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# Maintaining Continuity of Knowledge (CoK) of Spent Fuel Pools: Tool Survey

## Scenarios, Technology Considerations, and Evaluation Criteria

**January 2016**

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## **1.0 Introduction**

One of the main technical objective of international safeguards, as defined by the International Atomic Energy Agency (IAEA) is the timely detection of diversion of significant quantities of nuclear material. Due to the nature of irradiated, or spent fuel, the timely detection requirement for a significant quantity (8kg) of plutonium is 3 months. Therefore, it is imperative that the IAEA have the tools necessary to achieve its monitoring objectives. Maintaining continuity of knowledge (CoK) over spent fuel throughout its life cycle is a key objective of the IAEA, Long-Term R&D (LTR&D) Plan Milestone 5.4. Currently the most widely used containment and surveillance (C/S) measures deployed to meet this safeguards challenge are optical surveillance cameras, as the use of seals on fuel assemblies or fuel containers in the pool is not always possible. In the event lighting goes out in the facility for an extended period of time, CoK may be lost because the cameras cannot acquire usable images without adequate lighting. When this occurs, a time-consuming and resource-intensive effort must be undertaken to reestablish CoK and to ensure no diversion or substitution has occurred. This effort can entail a lengthy process of performing nondestructive assay (NDA) measurements on every spent fuel bundle in the pool. The purpose of this project is to perform a technology survey to identify alternatives to traditional surveillance equipment which can maintain CoK over spent fuel in the absence of light or in low light conditions. This survey will include technologies which can be installed either within the pool or exterior of the pool and will consider technologies from a variety of fields and applications outside of international safeguards (Examples include ultraviolet (UV) or infrared (IR) imaging, and ultrasonic or acoustic underwater monitoring).

The objective of this report is to identify the foundational elements which will drive the survey and evaluation of potential technologies to be considered to maintain CoK of spent fuel within a pool in the potential absence of light or in low light scenarios. These foundational elements include identifying use cases that highlight the type of environments in which the technologies may be asked to operate; the CoK elements required of the technologies, such as unique identification or presence/absence identification; the functional and operational requirements for the technologies; and the criteria against which the technologies will be evaluated.

## **2.0 Scenarios**

The scenarios discussed in this section will bound the problem space under consideration for this survey, and will represent environments and operational constraints likely to be encountered under IAEA safeguards monitoring of spent fuel pools.

### **2.1 Spent Fuel Pools**

There are a variety of spent fuel pool types which must be considered. As is shown for a few representative worldwide examples (below), spent fuel pools can vary in dimensions, light intensity throughout the pool, water clarity, and depth. Two of the biggest examples of this are power reactors and research reactors. There is a significant difference between the spent fuel pools at each type of reactor, due largely to the difference in throughput. For a given type of reactor (power or research), the spent fuel

pools will vary between facilities based on type, i.e. light-water or boiling-water reactor, and the design company, e.g. Westinghouse or Babcock and Wilcox (B&W).

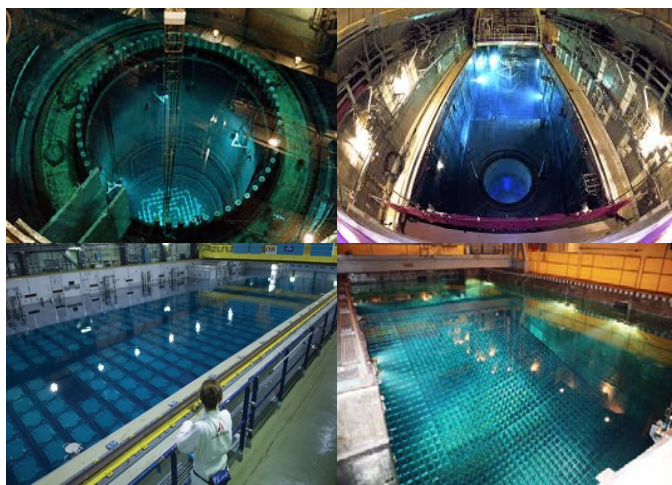


Figure 1: Examples of Spent Fuel Pools<sup>1234</sup>

The activities which occur within spent fuel pools also vary in frequency which must be accounted for. In power reactors,  $\frac{1}{4}$  to  $\frac{1}{3}$  of spent fuel is rotated through every 12 to 18 months. During these outages, there may be significant activity in a very short period of time within and around the spent fuel pool. Conversely, between outages, there may be minimal ongoing activities impacting the spent fuel pool. Similarly in reprocessing facilities, many activities will occur in batches with removals and additions whereas little to no activity will occur in between batches. In both cases, spent fuel bundles may be entering and leaving the pool or may be shifted around to accommodate new fuel bundles. Spent fuel bundles may also be transferred underwater to and from the reactor core and to a storage cask loading area.

In research reactors, spent fuel pool activity is less frenzied and sporadic than in power reactors. However, spent fuel is in many cases more accessible (smaller in size, less radioactivity), and the research nature of these reactors may make it difficult to identify a predictable pattern of activities as is present at power reactors. Additionally, many research reactors still utilize higher-enriched fuel, which makes the material more attractive from a proliferation standpoint thus increasing the importance of CoK. These few but important differences between power and research reactor spent fuel should be considered as part of this survey to cover the entire spectrum.

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<sup>1</sup> Top left image is Vermont Yankee Nuclear Power Plant. <http://www.csmonitor.com/USA/2011/0525/Report-Unacceptable-threat-from-spent-fuel-pools-at-US-nuclear-power-plants>

<sup>2</sup> Top right image is San Onofre Nuclear Power Plant. <http://www.enviroreporter.com/2014/10/lights-out/all/1/>

<sup>3</sup> Bottom left image is La Hague Reprocessing Plant. <http://www.neimagazine.com/features/featuredisposal-plans-part-1-spent-fuel/featuredisposal-plans-part-1-spent-fuel-2.html>

<sup>4</sup> Bottom right image is Gori Nuclear Power Plant, South Korea. [https://www.koreatimes.co.kr/www/news/biz/2014/06/123\\_159447.html](https://www.koreatimes.co.kr/www/news/biz/2014/06/123_159447.html)



## 2.2 Spent Fuel Pool Monitoring

Each year, the IAEA confirms a spent fuel inventory through a Physical Inventory Verification (PIV) inspection. Between PIVs, the IAEA may come on-site to perform a few interim inspections throughout the year to re-verify inventory or to be present during re-fueling or transfer of spent fuel to dry storage. To support inspections, confirm declarations, and confirm no diversion has occurred throughout the year the IAEA will implement unattended monitoring through the use of C/S. The main C/S technologies employed include cameras and seals. Together these technologies monitor and secure the spent fuel pool to account for any authorized or unauthorized changes to the inventory. Currently the IAEA relies on the few on-site inspections to verify inventory and confirm declarations. Looking to the future, the IAEA has an interest in having the capability to confirm inventory remotely. The IAEA has indicated in its “Development and Implementation Support Programme for Nuclear Verification 2014-2015” plan an interest in ultrasonic based surveillance technology and hydro-acoustic signals to generate an image of spent fuel items underwater. This capability can reduce the financial burden and reliance on on-site inspections without a reduction in confidence. Finally, as mentioned in section 1, in the event of a loss of lighting the current generation of cameras may not function adequately to confirm no diversion has occurred.

Building upon the current and future spent fuel monitoring needs just described, there are three monitoring objectives which will be considered throughout this survey. The first is the detection of items entering/exiting the spent fuel pool. In this case, detection of diversion is the only objective. More specifically, similar in function to a portal monitor, the objective is to detect items entering or leaving the monitored boundary. The second case includes diversion detection as in the first case, but adds the ability to confirm and monitor the total number of spent fuel bundles stored in the pool. In the third case, the ability to account for each individual spent fuel bundle through the verification of a serial number or unique ID is added. Therefore, the technologies to be considered must be able to track inventory changes, confirm gross inventory or confirm item specific inventory within a spent fuel pool.

Spent fuel residing in pools will have varying characteristics affecting C/S. Recently irradiated fuel can have varying burn-up, and will contain many short-lived fission products, resulting in very high dose rates. The amount of time spent fuel has been in residence in the pool, or cooling time, will also have a large impact on potential C/S as many of the short lived fission products will have died away (i.e., Cs-134 which is used in ratio with Cs-137 to verify burn-up), reducing both the dose rate of the bundle and the amount of Cerenkov light being generated.

International safeguards goals for spent fuel pools include the control of spent fuel static in the pool and the control of spent fuel going into and leaving the spent fuel pool. One important activity where spent fuel leaves the pool is via transfer to long-term dry storage, wherein this transfer may represent the last opportunity to confirm the unique identity of a spent fuel bundle. Having the capability to monitor static and dynamic activities in the spent fuel pool in the absence of light and low light conditions will help the IAEA meet its safeguards objectives to ensure the timely detection of diversion of significant quantities of special nuclear material.

The physical attributes of spent fuel pools, in conjunction with the myriad of activities, identify a wide set of bounds under which monitoring equipment must be able to successfully function. Success includes the ability to install equipment where it can count and account for spent fuel inventory and inventory

changes. Both in-pool and out-of-pool monitoring technologies are included as part of this survey, and this combination should identify a suite of potential technologies to meet the IAEA's monitoring goals and objectives now and into the future.

## **2.3 Bounding Scenarios**

The following section represents the bounding scenarios to be considered as part of this survey. These bounding scenarios are based on the discussions above in sections 2.1 and 2.2. The choice of bounds was selected to capture the wide range of facility conditions and reflect the various types and functions of spent fuel pools which fall under the monitoring purview of the IAEA.

### **2.3.1. Lighting**

- a. Low light above the pool
- b. Low light within the pool
- c. Loss of light within facility

### **2.3.2. Depth of Pool**

- a. Shallow
- b. Deep

### **2.3.3. Visibility of the Boundary of the Pool**

- a. Clear view of the surface of the pool and transfer channels
- b. View of the surface of the pool with some infrastructure limiting the view of small areas
- c. Presence of infrastructure limiting the view of a significant portion of the surface of the pool; transfer channels are covered/concealed.

### **2.3.4. Visibility Within Pool**

- a. Clear with minimal obstructions
- b. Clear with instrumentation and other infrastructure preventing a clear view of entire pool
- c. Presence of disturbances (thermal or operational) which limit the depth of view within pool
- d. Presence of non-fuel items on the pool which limit the view of fuel bundles and the propagation of acoustic waves

### **2.3.5. Pool Geometry**

- a. Cylindrical
- b. Square
- c. Rectangular (long and thin)

### **2.3.6. Operational Activities**

- a. Simultaneous facility operations and movement of spent fuel
- b. Continuous operation for periods of time up to two weeks (batched operations)
- c. Nearly static environment (between reactor refueling)

### **2.3.7. Monitoring Functions**

- a. Unattended operation
- b. Continuous monitoring
- c. Ability to function in the absence of light
- d. Ability to function in the absence of power for short periods of time
- e. Ability to achieve safeguards objectives on spent fuel spanning all expected characteristics (e.g. high and low dose rate, high and low burn-up)
- f. Ability to achieve safeguards objectives on spent fuel pools spanning all expected configurations

### **3.0 Technology Considerations/Constraints**

The following considerations and constraints are derived from IAEA safeguards objectives and current equipment requirements placed on deployed systems. This section will continue to evolve as the project progresses. The objective of this section is to identify requirements placed on currently deployed equipment to serve as a guide to help feed the evaluation and future research and development recommendations at the heart of this project. None of the considerations and constraints will be used to preemptively discount a given technology.

In order to meet the scenarios and monitoring objectives identified in sections 2.2 and 2.3, the identified equipment should:

#### **3.1. Operate within expected facility conditions:**

- a. Radiation environment
- b. Expected operating temperatures and humidity
- c. Robust against power fluctuations
- d. Robust against mechanical shocks and vibration

#### **3.2. Not interfere with facility operations**

- a. Crane movements
- b. Spent fuel bundle transfers
- c. Equipment maintenance

#### **3.3. Possess the ability to be installed with minimal impact to facility operations**

#### **3.4. Meet facility safety requirements**

- a. Electrical safety
- b. Fire safety
- c. Criticality safety

#### **3.5. If applicable, be able to function underwater for its operational lifetime**

- a. Must be waterproof
- b. Must not corrode or release material into the pool (consider water chemistry)

#### **3.6. Possess the ability to be protected (confirm equipment authenticity and integrity)**

- a. Ability to be sealed or secured in a tamper indicating enclosure

- b. Ability to authenticate (digitally sign) and/or encrypt data collected
  - c. Ability to store data for extended periods of time
- 3.7. Be reliable
- a. Have a high mean time between failure (MTBF) of parts
  - b. Have redundant or back-up power to prevent loss of data
  - c. Require minimal maintenance over operational lifetime
- 3.8. Possess the ability to meet at least one of the monitoring requirements of inventory and inventory change confirmation
- a. Have sufficient resolution to confirm spent fuel bundle IDs
  - b. Have sufficient resolution/sensitivity to provide an inspector the ability to differentiate fuel bundle versus pin removal
  - c. Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations

## **4.0 Evaluation Criteria**

This section describes a set of criteria against which each technology will be evaluated. The purpose of these criteria is not to rigorously rank and assess each technology using a formal systems engineering approach, but rather to provide a common set of important parameters to keep in mind when surveying and evaluating potential technologies. Each criterion will include a list of evaluation factors, or sub-criteria, which will help to identify important parameters within each criterion. These criteria will be based on, and will represent in summary, the technology considerations and constraints identified in section 3. Additionally, each set of criteria plus evaluation factors will be summarized as a question to ensure that each technology is evaluated in a consistent manner and that no underlying assumptions exist which may skew results.

### **4.1. Deployability**

- a. Safety: Can the equipment be installed without introducing additional hazards to the facility?
- b. Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?
- c. Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?

### **4.2. Operational Impact**

- a. Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?
- b. Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?

### **4.3. Cost**

- a. Equipment: Is the cost of the equipment reasonable?
- b. Lifecycle: Is the lifetime cost (parts, installation, maintenance) reasonable?

#### 4.4. Confidence Provided

- a. Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?
- b. Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?
- c. Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?

## **5.0 Conclusion**

The technology survey will draw heavily from this document. The objectives of this document are to define the project bounds, to identify constraints and considerations when selecting technologies to include, and select appropriate criteria against which to objectively evaluate selected technologies. These three objectives will provide the project team with the ability to identify and assess technologies with the potential to meet IAEA safeguards needs now and into the future, and identify specific areas of recommendation for continued research and development.



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