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Nuclear Safeguards via Remote Monitoring of Small Modular Reactors Deployed in Canada's North and Remote Regions

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ABSTRACT

Small modular reactors (SMRs) are an enabling technology that supports all four pillars of the Government of Canada's "Northern Strategy": sovereignty, environmental protection, economic development, and self-governance. The deployment of SMRs in Canada's northern and remote communities is also a key component of Canada's roadmap for SMRs. The deployment of SMRs in such communities presents challenges to traditional safeguards approaches (e.g., nuclear material accountancy, verification, and containment and surveillance), some of which can be addressed through remote monitoring. A literature review of currently employed remote monitoring approaches is presented, along with potential new approaches. Furthermore, we describe an assessment of where these approaches might be implemented in the North for likely SMR deployment in the near future. Various aspects of remote monitoring will be considered, such as unattended remote monitoring systems (URMS), methods for secure remote data transmission, and current and required infrastructure for reliable data transmission and digital connectivity in remote regions. Different components of safeguards that URMS could support are considered. Remote monitoring can also play a role in the effective integration of safeguards with safety and security. Overall, the applicability of these aspects to remote regions of Canada for SMRs will be discussed, and areas that require further development will be highlighted.

INTRODUCTION

Small modular reactors (SMRs) are an enabling technology that supports all four pillars of the Government of Canada's "Northern Strategy" [1]: sovereignty, environmental protection, economic development, and self-governance. The deployment of SMRs in Canada's northern and remote communities is also a key component of Canada's roadmap for SMRs [2].

According to Natural Resources Canada [3], there are approximately 277 remote communities (both commercial operations and settlements) in Canada that have year-round residents (total population 196,100), 140 of which are located above the 55th parallel. Of these 140 communities, 96 (total population 116,200) are above the 60th parallel ("northern" communities) and 44 (total population 22,000) lie between the 55th and 60th parallel ("near-northern" communities). The majority of these 140 communities are not connected to a provincial or territorial power grid, and many are also without year-round road access [4].

Canada is one of the world leaders in the production of variety of minerals, oils, and natural gas. Figure 1 shows the locations across Canada of various natural resource production sites and of the top 100 exploration sites [5]. The deployment of SMRs in Canada is being considered at a number of these locations.

Figure 1: Locations of Mining, Minerals, and Top 100 Exploration Projects in Canada [5]

The scale of power output of SMR units deployed in remote regions is expected to be on the order of 10 MWe (30 MWth), to meet typical heating and electricity supply needs of remote mining, military, and municipal operations [6]. This is in contrast to SMR deployments in urban settings where unit powers are projected to be an order of magnitude greater. A 2016 study by Hatch shortlisted nine SMR technology designs with gross electrical output of up to 32.5 MWe (seven of them with output of 10 MWe or lower) for potential deployment in off-grid remote mines in Canada, with special emphasis placed on northern Ontario [7]. The study found that all of the shortlisted SMR designs were economically competitive when compared with current diesel generators, and that a majority of the designs were compatible with remote applications. There are currently 9 SMR vendors with submitted designs under pre-licensing vendor design review by the Canadian Nuclear Safety Commission, three of which offer unit a power output of 10 MWe or lower. These three designs are the micro modular reactor (MMR) from Ultra Safe Nuclear Corporation, the U-Battery high-temperature gas reactor from U-Battery Canada Ltd., and the eVinci micro-reactor from Westinghouse Electric Company, LLC.

Over the long term, SMRs may be deployed at a large number of remote locations. LeadCold envisioned, for example, that 100 units of the SEALER reactor could be deployed in Canada [8]. Low-power reactor designs address the needs of potentially hundreds of difficult-to-access communities distributed over a large geographical area; this is a significant driver for providing reliable year-round off-site monitoring capabilities to ensure that safeguards goals are met in a manner that can be afforded by nuclear safeguards inspectorates [6].

Unattended and remote monitoring approaches for SMRs fall into four general categories: containment systems, surveillance systems, measurement systems, and other systems. Relevant aspects of each of these are reviewed here, along with an assessment of the infrastructure for secure remote data transmission (comparing what is present against what is required). The opportunity presented by remote monitoring for integrating nuclear safeguards with nuclear safety and security is also discussed.

UNATTENDED REMOTE MONITORING SYSTEMS

Unattended remote monitoring systems (URMSs) for containment purposes employ some form of electronic seal to record whenever an item or room has been accessed. This set of systems does not directly provide information on the activity of concern (which may be nuclear material diversion). However, in combination with other systems such as surveillance, the URMS can provide more information, which is of direct relevance for maintaining continuity of knowledge (CoK) in a manner that minimizes International Atomic Energy Agency (IAEA) resources. The containment measures are applied to the nuclear material as well as to the enclosure (case or cabinet or storage room) that houses the IAEA equipment in the facility to maintain CoK.

Table 1 lists various types of active reusable seals currently available or under further developed for use by the IAEA. This list covers different seal types but primarily those based on fiber optic cables, as these are less vulnerable to foul play without detection and can therefore deter any deviation from normal operation. In addition, each of these systems has a means to ensure authenticity of the generated data.

Table 1: Reusable Electronic Seals [10][11][12][12]

Name	**Means of Detection**
Two-Way Radio Frequency Sealing System (TRFS)	Radio Frequency
Integrable Reusable Electronic Seal (IRES)	Resistive Wire
Variable Coding Sealing System (VACOSS) Fiber Optic	Fiber Optic
Electro-Optical Sealing System (EOSS)	Fiber Optic
Remotely Monitored Sealing Array (RMSA)	Fiber Optic
Active Optical Loop Seal (AOLS)	Fiber Optic
Active Universal Asymmetric Seal (AUAS)	Fiber Optic
Laser Curtain for Containment (LCCT)	Laser

The IAEA is currently in the process of replacing its EOSS, as its components are obsolete (batteries have a life expectancy of only 3 years) and its protocols are inconvenient (such as the requirement for carrying a crypto-token) [12]. With this experience in mind, asymmetric optical seals that consumes ultra-low power, such as the AOLS and AUAS, are under development. However, the AOLS failed the radiation tests and their design is being considered for refinement.

The IAEA has come up with an alternate design of AUAS, and testing and field trials are planned. Similarly, LCCT is provisionally authorized at Atucha-1 and field-tested in Belgium and in Germany with plans for broader use.

Surveillance systems employ cameras to record images, which are generally activated using either a containment system (opening of a seal) or other system (infrared, motion sensors, or radiation measurement), to limit the information that the IAEA needs to review and assess. Multiple images are taken over a set interval to form a better understanding of the event, such as to determine the direction of movement.

The important functions with a surveillance system are its connection with the triggering events, acquisition of images, analog-to-digital conversion, and data compression, authentication, and encryption [9]. Other important aspects are its power consumption, battery life and backup, local data storage in case of failure of remote data transmission, and upgrade and maintenance capability.

The different types of surveillance systems, based on the application [12], can be categorized according to:

- Easy-to-access location (single camera and multiple cameras)
- Difficult-to-access location (single camera and multiple cameras), including underwater

These systems may or may not have remote monitoring capabilities [12][14]; for example, all-in-one surveillance (ALIS) and underwater TV (UWTV) do not usually have a remote monitoring feature, but the digital single/multi-camera optical surveillance system (DSOS/DMOS) does have remote monitoring capabilities. Most of these systems are based on digital camera module (DCM)-14 and are being currently replaced by the DCM-C5-based next-generation surveillance system (NGSS), which offers color images, enhanced tamper indication, and four separate channels each with different triggers and picture-taking intervals (for multiple stakeholders). NGSS-based systems include an all-in-one camera (XCAM), DCM-C5 in an old casing (XCOH), and a DSOS replacement (XSOS).

The NGSS is foreseen to be replaced by a subsequent improved surveillance technology by 2030; before then, an upgrade is anticipated in the data review software, as the number of images to be reviewed by the IAEA is expected to increase each year [14]. The integration of artificial intelligence with data review software is planned in the near future for field testing.

Measurement systems use (gamma- and neutron-based) radiation detectors to detect, characterize, and/or determine the direction of movement of nuclear material [10]. The detectors are generally physically separate from their data generation system; both detector and system as well as their connection require containment measures to ensure the eventual transmission of data that are authenticated.

There are a variety of measurement systems that the IAEA uses or that are under development [10][12][14]. Broadly speaking, measurement systems based on the miniature gamma ray and neutron detector (MiniGRAND) data acquisition system are employed mainly for monitoring material movement. Systems based on the shift register module, currently used for fuel reprocessing and fuel fabrication, can be used at facilities for SMR fuel fabrication as well as for process monitoring. CANDU integrated fuel monitors designed for the monitoring of spent fuel could also be adapted to SMRs. Other monitoring systems also exist for monitoring the transfer of spent fuel and for verifying fuel enrichment.

These measurement systems are accompanied by, apart from containment measure(s) for data authentication, surveillance and/or other systems (such as a global positioning system) to collect more information about the event. All of these systems are considered unattended monitoring systems, but not all are currently operated remotely, such as the MiniGRAND-based systems that use flash memory for data storage. However, in these cases, data transmission systems can be incorporated to achieve the URMS mode of operation.

Other remote monitoring systems are used by the IAEA for detecting or tracking movements (of nuclear material or personnel), assessing operations in a facility, or verifying the integrity of the equipment, among other functions. These systems are used either in a stand-alone mode as a distinct safeguards data source or as a trigger to activate the use of a surveillance or measurement system to collect more information, which is similar to the use of a containment system with a surveillance or measurement system. These systems typically use sensors to measure temperature, flow, volume, density, and mass. For example, in the Advanced Thermohydraulic Power Monitor (ATPM) system, temperature and flow rate sensors are used in the primary cooling loop of a research reactor to determine the energy produced and to verify this against declaration of the State. In contrast, an energy pulse is used in time domain reflectometry (TDR) to detect the location and magnitude of a defect in a cable to support data authentication in case of cable tampering [10][14].

Other sensors based on motion and pressure are used as triggers to activate the primary data generation system consisting of cameras or radiation measurement system (thereby reducing the amount of data to be analyzed by the IAEA). In general, the IAEA uses motion sensors to trigger the activation of the cameras, and it generates a number of images for review in each facility. As a result, there is motivation to leverage other systems as a trigger, and thus sensors based on vibration, acoustics, ultrasonics, radar, and magnetism are under consideration and under development [14].

APPLICATION OF URMS TO MICRO-REACTORS

Some of the URMSs described previously can be used in micro-reactor facilities that are considered for deployment in remote and northern regions of Canada. The key micro-reactors considered for deployment in Canada vary in terms of refueling approach (off-line refueling, or replacement of the complete core), refueling frequency (from up to 3 years to 20 years), fuel type ("battery" cores, or TRISO in prismatic fuel), and fuel coolant (gas, or heat pipe). These various factors play an important role in determining the URMS to deploy. Containment systems will generally feature electronic seals such as EOSS, AOLS, and AUAS in order to maintain CoK over nuclear material during the fuel fabrication, in the fresh or spent fuel assemblies, and in the reactor core, and in order to maintain the integrity of other systems (such as cameras). For the surveillance systems, DCM-C5-based NGSS cameras can be employed that are activated by the applied containment measures, which provides more information about the potential event. For measurement systems, ATPM can play an important role in verifying power generation in micro-reactors.

DATA COLLECTION SYSTEMS

A data collection system receives data from all sensors and detectors (via their respective data generator) at the facility. It has three main objectives:

- Monitor the state of health (SoH) of each deployed sensor or detector.
- Store data (received from each sensor or detector) locally until the data are transmitted to the IAEA.
- Provide access to the IAEA inspector when on-site for functions such as data review, system maintenance, or system upgrade.

For the URMS, the data collection system is a primary database of safeguards-relevant information until the data are transmitted, and thus has functional requirements to ensure that CoK is maintained. These requirements stem primarily from situations when the data are not sent to the IAEA, such as a network failure, as the inability to access these collected data would require the IAEA to later re-establish the CoK. Moreover, the data collection system is housed in a cabinet with an electronic seal to prevent undetected unauthorized access.

DATA TRANSMISSION

Depending upon the safeguards agreement, the data transmission system has three main objectives:

- Compress the collected, authenticated data and perform encryption (if required by the State).
- Transmit the collected data at a specified interval, including the SoH of all equipment.
- Provide remote access to the IAEA (and the State) but no data manipulation, and prevent unauthorized access.

The collected authentic data is compressed first to reduce the amount of data to be transmitted before performing encryption, which converts the information to ciphered text. For the encryption, there are several techniques such as, tiny encryption algorithm in TRFS, three data encryption standard algorithm in VACOSS, and asymmetric cryptography in AOLS/AUAS.

The transmission of data is done securely using a virtual private network over the internet. The access is controlled by the rules set up in the interface system, such as what kind of information can be transmitted and received, and the list of devices that can connect, preventing any unauthorized access. The system allows one to remotely monitor and assess the health of equipment and evaluate the need for system maintenance or upgrades. This system is also typically housed in a cabinet with an electronic seal to prevent unauthorized access.

Some of the guiding principles to realize a robust and reliable interface system are [9][10][15]:

- Perform vulnerability assessment for the system taking into account the facility, location, equipment, and infrastructure.

- Implement strong configuration controls for data security, and strong system access controls.
- Define and establish communication protocols.
- Use certified commercial-off-the-shelf (COTS) software and equipment.
- Use licensed and approved encryption algorithms.
- Define the procedure for transmission and remote access.

SAFETY, SECURITY, AND SAFEGUARDS INTERFACES

The safety, security, and safeguards (3S) concept, which has been around for over a decade, aims to build and maintain an efficient and strong national nuclear program [16]. There are several areas where the 3S may synergize, and others where they may conflict. Table 2 lists the interfaces of 3S within each component of the URMS, where each supports the safeguards implementation. As for safety and security, each of these components can have two facets, one that supports the objective and a second that raises an issue. For example, the data generation system can alert the facility operator about a safety incident in the near-real time, but this system could be the cause of the safety event itself. Similar to the safety aspect, the data generation system can alert regarding a security event but also can be the target. The data collection system can help identify the cause of a safety event but can be the target for an intruder. The data transmission system can be the cause of a safety concern and an entry point for the security breach. The data review and analysis system (at the IAEA) is considered not to play any role in safety, but could be the target for sabotage of the data or analysis.

Table 2: Interfaces of 3S in an URMS

System	Safety	Security	Safeguards
Data Generation	Can help alert about any safety concern*, although its related systems (e.g., power supply) can be the cause of a safety concern	Can help alert about any security concern, although this system can also be the target	Supports safeguards implementation
Data Collection	Can help diagnose the cause of a safety event	Can be the target of a security event	Supports safeguards implementation
Data Transmission	Can be the cause of a safety concern	Can be the entry point of a security breach	Supports safeguards implementation

*The data generation system can have distinct channels for each stakeholder; the facility operator can therefore use the information for safety assessment.

CURRENT INFRASTRUCTURE FOR REMOTE COMMUNICATIONS IN CANADA

The deployment of effective remote monitoring of reactors for safeguards purposes relies on the implementation of a reliable communications infrastructure. As shown in Figure 2, the availability of high-speed (50/10 Mbps) internet has historically been predominant in urban areas of Canada, with slower (5/1 Mbps) internet available in larger rural areas of southern Canada.

Wireless connectivity via Canada's wireless network providers provides very similar coverage of land area. A comparison of Figure 2 with Figure 1 shows that about 85% of the industrial and mining sites are covered. However, communities and operation sites in northern regions and remaining southern regions of Canada do not have such infrastructure, and rely upon satellite communication where it is feasible.

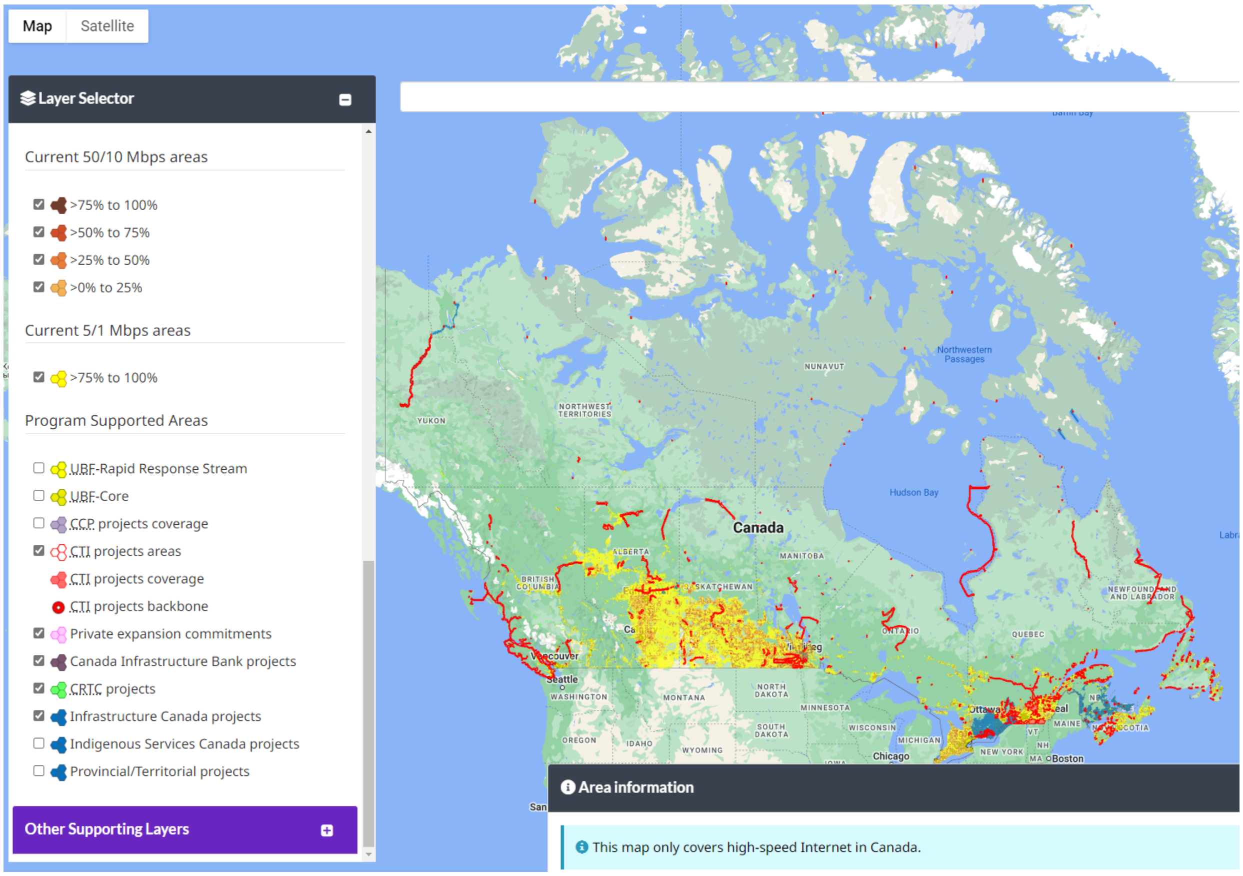

Figure 2: Government of Canada's National Broadband Internet Service Availability Map [17].

In 2016, the Canadian Radio-television and Telecommunications Commission (CRTC) declared access to high-speed internet to be an essential service that must be available to all Canadian residents, including those in rural and remote areas of Canada. Shortly after this, various provincial and federal initiatives were undertaken to improve infrastructure for internet connectivity. In particular, the Connect to Innovate (CTI) program since 2016 focused on building new backbone infrastructure to provide high-speed internet to 300 rural and remote communities across Canada [17]. The implemented expansion in backbone to date is shown in red in Figure 2; it is apparent that while infrastructure has improved in remote regions of Canada's southern provinces, more could be done in the Canada's arctic territories. To address this, the government of Canada has entered into an agreement with Telesat to secure high-speed internet capacity through Telesat's low Earth orbit satellite constellation. This satellite capacity is made available to internet service providers at a reduced rate, in order to make high-speed internet more accessible in Canada's rural and remote communities [18].

CONCLUSIONS

In the long term, it is envisioned that a large number of low-power reactors ("micro-reactors") could be deployed at geographically-dispersed remote locations in Canada. To help manage the challenge involved in meeting international safeguards goals for reactors deployed at a large number of sites in regions that are difficult to access, with reduced staffing at each site, URMSs will play a crucial role in providing the required data to the IAEA. Relevant aspects of URMSs for containment, surveillance, and unattended measurements were reviewed here, highlighting some of their recent developments and the implementations that would be suitable for micro-reactors in remote locations. Furthermore, some interfaces with the safety and security aspects of reactor facilities have been highlighted. Finally, a review of Canada's infrastructure for remote communications indicates that further work is needed in order to provide infrastructure for supporting broad deployment of SMRs across Canada's remote and rural regions. Nevertheless, the CRTC has made it a priority to further develop this infrastructure, which may well be ready in time for the first SMR deployments in such regions.

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