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AI-ENABLED MONITORING OPTIONS TOWARDS SECURE MICROREACTOR DEPLOYMENT AND OPERATIONS

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Changing the World's Energy Future

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ABSTRACT

Global nuclear energy deployment scenarios suggest favorable economics for smaller, more versatile, and self-contained reactor technologies. Recognizing their key features as integrated, autonomous and either semi-remotely operated or fully remotely operated systems, microreactors are expected to be deployed in large numbers servicing off/micro-grids, many in geographically remote locations. Integrated nature of these systems as well as ease of their transportation as complete units, simplified installation and relocation/decommissioning challenge traditional continuity-of-knowledge practices used for conventional light water reactors where refueling is done onsite at designated times only replacing portions of their cores and only after their full commissioning for operations including completion of their containment building with security and safeguards measures in place. This effort is exploring AI (artificial intelligence)-enabled monitoring options that would be design agnostic and would assure secure unit deployment and operations. The principle is to maintain situational awareness via real-time evaluations of simultaneous and remotely transmitted monitoring data capturing key safeguards attributes including such characteristics as temperature, radiation, vibrational signals (inter alia), and others. The key principle is to provide reliable and resilient security options while maintaining simplified and economical deployment. The paper will review feasible options for AI-enabled solutions for such evaluations.

Keywords:
microreactors, monitoring, autonomous operation, continuity of knowledge, secure deployment, artificial intelligence, AI-enabled surveillance and monitoring

INTRODUCTION

Advanced reactor designs are at the forefront among solutions allowing to meet increasing demands for clean load-following electricity along with CO_2 emission reduction objectives. Emerging reactor technologies offer a wide spectrum of physical sizes, targeted applications, and power ratings.[1,2]

Microreactors play a significant role in contemporary development and strategic considerations due to their favorable economics, versatility, and self-contained modalities. As such, most microreactors will employ high assay low enriched uranium (HALEU) fuel to be transported fully fueled from the factory to the operational site, and then returned physically unaltered to the originating State.[2,3]

Typical microreactor deployment scenarios assume operations with significantly reduced operating staff compared to contemporary nuclear power plants, or even consider fully autonomous operations.[4,5] The challenge is further complicated by the fact that these new reactor designs include extended fuel cycles which limit inspection intervals, load-following capabilities, and reduced access to critical components due to high degree of integration.

Recognizing their key features as integrated, autonomous and either semi-remotely operated or fully remotely operated systems, microreactors are expected to be deployed in large numbers servicing off/micro-grids, many in geographically remote locations. Integrated nature of these systems as well as ease of their transportation as complete units, simplified installation and relocation/decommissioning challenge traditional continuity-of-knowledge practices used for conventional light water reactors where refueling is done onsite at designated times only replacing portions of their cores and only after their full commissioning for operations including completion of their containment building with security and safeguards measures in place. Safe, reliable, and secure semi- or fully autonomous operations must be enabled through an on-line monitoring system that effectively detects and assesses any anomalies in the system.[1,6]

This effort is exploring AI (artificial intelligence)-enabled monitoring options that would be design agnostic and would assure secure unit deployment and operations. AI-technologies have revolutionized the field of monitoring by enabling more efficient, accurate, and automated solutions dramatically expanding surveillance options. In the context of secure microreactor lifecycle from their deployment to operations to decommissioning and removal, the principle is to maintain situational awareness via real-time evaluations of simultaneous and remotely transmitted monitoring data capturing key safeguards attributes including such characteristics as temperature, radiation, vibrational signals (inter alia), and others.

The key objective is to provide reliable and resilient security options while maintaining simplified and economical deployment. Fully assembled, highly integrated microreactors pose a unique challenge that is not present in contemporary light water reactor technologies.

The AI-enabled approach for the real-time detection of unknown anomalies is being developed that can support semi- or fully autonomous reactor operations. The methodology uses sensor measurements from around a reactor plant to draw conclusions on the health of the reactor.

The expected benefits of AI-enabled monitoring range from operational resilience due to enhanced predictive fault diagnostics capabilities to secure autonomy opportunities while meeting strict U.S. domestic and IAEA safeguards and security (S&S) requirements. The envisioned monitoring could begin at the factory with a fully fueled microreactor and continuing through its transportation, installation, operation, and eventual return to – and staging at – the originating country, where IAEA safeguards measures (may) terminate. It should also be possible to add monitoring capabilities leveraging remote sensing data streams irrespective of facility configurations.

LANDSCAPE OF EMERGING MICROREACTOR TECHNOLOGIES

In recent years, relatively new, highly deployable types of nuclear reactors are gaining increasing attention – small modular reactors and micro reactors, as the most promising near-term candidates. These are smaller units with thermal power generation capabilities under 30 MWth (10 MWel) for microreactors and under 1000 MWth (300 MWel) for small modular reactors.[1]

Several dozens of small modular reactors and microreactors are under active development in the United States and worldwide targeting their deployment in the next decade. These systems are expected to be highly deployable and commercially competitive.[1,6]

Microreactors are going to be factory-fabricated, highly transportable, and highly adaptable to deployment domains ranging from terrestrial urban environments and emergency response areas to space power and propulsion. Emerging small modular reactors and microreactor concepts are considered as Generation-IV reactors.

Table 1 summarizes principal advanced reactor technologies. Emerging novel power units with Generation-IV microreactors must be adaptable to energy grid architectures in their ability to meet load demands faster than traditional contemporary power plants. They are also expected to be capable to deliver process heat at various temperatures to meet needs of such applications as potable water production and hydrogen generation among many others.[1]

Table 1. Generation-IV Microreactor Technologies.

Reactor	Neutron Spectrum	Coolant	Temperature, ºC	Applications
HTR[1]	Thermal	He	650-1000	Electricity, H_2, process heat, waste management
SFR[2]	Fast	Na	550	Electricity, process heat, waste management
GFR[3]	Fast	He	850	Electricity, H_2, process heat, waste management
LFR[4]	Fast	Pb	800	Electricity, H_2, process heat, waste management
MSR[5]	Thermal/Fast	Fluoride salts Chloride Salts	700-800	Electricity, H_2, process heat, waste management

[1]VHTR –High Temperature Reactor; [2]SFR – Sodium-cooled Fast Reactor; [3]GFR – Gas Fast Reactor; [4]LFR – Lead-cooled Fast Reactor; [5]MSR – Molten Salt Reactor

Decades of technology development efforts for these systems serve as a foundation for accelerated commercial deployment perspectives, within next decade or so, assuming viable marketing-consumer cases can be established on a competitive basis against alternative energy technologies targeting 2030 – 2100.

OVERVIEW OF AI-ENABLED MONITORING OPTIONS

Artificial intelligence (AI) has revolutionized the field of monitoring by enabling more efficient, accurate, and automated solutions. The list of AI-enabled monitoring options includes:

- Optical and multispectral surveillance: AI has greatly enhanced traditional optical surveillance systems and emerging multispectral systems by incorporating computer vision methods. AI algorithms can analyze live or recorded and transmitted data to detect and identify objects, transients, and anomalies. This enables real-time monitoring, automated alerts for suspicious activities, and improved security in various settings.

- Network, energy grid, energy product delivery monitoring: AI-powered data traffic monitoring systems enable predictive characterization of operational features. These systems use machine learning algorithms to analyze network traffic patterns, detect anomalies, and identify potential security threats or performance issues. AI enables proactive monitoring, quick identification of breaches, and faster troubleshooting.
- Environmental monitoring: AI can assist in monitoring environmental conditions around facilities such as air and water characteristics. By analyzing large volumes of sensor data, AI algorithms can observe and assess operational details and identify potential anomalies. Within this project, the effort is focused on science and technology of predictive and on-demand characterization of localized developments on the Earth surface, subsurface and within the atmosphere.
- Media monitoring in relation to facility operations: AI algorithms can monitor media platforms to gather real-time insights related to activities associated with facility operations.
- Operational monitoring: AI-powered monitoring systems are widely used to optimize processes, ensure equipment reliability, and enhance safety. AI algorithms can analyze sensor data from machinery and predict failures or maintenance needs in advance. This allows for proactive maintenance scheduling, reducing downtime and optimizing productivity.

These are just a few examples of the numerous AI-enabled monitoring options available across various platforms. These methods are based on data gathering and forming signatures of events of interest for further evaluations. AI continues to advance rapidly, offering innovative solutions for monitoring and providing valuable insights for risk mitigation.

TECHNICAL APPROACH

This exploratory project is looking into multi-modal sensor options for microreactors employing high-assay low enriched uranium (HALEU) to maintain continuity-of-knowledge (CoK) on containment, surveillance, assay safeguards from fabrication of a fully fueled microreactor (MR) through transportation, installation, operation to return to the originating country. Sensor data parameters will yield physical design and performance metrics informing Safeguards Tamper-indicating Engineering Method (STEM) architectures tailored to accommodate emerging novel MR designs. This information will be used to formulate a Comprehensive Plan in the creation of a universal microreactor mobile unattended monitoring system (UMUMS) suite that can be adopted to any MR design.

A multitude of data-driven methods for fault detection at nuclear power plants have been developed in recent years. The current approach encompasses a continuous MR STEM operational lifecycle monitoring capability, with digital twin/machine learning (DT/ML) playing a critical role in the development process. Figure 1 illustrates the overall architecture of the method including continuous MR lifecycle monitoring. Data streams from different sensors around the reactor unit are collected to form a data signature.[7,8]

This platform is further augmented with remote sensing data streams. It is assumed that some localized events and processes might pose accessibility challenges for traditional monitoring methods but they may still be identifiable and accessible for monitoring using remote platforms. In such situations, the use of remote surveillance methods, such as orbital surveys, offers uninhibited access opportunities for assessing otherwise challenging locations in 3D from subsurface up to the upper atmosphere layers. Local feature observations can be organized to provide continuous data feeds or can be set up for discrete time intervals on-demand reporting targeting periods of interest.

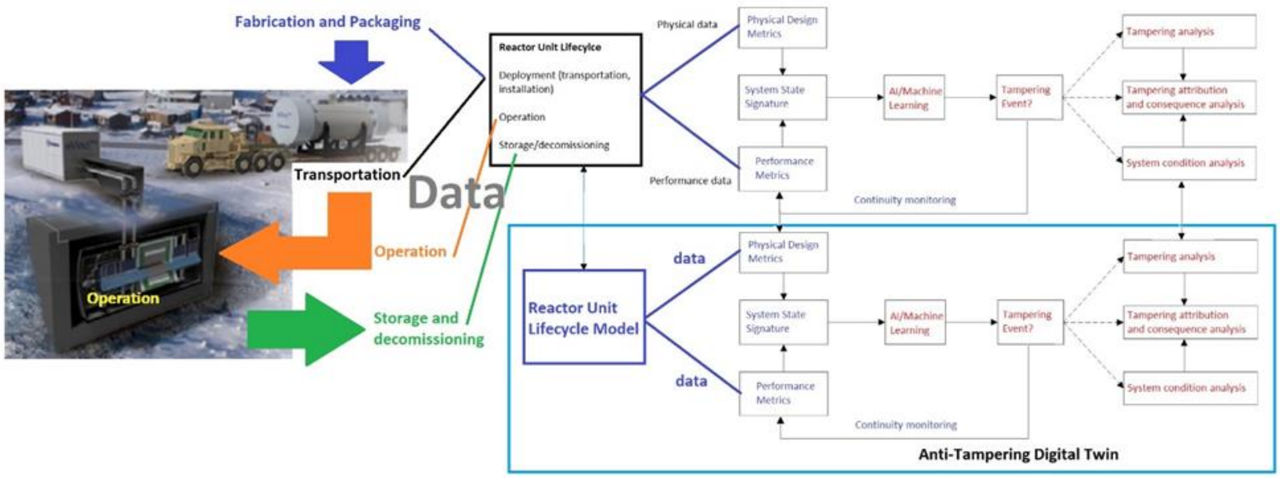

Figure 1. Safeguards Tamper-indicating Engineering Method (STEM) via DT/ML coupling.

The signature includes physical design and performance metrics leading to a Smart anti-Tamper Engineering Method (STEM) deployable for any MR. The principle is to maintain situational awareness in real-time, simultaneous and remotely transmitted monitoring data of key safeguards attributes. These include temperature, radiation, vibrational signals (inter alia) using proven technologies such as fiberoptics. GPS data feed can be added allowing for real-time MR global tracking.[9]

Cube Satellites (CubeSats) are expected to be used for their much more manageable size and cost for this project as most of the technology can be fit onto one of these satellites to accomplish this task. By being able to utilize Commercial Off The Shelf (COTS) components, often without modification, makes the use of CubeSats much more accessible to research and other space projects.

The ease and affordability of using and building a CubeSat makes it an attractive option for Low Earth Orbit (LEO) monitoring projects. By being able to create a constellation of these CubeSats, multiple types of sensors can be used to view an area, such as a nuclear facility.[10]

By using this approach, the overall plan is for this system to be used as a passive or on demand resource to examine phenomena of interest at a specific site. The goal of this effort is to develop a method to assist in the reliable monitoring of microreactors recognizing their normal and abnormal conditions. The method gathers needed data via remote sensing from satellite platforms. Large data sets are assumed to be processed via deep learning networks.[11]

Figure 2 shows the fuel cycle as seen from a satellite's point of view, and the expectation is to be able to monitor each of these facilities. Once the location is understood and specified, the next step would be to find out what processes and events are happening at the facility. This would be an attempt to find out if a reactor is running at a certain power level, as an example. This project explores remote sensing capabilities to monitor microreactor operations as an additional data stream feeding into the facility signature.

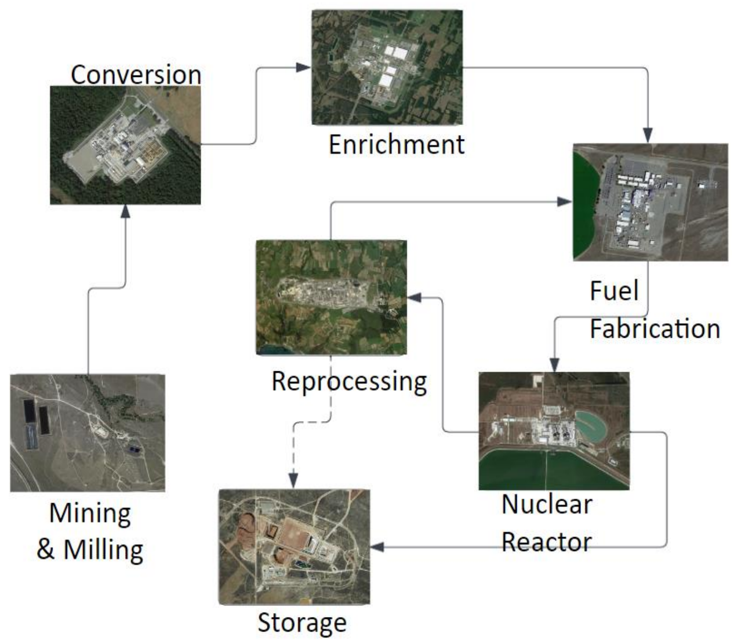

Figure 2. Facilities within the nuclear fuel cycle enterprise

The effort is focused on developing a resilient anomaly detection technology in remote conditions addressing the needs in the areas of surveillance and unattended monitoring for reliable high fidelity data measurements, assured data communication, and detection security in global deployment scenarios for microreactors. Figure 3 illustrates the data flow in the envisioned approach.[11,12]

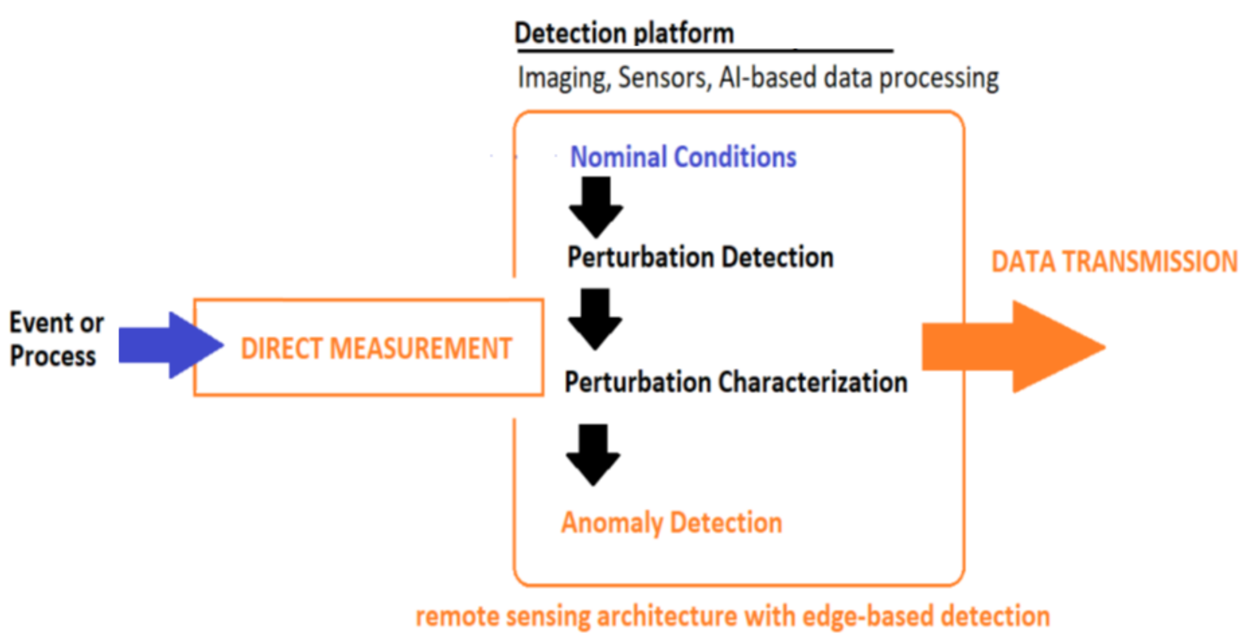

Figure. 3. AI-based evaluation approach for anomaly detection and evaluation.

SITUATIONAL AWARENESS THROUGH REAL TIME MONITORING

The effort will explore and demonstrate autonomous resilient AI-based remote sensing platforms for relevant proliferation scenarios as robust solutions to emerging challenges brought by remote monitoring needs, access limitations and security threats in microreactor deployment scenarios.

As shown in Figure 4, the principle of operations is to maintain situational awareness in real-time, simultaneous, and remotely transmitted monitoring data of key safeguards attributes. Embedded fiber optics as well as fiber-optics containing enclosures and wrapping options are among feasible options.

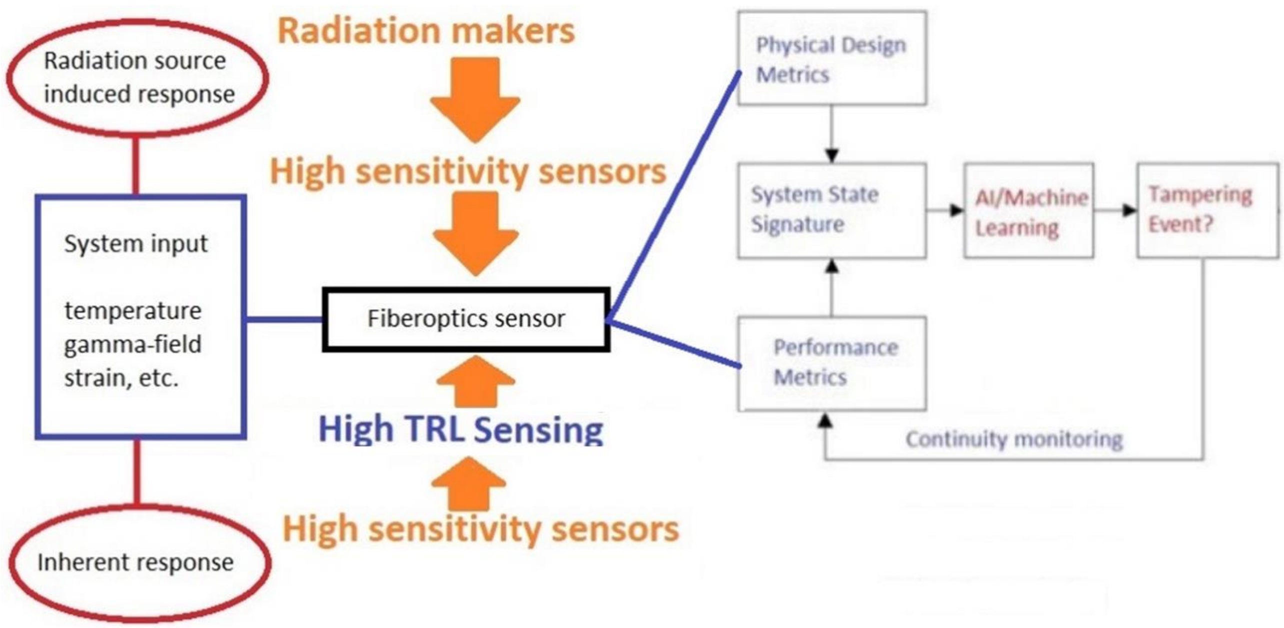

Figure 4. Proposed anti-tampering signature approach.

The effort will result in a Smart anti-Tamper Engineering Method (STEM) that allows continuity tracking through the unit lifecycle. STEM creates a sensor network around components of interest that will allow monitoring physical and functional states by gathering thermal and radiation field data triggered by embedded radioisotope markers and inherent characteristics. The STEM would be embedded within the reactor unit and will be following the lifecycle via the integrated digital twin tracking lifecycle signature.[12]

The few images the CubeSats collect as they briefly fly over the transport vehicle could help ensure the microreactor's integrity. The dimensions of the reactor and adjacent facilities can be observed with the panchromatic/multispectral sensors onboard the surveillance system.

Multispectral sensors in the infrared or ultraviolet regions could characterize water vapor plumes from the microreactor plant's air-cooled condensers or cooling towers. Like with the other phenomena of interest, however, enough data (or images) of microreactor plants are needed to adequately train the CubeSats' characterization methodology.

CONCLUSIONS

This effort focuses on and offers to develop a robust solution to the safeguardability challenge associated with microreactor technologies. Remote sensing data streams are integrated with data streams from on-site sensors to monitor microreactor operations.

The unique nature is in the use of AI-enabled data analysis together with radiation markers and high sensitivity sensors to form a comprehensive event signature that includes not only physical design but also performance metrics. The STEM hardware might be integrated with a anti-tampering digital twin that tracks the unit lifecycle signature.

Coupling of physical metrics and performance metrics adjusting for the lifecycle evolution in a robust anti-tamper approach dramatically enhances event detection providing vital attribution. Typical anti-tamper systems focus on physical characteristics and identification of the boundary breach. The comprehensive accounting for both physical metrics and performance metrics over the unit lifecycle leads to enhanced detection capabilities.

The work presented in this summary contributes to the development of a novel CubeSat-based surveillance system for on-demand characterization of phenomena pertaining to nuclear security. The development of a CubeSat surveillance system can have many advantages to the nuclear industry.

The experience and flight data gathered from a functioning, automated surveillance system in LEO can form a basis for the development of a reactor monitoring system for power units in remote locations. A constellation of CubeSats could monitor the integrity and presence of phenomena of interest during the transportation of microreactors or once installed at a plant.

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DISCLAIMER

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