutrons from the spent fuel to the waste and product. The neutrons originate from ^{235}U, ^{239}Pu and ^{241}Pu. Estimates of the neutron disposition between the waste and product can be made based on known chemical separation factors, so that actual neutron measurements have the potential to identify undeclared facility operation.

Process monitoring for MOX fuel fabrication facilities could include neutron monitoring of nuclear material movement within and/or between glove boxes [Shimizu, et al., 2006, and Xerri, et al., 2002]. Shimizu, et al., describe development of a NDA system to measure the plutonium inventory in glove boxes. Xeri, et al., discuss procedures and instrumentation used to minimize nuclear material holdup. These same systems could potentially be use to monitor the movement of plutonium within and/or between glove boxes where material movement should correspond to expected operations.

The Next Generation Safeguards Initiative (NGSI) process monitoring task is currently focused on demonstrating the ability to provide enhanced safeguards for a reprocessing facility. More specifically, the NGSI effort is concentrated on quantifying safeguards gains with PM beyond NMA alone. In order to achieve this goal, a number of tasks have been initiated and integrated with each other. The details of these tasks are described in the Discussion section.

2.0 DISCUSSION

As stated in the Introduction section, one of the objectives of the Next Generation Safeguards Initiative (NGSI) process monitoring (PM) project is to demonstrate the added value for safeguarding a spent fuel reprocessing facility with PM, in addition to nuclear material accountancy (NMA) alone. Additionally, through this effort to demonstrate added value it is expected that the required methodology being developed will also be directly useful for actual nuclear facilities. The methodology being developed is composed of a number of distinct tasks shown in Figure 1.

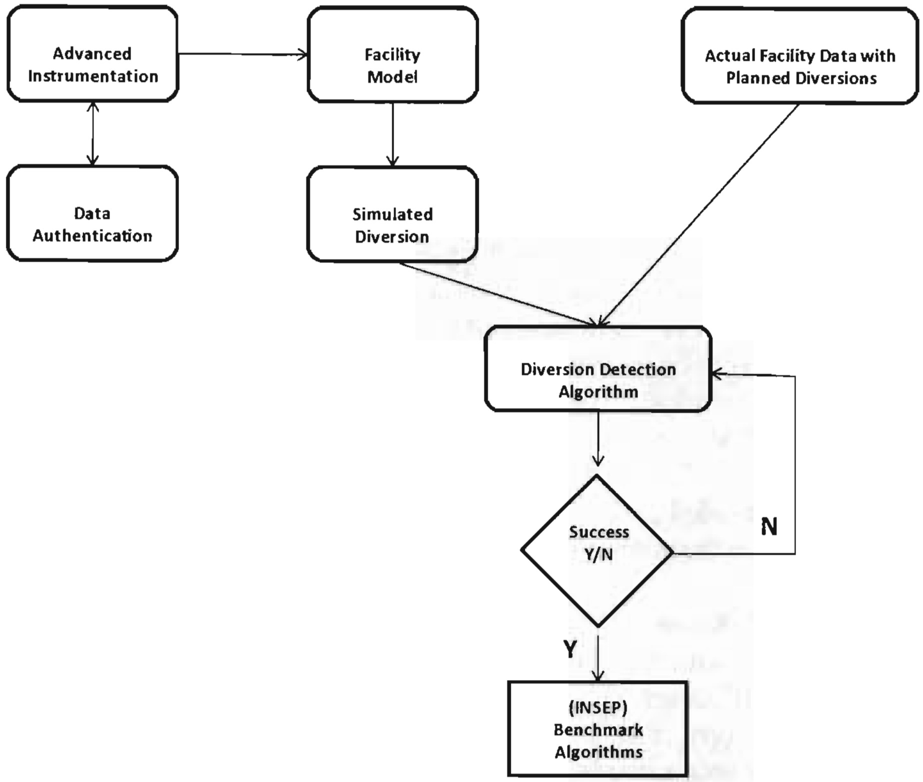

Figure 1. Components of NGSI Process Monitoring Methodology

The Diversion Detection Algorithm (DDA) with its associated quantitative assessment of the contribution to safeguards by PM is the foundation of the NGSI methodology shown in Figure 1. The other tasks shown in Figure 1 either allow the demonstration of the DDA or are used to verify the correctness of the DDA, with the exception of Advanced Instrumentation development. The Advanced Instrumentation task is essentially performed in parallel with the other tasks, but then aligned with actual facility needs by optimization with the DDA.

The Diversion Detection Algorithm (DDA) task consists of developing mathematical tools that can be used to interpret process monitoring instrumentation to detect undeclared operations. In order to exercise and test the DDA either actual plant operating data or simulated plant operating data with diversions, must be available. The DDA test will consist of determining the probability of detecting diversion with PM plus NMA and comparing it with NMA alone. Validation of the test results will be accomplished by benchmarking against a similar model proposed for developed by the Japan Atomic Energy Agency (JAEA) through a collaboration sponsored by the U.S. NNSA NA-24 International Nuclear Safeguards Engagement Program (INSEP). Benchmarking is often used in the nuclear industry where actual testing cannot be conducted, such as a nuclear reactor loss-of-coolant event. Benchmarking involves comparing the results of two or more independently developed models for the operating scenario of interest. Following validation by benchmarking, the simulated plant operating data will be modified to include advanced instrumentation to determine if the probability of detecting diversion can be improved.

2.1 Facility Model and Simulated Diversion

In order to test the DDAs either actual plant data with a known diversion or simulated plant data with a diversion is required. Because actual plant data was not available, the NGSI PM team selected a diversion to be simulated, and Bakel, et al., (2010) at Argonne National Laboratory prepared a partial reprocessing plant model to generate process data representative of the diversion. The initial diversion scenario involved incomplete dissolution of the fuel, for PUREX-type reprocessing, that resulted in greater than usual plutonium remaining in the waste spent fuel cladding. Incomplete dissolution was accomplished by reducing the nitric acid concentration and/or reducing the solution temperature. The DDA was combined with the simulated process data to determine detectability of the diversion through the use of existing process control instrumentation.

2.2 Diversion Detection Algorithm

Detection Algorithms have been developed by Garcia, et al., (2010) at Idaho National Laboratory (INL) and Burr, at al., (2010) at Los Alamos National Laboratory (LANL) to attempt detection of the diversion from the simulated process data. With knowledge of the reprocessing plant process control instrumentation and the expected distribution of nuclear material within the plant following the diversion (as determined by the plant simulation), the detection algorithm was used to provide an estimate of the likelihood that the diversion can be detected by PM. The Detection Algorithms developed by INL and LANL were also used for identifying new instrumentation that could provide for improved detection of the selected diversion path, and can be used in the future for other diversion paths to be studied.

2.3 Advanced Instrumentation and Data Authentication

Results of the Diversion Detection Algorithm can be used to identify measurement locations and associated advanced instrumentation that can provide significant detection gains over existing process control data. Orton, at al., (2010) at Pacific Northwest national Laboratory (PNNL) are developing real-time Raman/UV-vis-NIR spectroscopic monitoring and the Multi-Isotope Process (MIP) monitoring, for in-line mass measurement of plutonium. Eventually, the Raman/UV-vis-NIR spectroscopic monitor and the Multi-Isotope Process (MIP) monitor will be evaluated for their contribution to the detection of specific diversions using the DDAs. Associated with development of real-time spectroscopic use for process monitoring is the development of data authentication techniques. For independent use of operator's data by the IAEA, authentication will likely be required in most cases.

2.4 Actual Facility Data with Planned Diversions

Actual facility data that includes deliberate diversions for safeguards testing was collected during cold testing at the Barnwell facility in the United States during the early 1980s. The plan for the NGSI PM project was to apply the DDAs to instrument readings recorded during the testing and determine if the diversion could be detected. Complete interpretation of the original Barnwell data from the 1980s has not yet been successful. Current NGSI efforts related to the Barnwell data involve digitizing graphical data from prior reports. Other facilities with real-data considered by the NGSI PM team include the Chemical Plant Facility at INL, the Integrated

Equipment Test Facility at Oak Ridge National Laboratory (ORNL), Hanford operations at PNNL, and the canyon operations at the Savannah River Site (SRS). Historical data from foreign reprocessing plants at Tokai-mura and Rokkasho-mura in Japan, as well as La Hague in France, and the Thorp plant in the United Kingdom have also been considered; however, data from all but Tokai-mura are of a proprietary nature.

2.5 Benchmark Algorithms
Recent joint discussions between the U.S. and JAEA related to the International Nuclear Safeguards Engagement Program (INSEP) have identified a safeguards topic for joint collaboration, "Benchmarking Process Monitoring Models for Reprocessing in support of Joint Safeguards Modeling & Simulation". Plans are being made for independent development of process monitoring models by the U.S. and JAEA to avoid conflicts due to Export Control and Intellectual Property. Identical diversion scenarios will be evaluated for detectability with U.S. and Japanese process monitoring models. The use of actual data will be minimal, if any, to avoid Proprietary Information concerns. Benchmarking will be used in a fashion similar to that done by the U.S. Nuclear Regulatory Commission (NRC) for thermal-hydraulic codes, where actual reactor loss-of-coolant data is limited, and therefore the results of independent codes based on synthetic scenarios are compared (i.e. benchmarked) for validation.

3.0 CONCLUSIONS

Results to date for the NGSI PM project include (1) development of a partial reprocessing plant model to generate process data representative of diversion, (2) identification of a diversion path to study, that involves incomplete dissolution by reducing the nitric acid concentration and/or reducing the solution temperature, (3) review of actual facility data that includes deliberate diversions for safeguards testing, (4) development of advanced instrumentation for process monitoring such as the Raman/UV-vis-NIR spectroscopic monitor and the Multi-Isotope Process (MIP) monitor, and (5) planning for benchmarking the NGSI PM methodology with independent JAEA efforts.

While the NGSI DDAs developed to date have demonstrated the ability to detect simulated diversion, the added value for safeguarding a spent fuel reprocessing facility with PM in addition to nuclear material accountancy (NMA) alone, has not yet been demonstrated. This is due to fact that the task of combining PM DDAs with NMA detection has not yet being completed. More specifically, results to date are related to the demonstration of process monitoring for the selected diversion path (incomplete dissolution), and confirmation of the usefulness of the overall methodology shown in Figure 1, for further development of process monitoring techniques. As discussed by Bakel, et al., (2010) for the selected diversion path of incomplete dissolution of the spent fuel, in order to divert a significant quantity of the plutonium in the cladding waste in a timely period, a substantial decrease in nitric acid and/or temperature would be required. Given the estimated decrease in nitric acid and/or temperature required, Garcia, et al., (2010) determined that there was a high probability of detecting abnormal operation with existing process control instrumentation in a PUREX reprocessing plant. As for validation of the overall methodology shown in Figure 1, this assessment will require completion of the benchmarking activity.

The NGI PM project is closely coupled with the NGSI Safeguards by Design project because, PM will be critical for future safeguards designs due to the difficulty in improving NMA for large throughput nuclear facilities, and early consideration of PM in the overall facility design activity will be necessary to avoid proprietary data concerns and provide for adequate data authentication.

ACKNOWLEDGEMENT

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