Annals of Nuclear Energy 103 (2017) 60–73

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Application of process monitoring to anomaly detection in nuclear material processing systems via system-centric event interpretation of data from multiple sensors of varying reliability

Humberto E. Garcia [a,*], Michael F. Simpson [b], Wen-Chiao Lin [a], Reed B. Carlson [a], Tae-Sic Yoo [a]

[a] Idaho National Laboratory, Idaho Falls, ID 83415, United States

[b] University of Utah, Department of Metallurgical Engineering, Salt Lake City, UT 84112, United States

ARTICLE INFO

Article history:
Received 20 October 2016
Received in revised form 5 January 2017
Accepted 5 January 2017

Keywords:
Advanced safeguards
Process monitoring
System-centric anomaly detection
Integrated time- and event-driven analysis
Nuclear fuel cycles

ABSTRACT

In this paper, we apply an advanced safeguards approach and associated methods for process monitoring to a hypothetical nuclear material processing system. The assessment regarding the state of the processing facility is conducted at a system-centric level formulated in a hybrid framework. This utilizes architecture for integrating both time- and event-driven data and analysis for decision making. While the time-driven layers of the proposed architecture encompass more traditional process monitoring methods based on time series data and analysis, the event-driven layers encompass operation monitoring methods based on discrete event data and analysis. By integrating process- and operation-related information and methodologies within a unified framework, the task of anomaly detection is greatly improved. This is because decision-making can benefit from not only known time-series relationships among measured signals but also from known event sequence relationships among generated events. This available knowledge at both time series and discrete event layers can then be effectively used to synthesize observation solutions that optimally balance sensor and data processing requirements. The application of the proposed approach is then implemented on an illustrative monitored system based on pyroprocessing and results are discussed.

1. Introduction and motivation

It has been widely accepted that process monitoring (PM) of nuclear facility operations can significantly improve the detectability of facility misuse and/or material diversion activities. In order to monitor and assess the safeguards health of complex nuclear systems, it is often the interest to promptly detect the occurrence of abnormal (e.g., undeclared or unauthorized) operations, even before they may be discovered by utilizing the traditional nuclear material accountancy (NMA) approach. For example, one may be interested in how many times a particular material is routed to a certain workstation. It may also be useful to detect and record when a given unit operation exhibits abnormal behavior due to excessively high concentration of a certain chemical compound, for example, that may be a precursor of a nuclear proliferation-related activity—material diversion.

Pyroprocessing is an emerging technology that is currently being developed for potentially closing the back end of the nuclear fuel cycle. It features electrochemical separation processes at high temperatures with molten salt electrolytes. Its compact facility footprint makes it very appealing, especially for integrated or on-site reprocessing of used nuclear fuel from a fast reactor. The Republic of Korea (ROK) is currently researching pyroprocessing as its leading candidate technology to reduce the volume of its spent pressurized water reactor fuel and recover U/TRU for future fabrication of fast reactor fuel. From a policy perspective, the problem is that ROK is not a nuclear weapons state and has an active nuclear cooperation agreement with the United States that forbids pyroprocessing or any other reprocessing technology be applied to spent nuclear fuel within ROK borders. This is not entirely a stalemate situation, however, as there is currently a 10-year Joint Fuel Cycle Study (JFCS) being carried out by U.S. and ROK in collaboration to evaluate various aspects of the feasibility of using pyroprocessing for this purpose. One of the most important issues being studied is the safeguardability of the process. A positive finding from this study may pave the path for ROK receiving consent from the United States to build pyroprocessing facilities and operate them for treatment of their spent fuel. NMA is viewed as being very difficult to implement in a pyroprocessing facility because of (1)

* Corresponding author.
E-mail address: humberto.garcia@inl.gov (H.E. Garcia).

http://dx.doi.org/10.1016/j.anucene.2017.01.006
0306-4549/Published by Elsevier Ltd.

lack of input accountability, (2) high accumulation of fissile material in process equipment, and (3) the heterogeneity of the process materials and products (Simpson et al., 2014). The goal of closing the plutonium mass balance within a significant quantity (8 kg) is daunting at even sub-commercial scales. Technology for PM as a supplemental safeguards tool is being studied both within and outside of the JFCS. A new term, Signature Based Safeguards (SBS), has been used in reference to applying PM for detection of misuse of pyroprocessing systems and perhaps support NMA in a complementary fashion (Simpson et al., 2014; Lafreniere et al., 2015). But there have been little specifics for how SBS would be implemented or how PM would otherwise be used for safeguards. The scope of this paper includes the introduction of an algorithm for using PM to detect misuse in a pyroprocessing system. A simplified system has been constructed that includes three key pyroprocessing unit operations—oxide reduction, electrorefining, and electrowinning. The chemical separations achieved by each unit operation are included in the model. Several sensors based on mature technology are included as well. The model generated time-driven and event-driven dynamics which are analyzed by the algorithm to detect anomalous process events. The model is evaluated up against three hypothetical process anomalies with encouraging results. This paper sets the groundwork for a future study involving analysis of real operational process data.

2. Methodology/Framework for anomaly detection

The detection and interpretation of special events or anomalies may be accomplished without much difficulty if sensors for exactly identifying them are available. However, relying on a single sensor to provide the required detection sensitivity is difficult, as it may require costly or unattainable sensor performance. For instance, measuring the concentration level of certain material in a given flow stream may not be possible at the required sensitivity level for facility misuse detection. In these cases, a solution may be to combine the data collected from a system of sensors to attain the necessary level of confidence for declaring the potential occurrence of an event under consideration. This integration of data collected from multiple sensors may be accomplished in both space and time. Under space-only data integration, data collected from distinct distributed sensors are integrated at each time period and an assessment of the plant condition is determined at that moment. Under time-only data integration, data generated from sensors collected at different time periods are integrated to compute the plant state at that moment. Under either case, models are needed that relate in space, time, or both these distributed information. Such models may be derived from physical or/and logical relationships, for example.

While space data integration has received significant attention for many years, time data integration is a relatively new area of research and development. This is mainly due to the following factor. For implementing space data integration, what is mainly needed is a "correlation" model that indicates how the correlation (or lack) of two or more sensor data sets supports a given hypothesis. This correlation model may be derived from first principles knowledge or statistical analysis, for example. Examples of typical techniques used here include kernel-based regression algorithms, multivariate statistical methods, principal component analysis, and neural computing. On the other hand, for implementing time data integration, a model of the system operations is needed characterizing how events and operations occurred and conducted at different time periods relate among them. Such operations models are often formulated as discrete event system (DES) models (e.g., finite state machines, Markov models, and stochastic automata), where the passing of time and change in plant state is due to the occurrence of "events". An event may indicate "tank is full," "concentration of given component is high," or "unusual pattern of gamma-emitting contaminants in given stream". The area of DES theory and application is a relatively recent development, hence the limited utilization of time data integration. However, as the more information one uses should lead into lessen requirements for sensor performance, a hybrid monitoring solution is suggested in this paper, where not only space but also time data integration is conducted in order to assert the occurrence of special (e.g., abnormal) events and behaviors. Under a hybrid space–time process monitoring (PM) approach, not only current but also past plant behaviors are effectively integrated and used during decision-making. This information-rich approach for PM and decision-making demands for the implementation of system-centric solutions, where systems of sensors, as opposed to single sensors, are used to assert plant conditions and declare the occurrence of facility misuse or material diversion.

In view of the above rationale, system-centric observation platforms for PM are here suggested to effectively monitor large facilities despite (often unavoidable) sensor unavailability and unreliability issues. An architecture for implementing system-centric integrated observation platforms is illustrated in Fig. 1. In order to facilitate its implementation, particularly when addressing complex systems such as nuclear reprocessing facilities, rigorous algorithms are needed for not only synthesizing but also optimizing observation platforms. Under the former, it is assumed that the particular sensor configuration (e.g., set of sensors) is given and the task is to design optimized data analysis algorithms (i.e., diagnosers) to meet the required observability performance. Under the latter, not only optimal sensor configurations but also their corresponding data analysis algorithms are selected to meet the required observability performance, under given constraints.

For large throughput nuclear facilities, such as commercial reprocessing plants, it is difficult to satisfy the IAEA safeguards accountancy goal for the detection of one significant quantity of material diversion within the specified time period. Several recent publications have demonstrated, although via simulations and still tentative, the safeguards benefit from using PM on nuclear facilities, as a complementary safeguards measure to NMA (e.g., Garcia et al., 2013, 2012, 2011, 2010). One main interest under PM is to detect operational anomalies as the process progresses rather than detecting them by measuring mass balance inconsistencies resulting from abnormal activities. Anomalies of interest for detection may represent undesired plant operations

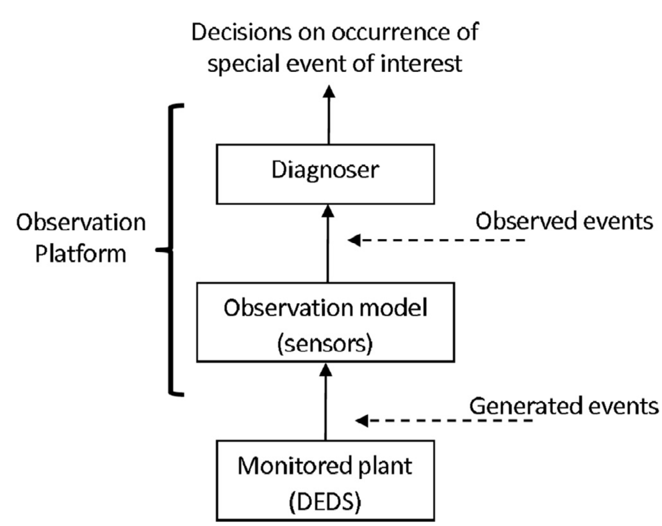

Fig. 1. Monitoring architecture.