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Maintaining Continuity of Knowledge of Spent Fuel Pools: Tool Survey

August 2016

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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1. Introduction

1.1. Objectives and Drivers

One of the main technical objectives of international safeguards, as defined by the International Atomic Energy Agency (IAEA) is the timely detection of diversion of significant quantities of nuclear material, including spent nuclear fuel. To detect diversion, the IAEA receives declarations from the facility on material quantity and location as well as performing measurements and inspections to verify these declarations. As inspectors are not permanently on-site at a facility, once they have performed an inspection, they will establish and seek to maintain Continuity of Knowledge (CoK) over the spent nuclear fuel throughout its lifecycle. Continuity of Knowledge can be maintained using Containment and Surveillance (C/S) measures.

Currently, the most widely used C/S measures deployed to meet this safeguards objective are optical surveillance cameras with a view of the pool and portals, and seals on canal gates and portals. The use of seals on fuel assemblies is limited due to the environment in which they would be deployed (underwater and high radiation levels) and verification difficulty. Underwater cameras may be used for attended operations – mostly to verify fuel assembly identification numbers (IDs). A concern, however, is that currently deployed optical surveillance cameras may not be able to provide adequate imagery in the event facility lighting is lost, which represents a potential single point of failure in CoK. The IAEA cannot simply rely on back-up power or other facility measures. If for any reason the host recovery measures are inadequate or the IAEA C/S is maliciously tampered with, CoK may be lost over the spent fuel in the pool. If CoK is lost, a time-consuming and resource-intensive effort must be undertaken — possibly involving a lengthy process of performing nondestructive assay (NDA) measurements and ID verification on a statistical sampling of spent fuel assemblies in the pool — to reestablish CoK, and to ensure that no diversion or substitution has occurred. The statistical sampling is based on the confidence required, the numbers of significant quantities present, and the population of spent fuel assemblies present in the pool.

One major objective of this project is to survey potential solutions which prevent the need for inspectors to travel to the facility to re-confirm inventories. Another objective is to survey potential tools which can operate in a wide variety of spent fuel pool/hall environments and can provide CoK over spent fuel with high confidence. Various environments will be discussed in greater detail in this report, but one example includes low-light spent fuel halls. This project examines supplemental tools that can be used in addition to optical surveillance cameras to maintain CoK in low-to-no light conditions, and increase the efficiency and effectiveness of spent fuel CoK, including item counting and ID verification, in challenging conditions.

1.2. Continuity of Knowledge (CoK): Containment and Surveillance (C/S)

In traditional international safeguards, accountancy ensures that nuclear materials are present and used as intended. A State declares nuclear materials and activities at facilities, and independent inspections periodically verify the declaration. C/S are technical means to maintain CoK between inspection intervals and help reduce the effort required to carry out nuclear material accountancy verification, given CoK applies. Under the Additional Protocol (AP), C/S measures with unattended and remote monitoring capabilities allow the IAEA to reallocate resources to focus more on qualitative safeguards measures.

The definition of C/S measures from the IAEA safeguards glossary [1] is: Application of containment and/or surveillance; an important safeguards measure complementing nuclear material accountancy. The application of C/S measures is aimed at verifying information on movement of and access to nuclear and other materials, devices and samples, or preserving the integrity of safeguards relevant data. In many instances, C/S measures cover the periods when the inspector is absent, which contributes to cost effective safeguards. C/S measures are applied, for instance,

- to ensure that each item is inventoried during material transfers and inventory verification without duplication, and that integrity of samples is preserved, and
- to extend the validity of previous measurements and thereby reduce the need for re-measuring previously verified items.

From "IAEA Techniques and Equipment 2011" [2], "Containment and surveillance (C/S) techniques, based mainly on optical surveillance and sealing systems, are applied to supplement nuclear material accountancy by providing means by which access to nuclear material can be controlled and any undeclared movement of nuclear material detected." These techniques reduce inspection costs and level of intrusiveness of IAEA into normal operational activity. C/S measures are applied in a systematic manner to monitor all diversion paths considered credible at the boundary of a facility – this is known as the safeguards approach and varies by facility.

1.3. Spent Fuel Pools [3] – Background

1.3.1. Commercial Power Reactors

Approximately every 12 – 24 months, about a third of the total fuel load of a nuclear reactor is removed and replaced with fresh fuel. The irradiated or spent fuel is very hot and highly radioactive, and the entire refueling and discharge process must be carried out underwater to ensure personnel protection. To do this, the following steps are performed. The reactor head is unbolted and the refueling cavity, in which the reactor vessel is located, is slowly flooded with water. When the water reaches a depth of at least 20 feet above the reactor head, the head is stored and an underwater tunnel between the cavity and the spent fuel pool is opened. One-by-one, spent fuel assemblies are lifted out of the core with fuel handling equipment (crane), but kept underwater at all times, and transported into the spent fuel pool, located nearby or in an adjacent building. There, fuel handling equipment lifts the fuel assembly and inserts it into a fuel storage rack in the spent fuel pool.

Spent fuel pools vary in dimensions; however, pools are typically 40 or more feet deep, with the bottom equipped with storage racks (see Figure 1) designed to hold fuel assemblies that have been removed from the reactor (and keep them in a safe configuration). Only about 20 feet of water above the fuel assemblies is necessary to keep radiation levels below acceptable levels above the pool, and in fact, the top of the spent fuel pool has little radiation. Spent fuel remains in the pool for at least a year, and more commonly 5 years and beyond. To remove the spent fuel from the pool, a canister is placed into a transport cask, lowered into the spent fuel pool by the fuel handling equipment, and loaded with fuel assemblies underwater (see Figure 2). A lid is placed on the transport cask, which provides radiation shielding when the cask is removed from the water. The transport cask is removed to an area where it can be drained and decontaminated. The canister lid is welded on, all water and air is removed from the canister, and the interior is inerted with helium.

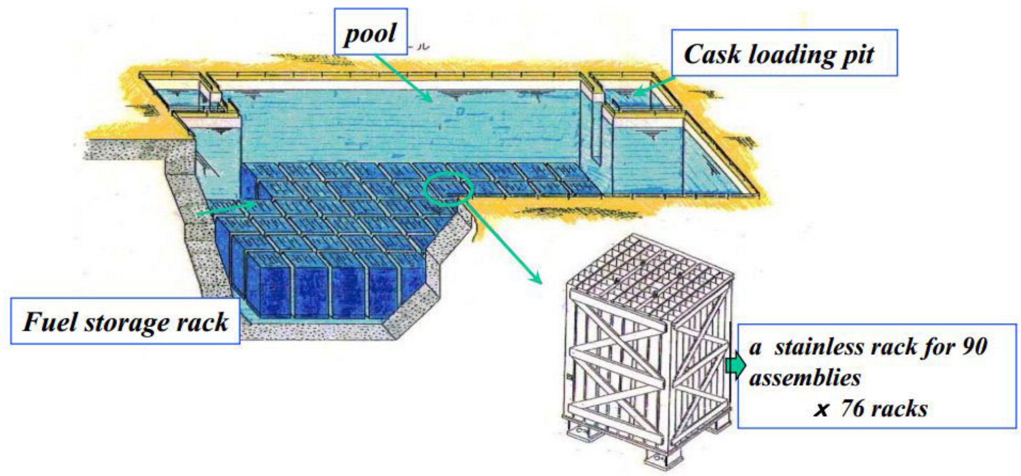

Figure 1: Example layout of a spent fuel pool. Image from TEPCO.

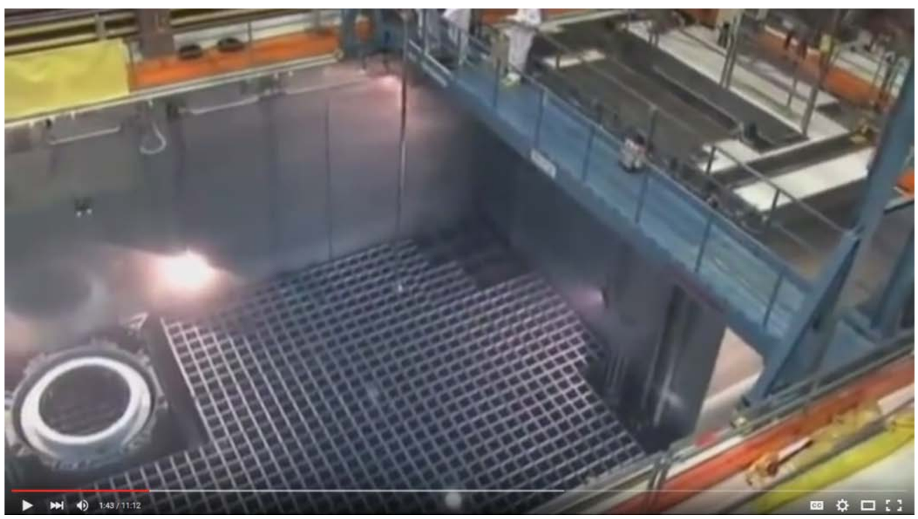

Figure 2: Spent fuel pool with view of fuel storage racks and transport cask. Credit: PG&E [4]

1.3.2. Research Reactors

Research reactors [5] are used for research and training, materials testing, or production of radioisotopes for medicine and industry. They are smaller than power reactors, and many are located on university campuses. As of September 2015, there were about 240 research reactors in 56 countries.

Research reactors differ from power reactors in their design, fuel, and various operating modes, among other features. Some reactors still require highly enriched uranium fuel – above 20% U-235. Others have converted to lower enriched fuel – typically just below 20% U-235. There is a wider array of designs in use for research reactors than for power reactors. A common design is a pool type reactor (67 units) where the core is a cluster of fuel elements sitting in a large pool of water. TRIGA is another common design (40 units). The core sits in a pool of water and contains 60-100 cylindrical fuel elements about 36 mm in diameter.

Like power reactors, research reactors fall under IAEA safeguards. The IAEA applies safeguards to over 150 research reactors and critical assemblies (RRCA) targeting mostly research reactors with higher power levels (i.e., those reactors with more than 25MWt). Although the safeguards measures vary for different types of research reactors depending on their design, power level, and fuel, the objectives are the same; detect diversion of fuel and detect any undeclared irradiation that could produce material of proliferation concern. Standard safeguards measures are much the same as at commercial power reactors and include containment and surveillance, non-destructive assay measurements on fuel, and physical inventory verification. In addition, power monitoring is used to verify the operating history of a research reactor where there is excess reactivity that would allow for irradiation of undeclared material.

1.3.3. Application of C/S

The application of C/S depends on the type of reactor. Generally, inspectors perform a Physical Inventory Verification (PIV) on a frequency based on the timeliness goal of the nuclear material. During the PIV, spent fuel pools are verified 100% for gross defects. The improved Cerenkov Viewing Device (ICVD) can be used for item counting [6]. The identity of the fuel assemblies can be verified using an underwater camera, although this is typically only done on core fuel and during spent fuel transfers. In particular, the IAEA uses the Underwater Closed Circuit Television (UWTV) for inspector attended fuel ID verification [2]. The UWTV (Figure 3) consists of a radiation hardened camera, a camera control unit, and a lighting system. The camera is capable of reading small letters under limited light conditions in high radiation underwater environments. Review is on-site using a built-in monochrome monitor. The IAEA also can use the modular high intensity LED light (HILL) as a back-up external light source for either in-air or underwater surveillance applications. The light is battery powered in the event of facility power failures, and is extremely reliable and does not need maintenance for its entire life.

Figure 3: Underwater TV. From IAEA Techniques and Equipment 2011 [2].

After the fuel assemblies have been item counted and verified 100% for gross defects, optical surveillance and seals outside the pool are used to maintain CoK. Optical surveillance system(s) are placed with a view of the spent fuel pool and any entrances/exits that are large enough for passage of fuel assemblies.

Seals may be placed on the canal gate between the reactor and the spent fuel pool as well as entrances/exits.
As an example, for a Light Water Reactor (LWR) type 1, seals are placed on the reactor vessel head after refueling and on the canal gate after fuel passage. An optical surveillance system can view the spent fuel pool, reactor core, and the equipment door. Figure 4 shows a diagram of the LWR type 1 reactor with the C/S measures applied.

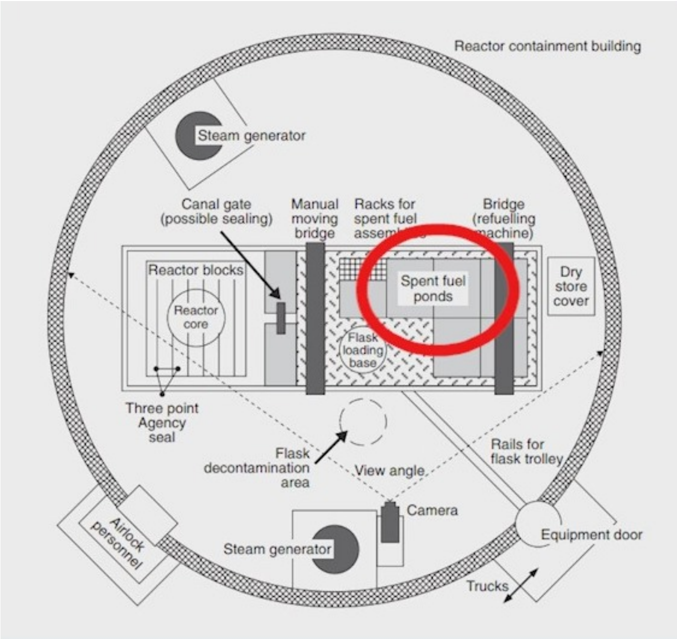

Figure 4: LWR type 1 reactor [7].

For LWR type 2, the spent fuel pool is located in a separate building. Seals are placed on the cable tray and reactor blocks of the reactor as well as on the canal gate and equipment doors. Optical surveillance cameras are deployed in the reactor building and the spent fuel pool building. In the spent fuel pool building, cameras are placed outside the equipment door, at the exit hatch to the spent fuel pool, any other exit hatches, and with the view of the spent fuel pool itself.

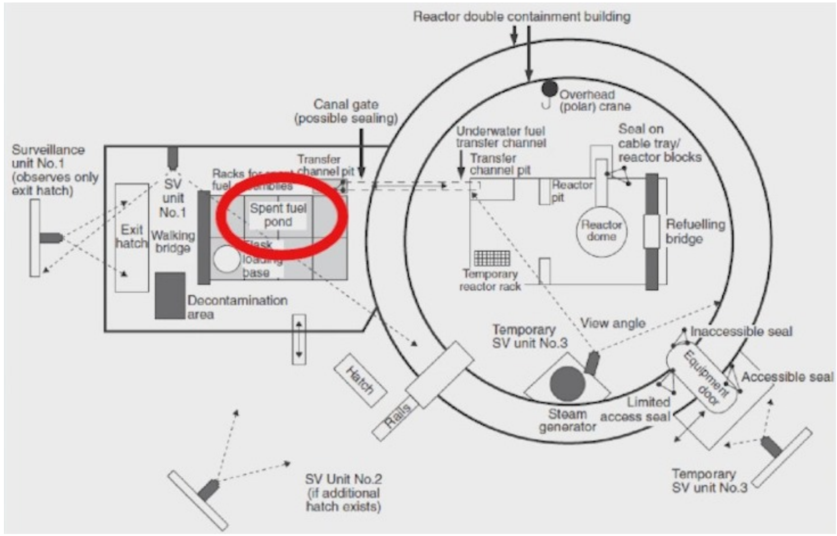

Figure 5: LWR type 2 reactor [7].

For CANDU reactors, the JCSS (JRC CANDU sealing system) can be used for underwater stack sealing of fuel bundles. We will describe more about ultrasonic sealing bolts in the technology section.

During transfers of spent fuel out of the pool, underwater camera systems may be used to view the serial number of the spent fuel before placement into the canister. This is an attended operation. Seals are placed on the canister – typically a metal cup seal and a second type of seal, or a metal cup seal and use of optical surveillance.

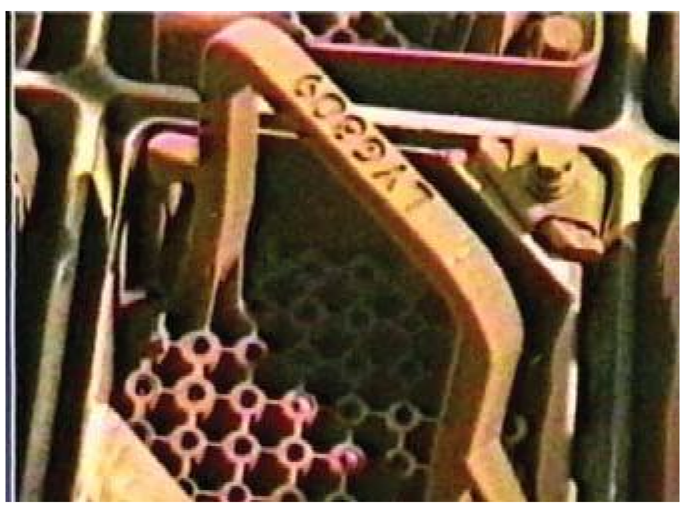

Figure 6: Serial number engraved on fuel assembly handle. Image from GE Measurement and Control [8].

An ANSI standard [9] exists for fuel assembly identification. It was developed primarily for light-water reactor fuel but may be used for any reactor fuel contained in discrete fuel assemblies. The identification number is based on a six character numbering system, with a prefix of two alphabetic characters that identify the individual fabrication facility, followed by four alphanumeric characters. The four characters following the prefix are selected from Arabic numerals 0 to 9 and capital English letters except B, F, I, O, Q and Z. The identification number is casted, machined, engraved, or similarly integrated with the fuel assembly and must be provided on the upper end fitting, nozzle or other integral part of the fuel assembly. The location and size must be agreed upon by the fuel fabricator and the user.

At most research reactors, as with commercial power reactors, C/S measures are limited to sealing of fresh fuel and equipment and surveillance of the fresh and spent fuel pools, the reactor, and all access points. Seals may be used, for example, on fresh fuel areas and reactor cores (if applicable). Surveillance can include the use of cameras as well as radiation detectors (neutron and gamma). Because of the mission of research reactors, there may be many penetrations and access ports that are constantly in use and therefore cannot be sealed.

2. Background and Implementation of Equipment Survey and Assessment

2.1. Scenarios

Three scenarios have been constructed for which technology solutions are desired. The first is the detection of items entering/exiting the spent fuel pool. In this case, detection of diversion is the only objective and is tied directly to the main international safeguards 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 assemblies stored in the pool. This adds efficiency and effectiveness to the inspection process. In the third case, the ability to account for each individual spent fuel assembly through the verification of a serial number or unique ID is added (also providing increased efficiency and effectiveness). 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. For the second and third scenarios, the increased efficiency and effectiveness of the inspection process is due to the fact that having the ability to confirm aggregate count and unique ID would preclude the need for the inspector to have to statistically sample spent fuel bundles for reconfirmation.

While one assumption is that spent fuel only enters the spent fuel pool via the recognized underwater path and exits the spent fuel pool via cask due to the large, heavy, specialized equipment required (the fuel handling equipment) and radiation dangers to personnel, a proliferator may not be concerned about loss of life. Diversion will be considered both from the standpoint that only fuel handling equipment is used and point out where diversion detection can occur at other locations (meaning other equipment is used and safety may not be a priority).

2.2. Criteria

Technologies used by the IAEA must meet certain requirements in order to meet Agency operational, functional, and financial requirements. The IAEA has a mandate that it must be able to make independent measurements in order to draw independent and unbiased safeguards conclusions. The IAEA also has an obligation to attempt to minimize the impact of safeguards application on the host facility. Finally, the IAEA has the increasing challenge of monitoring more facilities with a resource limited budget. Therefore, the Agency must consider tools and techniques which can meet the other objectives in a cost-effective manner.

This project considered thirteen criteria which were posed as a set of questions to keep in mind when surveying and evaluating potential technologies. These criteria are organized by broad category and given below.

- Deployability
    - Safety: Can the equipment be installed without introducing additional hazards to the facility?
    - Timeliness: Can the equipment as it currently exists be deployed, or is additional development or modifications required?
    - Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility? Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?

- Operational Impact
    - Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?
    - Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?
    - Category: How difficult is it to extract or interrogate monitoring data? Is it in a useful format for manipulation, filtering, and storage?

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

- Confidence Provided
    - Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?
    - Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?

- Maintainability
    - Robustness: Can the equipment function properly in the expected operating environments, including rough handling or being dropped?
    - Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?
    - Minimization of Maintenance: How frequently does the equipment need to be serviced or repaired?

2.3. Challenges

There are a myriad of challenges facing the potential technologies that are being considered as part of this project. The challenges all tie back to the project scenarios, and attempt to answer the question of how the technologies can meet all or a subset of the scenarios. The examples provided below highlight the difficulty of maintaining CoK over spent fuel pools in a realistic environment that must be addressed by any proposed technology.

2.3.1. Spent Fuel Pool Conditions

Due to the wide variety of facilities under the purview of IAEA monitoring, there also exist a variety of spent fuel pools with differing characteristics which may make maintaining CoK over them challenging. The geometry of the pools is one example. There are cylindrical, square and rectangular pools, which may have various depths. Visibility may also be less than optimal in certain environments. This may be due to the presence of facility infrastructure limiting fields of view of the interior or boundary of the spent fuel pools. There may also be disturbances in the water from either thermal or operational events. One example of operational is a bubbler which is part of the water conditioning system. There may also be non-fuel items present in the pool which may limit field of view, or which the operator may have a legitimate need to move or access frequently.

2.3.2. Operational Environments

Operational environments pose significant challenges as well. For example, there may be situations where the facility lighting is low either within the pool or above the pool. Additionally, there may be situations in which ongoing facility operations during fuel handling moves impede monitoring. Some facility operations are conducted in campaigns which may occur for anywhere from daily (for CANDU reactors) to periods up to two weeks (LWR refueling). These activities would be in contrast to other times where the environment is nearly static.

2.3.3. Technology Requirements

In order to meet the monitoring needs of the IAEA, there are many requirements placed on the technologies themselves. These include the ability to operate in unattended mode, provide continuous monitoring, and have the capability to function for periods of time without facility power. Specific to monitoring spent fuel pools, the technologies must also have the capability to function in the absence of light, function in high radiation and contaminated environments, and be able to accommodate the challenges presented in 2.3.1 and 2.3.2.

3. Technologies

The following section describes possible supplemental tools that may be used in complement to currently deployed optical surveillance systems. There may be additional technologies not listed here. The technologies are divided into in-pool and out-of-pool technologies, and consideration is given to both categories for data reduction (typically either a software data reduction or a hardware trigger). We have made an assumption that in a low-to-no light situation, the most useful supplemental technology will provide imaging capabilities for anomaly resolution.

The term “surveillance” is most often associated with images or videos captured in the visible region of the electromagnetic (EM) spectrum (Figure 7) – approximately 400 to 750 nanometers, as this is where the human eye can see. However, the EM spectrum is vast and possibly other information can be extracted using systems that are sensitive to other wavelengths or techniques that could exploit what has been non-traditional information. This additional information might be useful in applications where lighting is low or obscured.

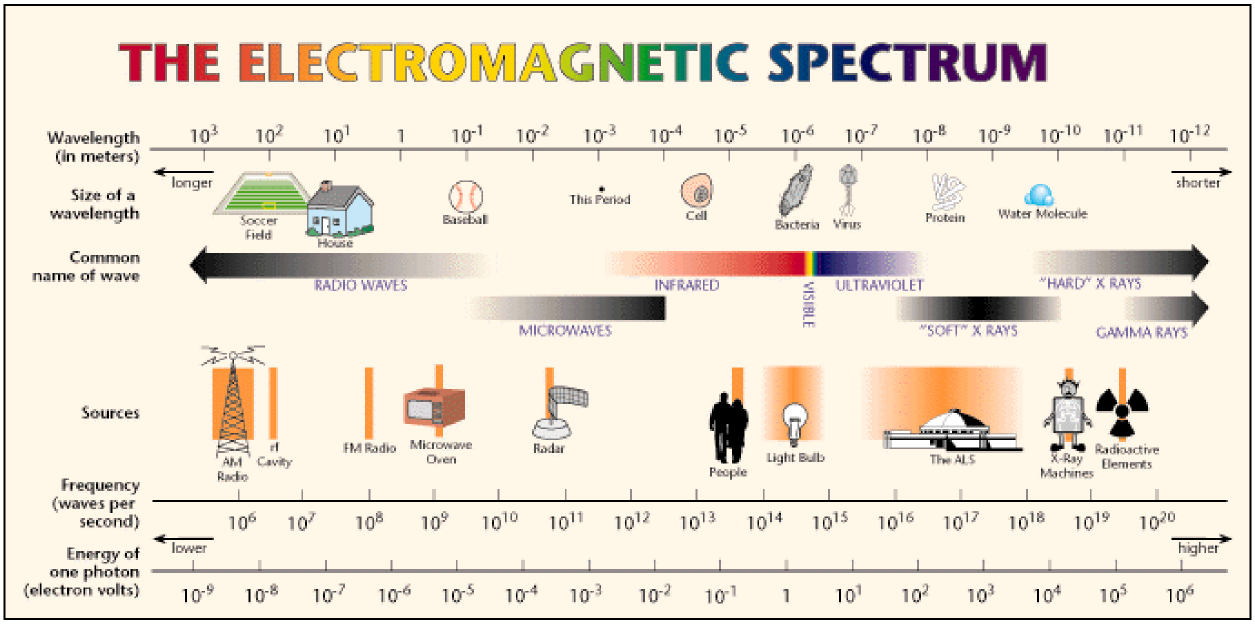

Figure 7: The electromagnetic spectrum. Image courtesy Remote Sensing Tutorial [10].

3.1. Imaging Sonar (In-Pool C/S Technologies)

3.1.1. Description

The IAEA has indicated in its "Development and Implementation Support Programme for Nuclear Verification 2014-2015" plan [11] an interest in ultrasonic based surveillance technology and hydro-acoustic signals to generate an image of spent fuel items underwater. Hydro-acoustic is the study of underwater sound, and ultrasonic refers to extremely high acoustic frequencies.

Imaging sonars transmit sound pulses and convert the returning echoes into digital images. The advantage is that they can "see" what's going on through dark or turbid (cloudy) water in zero visibility conditions [12]. Spent fuel pools are generally clear and thus the advantage of imaging sonar is the ability to acquire images in low or no light conditions.

The performance of an imaging sonar—from the distance at which they can detect an object, to the clarity of the image, to the number of images they can display per second—are determined by a number of specifications, most notably the operating frequency, acoustic beam width and processing power and time to form an image. Generally speaking, a lower frequency increases the distance at which an image can be captured. A higher frequency and a smaller beam width used to map an object will deliver higher resolution images. The depth at which the sonar is deployed has no direct effect on how clearly imaging sonar can capture a target.

3.1.2. Applicability to Gross Change Detection

As there is a trade-off between the range, range resolution, and field-of-view (FOV) of imaging sonar instruments, we envision the use of imaging sonar in all three of the scenarios but with varying configurations and objectives. For diversion detection assuming the fuel handling equipment is required, the imaging sonar would be placed with its FOV capturing the fuel assemblies as they enter from the reactor and at the cask loading location. If it is assumed that the fuel handling equipment is by-passed, the imaging sonar could be equipped with a rotator mount and pan across the pool such that its FOV covered all fuel assembly locations, or multiple imaging sonars could be deployed for full pool coverage. The direction of pan and the timing should be set such that diversion cannot occur by predicting when the instrument's FOV is not covering the fuel assemblies of interest. An issue with adding the rotator mount is that a tamper-indicating enclosure becomes more difficult to design and envelop the instrument. High resolution imagery would not be required, but the imaging sonar would need to be able to discern fuel assemblies entering or exiting the pool. The imaging sonar would be located at the top of the pool, but underwater, to minimize radiation exposure.

3.1.3. Applicability to Aggregate Counting

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 assemblies stored in the pool. In this case, multiple imaging sonars would likely be required to fully capture the FOV of all fuel locations and the entry/exit points. The number of imaging sonars would depend on the FOV and the particular dimensions of the spent fuel pool. The important imaging sonar settings would be a balance between range and ability to count spent fuel assemblies in storage.

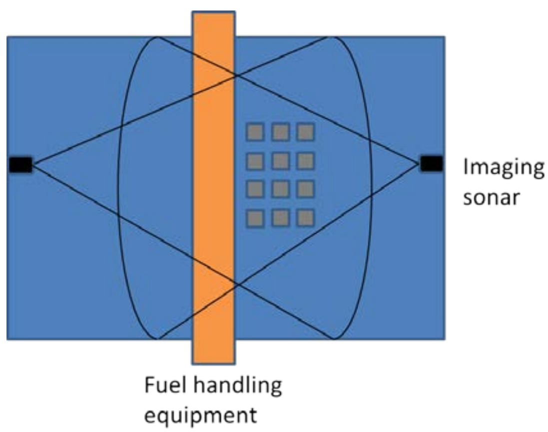

Figure 8: Multiple imaging sonars likely are required to count and detect diversion in the spent fuel pool, depending on pool dimensions. An alternative is to use the pan feature on a rotator mount. Settings will need adjusted to maximize range, field-of-view, and ability to discern (count) fuel assemblies.

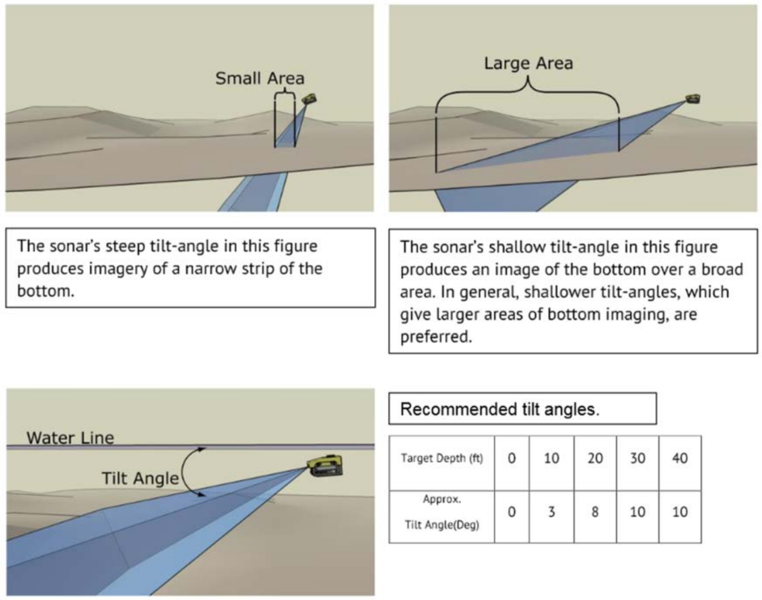

Figure 9: Recommended tilt angles for various target depths. Image courtesy Blueview [13].

3.1.4. Applicability for Unique Identification

To account for individual spent fuel assemblies as they enter or exit the pool (but not during storage in the pool), the imaging sonar would be set to the highest resolution. The imaging sonar would be placed at the entrance and exit only and would not be able to image the entire pool. An assumption is made that the fuel assemblies contain an ID large enough to be read by the imaging sonar and it may be required that the ID is 3-dimensional such that the sound waves can reflect off of the surface. Again, the imaging sonar would be located at the top of the pool, at a distance to acquire IDs of the spent fuel assemblies but enough distance to minimize radiation exposure.

3.1.5. Readiness for Use in C/S

Two imaging sonars with high frequency capabilities for high resolution image capture have been researched for this evaluation: ARIS Explorer 3000 from Sound Metrics and M900-2250 from Blueview.

Table 1: Specifications of imaging sonars under evaluation.

	ARIS Explorer 3000	M900-2250 Blueview (specs given in 900kHz/2250kHz)
Field of view (FOV)	30° x 14°	130°
Range resolution	Down to 0.3 cm (0.118 in)	Down to 1.3 cm/0.6 cm (0.512 in/0.236 in)
Range	5 m (16.4 ft) at 3MHz for identification; 15 m (49.2 ft) at 1.8MHz for detection	100 m (328 ft)/10 m (33 ft)
Frame rate	15 frames/second, with 1 frame/second minimum	Up to 12.5 frames/second
Power consumption	20 watts	20 watts/25.8 watts
Dimensions	10.2 in x 6.3 in x 5.5 in	8.6 in x 5 in

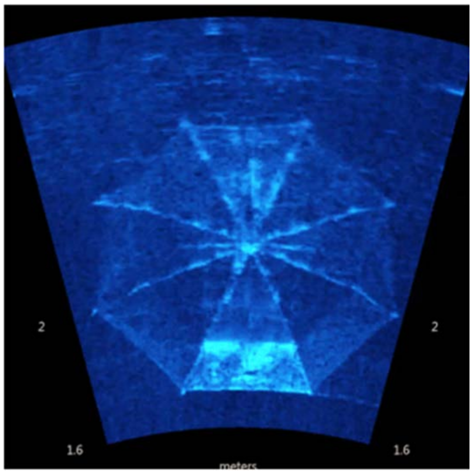

Figure 10: An umbrella imaged with ARIS 3000 from Sound Metrics [14].

These technologies require analysis in conjunction with bounding scenarios and evaluation criteria. The table below provides metrics for the ARIS 3000 and M900/2250 Blueview systems against technical considerations and evaluation criteria. An entry of "unknown" means no information was found in literature and the condition may require testing. An entry of "likely" means no information was found in literature but the authors have subject matter expertise to provide an estimate. Where possible, the authors have listed as much information as available.

Table 2: Technical considerations and evaluation criteria for imaging sonars

TECH CONSIDERATIONS	ARIS 3000	M900/2250 BlueView
Operate within radiation environment	Unknown/untested. Would require placement near top of pool in area of low radiation or testing of shielded enclosure.	No, not without adequate shielding according to manufacturer; can we separate components out of radiation environment?
Operate within expected temperatures and humidity (temperatures as high as 50° C, in practice between 25° C and 35° C)	Can operate up to 40° C continuous, higher intermittent	Unknown
Robust against power fluctuations	Use UPS	Use UPS
Robust against mechanical shocks and vibration	Tested against MIL-standard; report available	Likely
Not interfere with crane movements	Depends on placement	Depends on placement
Not interfere with spent fuel bundle transfers	Depends on placement	Depends on placement
Not interfere with equipment maintenance	Depends on placement	Depends on placement
Possess the ability to be installed with minimal impact to facility ops	Yes	Yes

Meet facility safety requirements - electrical	Unknown	Unknown
Meet facility safety requirements - fire	Unknown	Unknown
Meet facility safety requirements – criticality	Unknown	Unknown
Waterproof	Yes (all but data acquisition computer)	Yes (all but data acquisition computer)
Must not corrode or release material into the pool	No known corrosion or release issues	No known corrosion or release issues
Ability to be sealed or secured in a tamper indicating enclosure (TIE)	Possible, but difficult if AR2 (rotator mount) is implemented; consider TID between imaging sonar and pool structure	Likely
Ability to authenticate (digitally sign) and/or encrypt data collected	Not at sensor level; could add Enhanced Digital Authentication System (EDAS) just outside water in conjunction with TIE	Not at sensor level; could add EDAS just outside water in conjunction with TIE
Ability to store data for extended periods of time	Data is not stored on instrument but stored on data acquisition system topside	Data is not stored on instrument but stored on data acquisition system topside
Have a high mean time between failure (MTBF) of parts	Unknown	Unknown
Have redundant or back-up power to prevent loss of data	Facility power with UPS recommended	Facility power with UPS recommended
Require minimal maintenance over operational lifetime	Maintenance related to pressure changes	Unknown
Have sufficient resolution to confirm spent fuel bundle IDs	Likely - can resolve 3mm at 3-5m range; needs testing or analysis	Likely, needs testing or analysis
Have sufficient resolution/sensitivity to provide an inspector the ability to count spent fuel bundles and distinguish normal and off-normal operations	Yes	Yes
Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations	Yes	Yes
EVALUATION CRITERA		
Safety: can the equipment be installed without introducing additional hazards to the facility?	Yes, placement should be negotiated and optimized	Yes, placement should be negotiated and optimized
Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?	No	No

Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?	No	No
Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?	No	No
Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?	Depends on operator and installation	Depends on operator and installation
Equipment: Is the cost of the equipment reasonable?	~$100k including software; rental cost $600 per day or $15k per 30 days	Rental cost of $150 per day; unknown purchase cost
Lifecycle: Is the lifetime cost (parts, installation, and maintenance) reasonable?	Yes	Unknown
Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?	Likely	Likely
Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?	Yes	Yes
Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?	Yes – maintenance is low if instrument is relatively static in water; maintenance required due to pressure changes (air travel, frequent removal from water); failure rate unknown but 1 – 2 units out of 600 are repaired monthly; power is facility power, backup would be UPS	Unknown

The ARIS 3000 operates as a video camera with a non-configurable 15 frames/second acquisition. This is significantly different than the IAEA-deployed optical surveillance systems that acquire 1 image/second at the most, and typically operates as a triggered system. The video nature of the imaging sonar system produces significant amounts of data, most of which will show no changes between frames. As such, data reduction methods are required for imaging sonar. The ARIS 3000 does not accept a hardware trigger, but does have two software methods that can be used for data reduction. The first is to use threshold detection of sizes – the user can configure a region of interest or a size box and only those frames in which changes are detected on the order of those sizes are saved. The second method uses an echogram, which will create an image mostly of still "black" if there are no changes. Any "white" in the time space is an indication of motion. This method requires an inspector to view, although it appears that the review can be done rapidly.

The Blueview system can accept hardware triggers, but it is not yet known the exact input of these triggers. Initial thoughts are that a laser breakbeam or microwave infrared sensor across the spent fuel pool could be used as a trigger, and data acquisition only takes place for a period after the trigger.

3.2.Sealing Bolt (In-Pool C/S Technologies)

3.2.1.Description

The ultrasonic sealing bolt (USSB) is not an imaging system; however due to its capability to be deployed underwater in high radiation environments, it is worth describing as a potential supplemental technology. The Joint Research Center (JRC) in Ispra, Italy, has been researching and developing the USSB, in particular for underwater applications where other seals are unviable [15]. The principle behind the bolts is ultrasonic sound waves that reflect at interfaces and by internally designed flaws. A transducer in pulse-echo mode (one single transducer sends and receives the pulsed waves) is used to read the amplitude of received pulses versus travel time of emitted pulses. The interior of the seal is composed of many stainless steel disks brazed together to form a unique signature, i.e. the disks induce artificial flaws that are read by the transducer. The integrity of the seal is based on a "breaking" zone in the ultrasonic window.

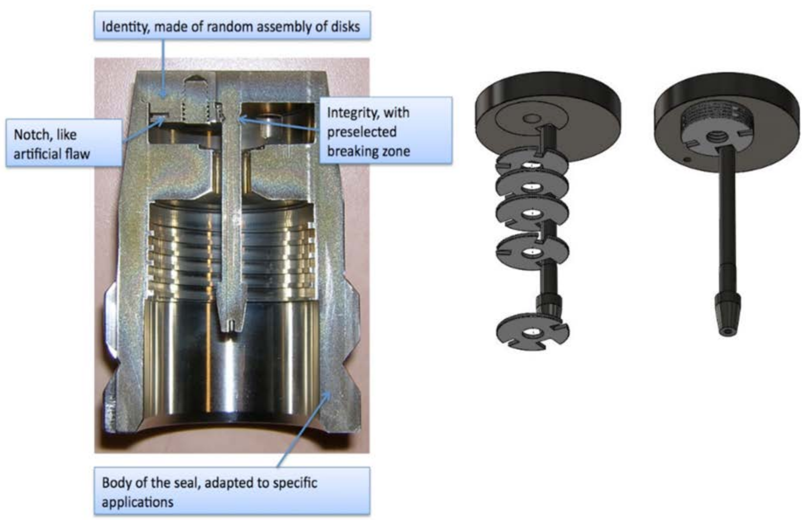

Figure 11: Ultrasonic Sealing Bolt. Image from JRC, Ispra.

3.2.2.Applicability for Gross Change Detection

The USSB could be attached to the fuel assembly storage racks in such a way that fuel assemblies could not be removed without detection, i.e. without removing the bolt and altering its integrity. The assumption is made in this case that there is a mechanism to deploy the USSB in such a manner that the assemblies cannot be removed. The verification would occur during interim inspections and PIVs, as the USSB does not have remote monitoring capabilities.

3.2.3. Applicability for Aggregate Counting

While one could infer that as long as the USSB has not been removed from a group of fuel assemblies, and no fuel assemblies can enter or exit storage without removal of the USSB, CoK on the number of fuel assemblies can be maintained. However, this can only be verified by the IAEA during inspections. This procedure could save time during inspections as the IAEA could make assumptions about the number of fuel assemblies under USSB; however, it does not seem realistic as the operator would never be able to alter the locations of fuel assemblies nor allow fuel assemblies to exit or enter without IAEA presence.

3.2.4. Applicability for Unique Identification

This situation is similar to the above, and does not seem like a feasible procedure.

3.2.5. Readiness for Use in C/S

The USSB is designed for underwater, high radiation environments, including spent fuel pools. Its readiness for use in C/S has only to do with the particular scenario in which we may be interested (and possibly what mechanisms are already in place to support its use).

Table 3: Technical considerations and evaluation criteria for USSB.

TECH CONSIDERATIONS	USSB
Operate within radiation environment	Yes
Operate within expected temperatures and humidity	Yes
Robust against power fluctuations	N/A (passive)
Robust against mechanical shocks and vibration	Yes
Not interfere with crane movements	Will not
Not interfere with spent fuel bundle transfers	USSB will have to be removed before assemblies are placed in a rack
Not interfere with equipment maintenance	Will not
Possess the ability to be installed with minimal impact to facility ops	Yes
Meet facility safety requirements - electrical	Yes
Meet facility safety requirements - fire	Yes
Meet facility safety requirements – criticality	Yes
Waterproof	Yes
Must not corrode or release material into the pool	Yes
Ability to be sealed or secured in a tamper indicating enclosure (TIE)	Yes (already is)
Ability to authenticate (digitally sign) and/or encrypt data collected	N/A
Ability to store data for extended periods of time	N/A
Have a high mean time between failure (MTBF) of parts	Yes
Have redundant or back-up power to prevent loss of data	N/A
Require minimal maintenance over operational lifetime	Yes
Have sufficient resolution to confirm spent fuel bundle IDs	No
Have sufficient resolution/sensitivity to provide an inspector the ability to count spent fuel bundles and distinguish normal and off-normal operations	No

Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations	Yes
EVALUATION CRITERA	
Safety: can the equipment be installed without introducing additional hazards to the facility?	Yes
Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?	No
Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?	Unknown. Facility dependent.
Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?	No
Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?	No
Equipment: Is the cost of the equipment reasonable?	Yes
Lifecycle: Is the lifetime cost (parts, installation, and maintenance) reasonable?	Yes
Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?	Partial
Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?	Partial
Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?	Yes

3.3. LWIR Thermal Imaging (Out-of-Pool C/S Technologies)

3.3.1. Description

The thermal band of the EM spectrum technically ranges from 2.5 to 7 microns for the mid-wave infrared (MWIR) and 7 to 15 microns for the long-wave infrared (LWIR); however, only the regions from 3.3 to 5 microns for MWIR and 8 to 14 microns for LWIR are usable for imaging due to lack of atmospheric transmission in the other regions. Thermal imaging cameras are sensitive to the temperature differences between objects in these regions due to emission of thermal energy.

Thermal imaging has advanced in recent years from a high-cost technology only available to military customers, to ubiquitous detectors available in commercial sectors. In the past, infrared detectors had to be cooled to liquid nitrogen temperatures (77K) to reduce detector noise. New detector materials and other advancements in integrated circuits have allowed for uncooled detectors. Microbolometers are one such type of uncooled detector, and have allowed for small, lightweight, and low power detectors. Uncooled detectors also allowed for large capacity production, and the first commercial applications were for night-time driving aids in BMW vehicles. Uncooled microbolometers utilize either amorphous-Silicon (a-Si), vanadium oxide (VOx), or indium antimonide (InSb) as the detector material. Because they are uncooled, design life of the detector material can be as high as 15 years [16]. Additionally, microbolometers have thermal sensitivity where they can detect thermal differences of less than 1 mK.

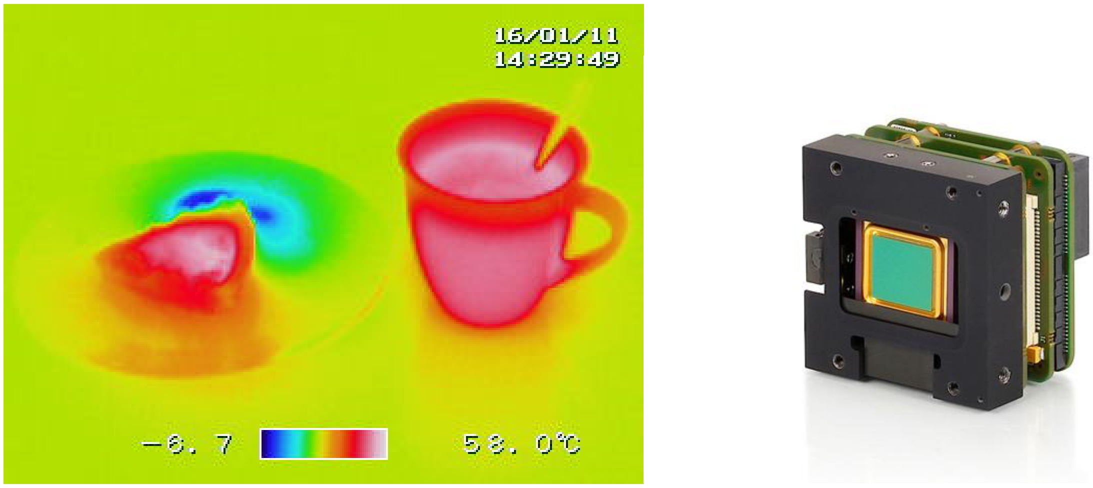

Figure 12: (Left) Coffee and apple pie image in the LWIR, using an uncooled detector (microbolometer) commercial thermal imager (Photo courtesy Pieter Kuiper using an NEC Thermo Shot camera). (Right) Example image of a-Si microbolometer core (http://www.xenics.com/en/application/lwir-uncooled-bolometer-cores)

Because of the drop in price, thermal imaging is becoming a more affordable option for security and surveillance applications. Standard cameras may rely on auxiliary lighting for illumination, whether from sunlight or active near-infrared (NIR) illuminators. Thermal imagers do not require additional illumination as they image differences in temperature from the thermal radiation emission of objects in a scene. This allows for night-time imaging as well as imaging in other poor lighting conditions. The thermal sensitivity achievable also enhances the resolution of images in environments where there is not a large temperature gradient.

The U.S. Nuclear Regulatory Commission (NRC) has recently required nuclear facilities to provide continuous 24-hour surveillance, observation, and monitoring of their perimeter and control area [17], and thermal imaging is being installed at many facilities for this purpose [18].

3.3.2. Applicability for Gross Change Detection

Thermal imaging cameras could be installed with a view above the spent fuel pool, capturing both the entrance and exit locations as well as the spent fuel assembly locations within the storage racks for diversion detection. The thermal gradients created by the spent fuel entering or leaving the pool should be visible.

3.3.3. Applicability for Aggregate Counting

We do not believe thermal imaging would have the capability to perform counting of spent fuel assemblies in all pool geometries as the surface temperature of the pool may be relatively uniform. Further evaluation is needed to either confirm or dispute this assumption.

3.3.4. Applicability for Unique Identification

Thermal imaging would not have the capability to perform individual spent fuel assembly ID.

3.3.5. Readiness for Use in C/S

FLIR is the leading manufacturer of thermal imaging solutions. Products include the SR-series, which is analog only, D-series with a rugged dome for outdoor conditions, PT-series with pan/tilt, and a series that uses cooled detectors for ultra-long range imaging. The FC-series cameras include analog and IP capability, ability to be externally triggered, and intelligent motion detection based either on radiography or regions of interest and is a likely candidate for the spent fuel pools. As these products are video cameras, we likely would use the external trigger capability and connect to devices that indicated anomalous motion or perhaps even a light sensor such that videos were captured only during low or no light situations.

Table 4: Technical considerations and evaluation criteria for long-wave IR thermal imaging cameras

TECH CONSIDERATIONS	FLIR FC-series
Operate within radiation environment	Likely, as can be mounted above spent fuel pool
Operate within expected temperatures and humidity	Yes, -50° C to 70° C continuous Humidity 0-95% relative
Robust against power fluctuations	Use UPS
Robust against mechanical shocks and vibration	Yes, IEC 60068-2-27 shock Vibe MIL-STD-810F "Transportation"
Not interfere with crane movements	Depends on placement
Not interfere with spent fuel bundle transfers	Will not
Not interfere with equipment maintenance	Will not
Possess the ability to be installed with minimal impact to facility ops	Yes
Meet facility safety requirements - electrical	Unknown
Meet facility safety requirements - fire	Unknown
Meet facility safety requirements – criticality	Yes. Will be located outside of pool
Waterproof	N/A
Must not corrode or release material into the pool	N/A
Ability to be sealed or secured in a tamper indicating enclosure (TIE)	Likely
Ability to authenticate (digitally sign) and/or encrypt data collected	Data is not currently signed at creation; can add EDAS
Ability to store data for extended periods of time	No on-device storage; video transferred to data acquisition system via IP
Have a high mean time between failure (MTBF) of parts	Unknown
Have redundant or back-up power to prevent loss of data	Facility power with UPS recommended
Require minimal maintenance over operational lifetime	Unknown
Have sufficient resolution to confirm spent fuel bundle IDs	No
Have sufficient resolution/sensitivity to provide an inspector the ability to count spent fuel bundles and distinguish normal and off-normal operations	Unknown. Further evaluation is required
Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations	Yes, and motion detection possible
EVALUATION CRITERA	

Safety: can the equipment be installed without introducing additional hazards to the facility?	Yes, placement should be negotiated and optimized
Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?	No
Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?	No
Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?	No
Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?	Likely has capability and resolution. Activity dependent
Equipment: Is the cost of the equipment reasonable?	~$45k for a 640KTSX version (ITAR controlled)
Lifecycle: Is the lifetime cost (parts, installation, and maintenance) reasonable?	Yes. Given reliability and MTBF of equipment
Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?	Likely (some)
Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?	Yes
Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?	Likely

For the out-of-pool imaging technologies, a trigger is likely required to minimize the amount of imagery collected (otherwise they collect continuously). Just as the IAEA's DCM-based optical surveillance systems use an electronic seal trigger or scene change detection, the infrared imaging systems can also perform onboard intelligent data reduction or accept hardware triggers. The next section highlights possible triggers.

3.4. SWIR Imaging [23] (Out-of-Pool C/S Technologies)

3.4.1. Description

The short-wave infrared (SWIR) has a wavelength range from 0.9 to 1.7 microns in the EM spectrum, just beyond the visible region. SWIR, like visible, is based on reflected light or heat, and images acquired from SWIR sensors are similar in resolution and interpretation to visible images (unlike thermal). SWIR cameras can work in the day, very dark conditions, or in conditions with obscurants such as smoke. Indium Gallium Arsenide (InGaAs) sensor technology has resulted in SWIR cameras that are uncooled, low power and small. Unfortunately, many of the SWIR products are considered sensitive technology and may be export controlled.

While thermal imaging can detect the presence of warm objects against cool backgrounds, SWIR cameras can identify what the object is. Thermal imagers do not have the resolution and dynamic range of imaging possible with InGaAs SWIR cameras.

Figure 13: Two images of a swimming pool – (Left) MWIR, (Right) SWIR. Image courtesy Sensors Unlimited [23].

Figure 14: (Left) Sensors Unlimited Micro-SWIR 640CSX non-ITAR SWIR Camera. (Right) Sensors Unlimited 640HSX-1.7RT High Sensitivity SWIR Camera, ITAR controlled.

3.4.2. Applicability for Gross Change Detection

A SWIR imaging system with view of the spent fuel pool area should perform well in daytime (lighted) conditions, low-light or no light conditions, whether due to absence of light or obscurants. Spent fuel assemblies leaving the pool should be easily identified in the imagery.

3.4.3. Applicability for Aggregate Counting

It is unknown how well, if at all, a SWIR imaging system can see the spent fuel assemblies within the water.

3.4.4. Applicability for Unique Identification

It is unlikely that the SWIR imaging system can identify spent fuel assemblies by their serial numbers within the spent fuel pool.

3.4.5. Readiness for Use in C/S

As of February 2016, Sensors Unlimited has developed and released the Micro-SWIR 640CSX camera, which is non-ITAR. The camera is small – 1.25x1.25x1.10”, consumes 1.5W power at 20° C, operates from -40° to 70° C, and has been environmentally tested to MIL-STD-810G.

Table 5: Technical considerations and evaluation criteria for short-wave IR thermal imaging cameras

TECH CONSIDERATIONS	Micro-SWIR 640CSX

Operate within radiation environment	N/A (outside pool)
Operate within expected temperatures and humidity	-40° to 70° C 95% RH non-condensing
Robust against power fluctuations	Recommend UPS
Robust against mechanical shocks and vibration	Yes MIL-STD-810G
Not interfere with crane movements	Will not
Not interfere with spent fuel bundle transfers	Will not
Not interfere with equipment maintenance	Will not
Possess the ability to be installed with minimal impact to facility ops	Yes
Meet facility safety requirements - electrical	Yes. Is available internationally, and can accept a range of input voltages present internationally. Is CE certified: EN 61326-1:2006, Class A, EN 61000-3-3:2006, and EN 61000-3-3:1995 A1:2001, A2:2005
Meet facility safety requirements - fire	Yes. Will not be located in high explosive or similar area
Meet facility safety requirements – criticality	Yes. Will be located outside of pool
Waterproof	N/A
Must not corrode or release material into the pool	N/A
Ability to be sealed or secured in a tamper indicating enclosure (TIE)	Likely
Ability to authenticate (digitally sign) and/or encrypt data collected	Data is not currently signed at creation; can add EDAS
Ability to store data for extended periods of time	No on-device storage; video transferred to data acquisition system via IP
Have a high mean time between failure (MTBF) of parts	Yes. >10,000 hrs
Have redundant or back-up power to prevent loss of data	Facility power with UPS recommended
Require minimal maintenance over operational lifetime	Yes. Conforms to MIL-HDBK-217F N2 for reliability prediction
Have sufficient resolution to confirm spent fuel bundle IDs	No
Have sufficient resolution/sensitivity to provide an inspector the ability to count spent fuel bundles and distinguish normal and off-normal operations	Unknown; Requires further testing
Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations	Yes
EVALUATION CRITERA	
Safety: can the equipment be installed without introducing additional hazards to the facility?	Yes

Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?	No
Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?	No
Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?	No
Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?	Has the resolution and capability.
Equipment: Is the cost of the equipment reasonable?	Unknown. Expected cost is $40K - $50K per unit
Lifecycle: Is the lifetime cost (parts, installation, and maintenance) reasonable?	Yes. Given reliability and MTBF of components
Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?	Partial
Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?	Yes
Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?	Likely

The same set of seal and motion detector technologies described in the LWIR section are applicable for triggering the SWIR camera. Refer to section 3.3.5 for more details.

3.5 Other Out-Of-Pool Technologies

3.5.1 Balanced Magnetic Switch

Seals or other technology such as a balanced magnetic switch (BMS) could be placed on the fuel handling equipment to determine if it has been utilized during unauthorized times and act as a trigger to the imaging system.

There currently exists the “Authenticated Switch” based on Sandia National Laboratories’ Secure Sensor Platform (SSP) technology. It is low power and employs authentication to report changes in status securely to a nearby wireless data collection system, thus allowing remote data transmission.

Hall Effect sensors, the technology behind the BMS, are devices that are activated by an external magnetic field. It produces an electrical output signal based on the magnetic field density around the device such as from an energized motor. Most Hall Effect sensors have a pre-set threshold that needs to be crossed before producing an electrical output signal.

3.5.2 Electronic Seals

Electronic seals would serve a similar role as the BMS as a triggering mechanism for the fuel handling equipment. The benefit of electronic seals is that they record any opening or closing of a fiber optic loop that would be threaded around the fuel handling equipment in such a manner that the loop would require removal to operate the equipment. This time stamped information is authenticated and either sent wirelessly to a data collection system or can be verified locally using a physical cable. The two electronic seals that can provide this capability are the Remotely Monitored Sealing Array (RMSA) [19] whereby the status is sent wirelessly, and the Electronic Optical Sealing System (EOSS) [20], with a physical cable attached between the seal and a reader.

3.5.3 Laser Break-beam or Microwave

A laser break-beam or microwave infrared sensor could be used to determine if the fuel handling equipment had been utilized, possibly indicating diversion. A microwave infrared sensor with FOV across the pool could also detect any movement into or out of the pool. Either sensor could be used as a hardware trigger for an imaging technology, but they do not typically implement authentication and thus would require additional capability.

Break-beam sensors consist of two parts – the transmitter and receiver. The transmitter is made up of an infrared LED or laser that illuminates at around 36 KHz. The receiver has a phototransistor with an amplifier to detect the light from the LED. Typically they are located some distance apart and when a moving object obstructs the light and the receiver detects no incoming light it can trigger an alarm or other mechanism. The transmitter and receiver can be co-located together utilizing the optical reflection off an object for detection. The optical wavelength of the infrared is immune to sunlight and artificial lighting. Ultrasonic beams could also be used for object detection and ranging just the like optical beams.

3.5.4 Accelerometer or Load Sensor

Similar in function to the BMS, an accelerometer is a small sensor which can be placed on the fuel handling equipment to detect movement and trigger an imaging technology. Accelerometers are very small and could be incorporated into an electronic seal to provide real-time evidence of movement. A load sensor can also be used to identify movement of the fuel handling equipment. However, if the load sensor is placed on the crane portion, then it has the capability to differentiate simple movement from actual use. This should reduce false alarms and further limit the amount of data needing to be reviewed. The IAEA already uses the Load-Cell Based Weighing System (LCBS) to weigh UF6 cylinders. It may be possible to modify this technology for our application.

An accelerometer is a device that measures changes in acceleration; it can also detect tilt and vibration. They can monitor 1, 2 or 3 axis, depending on the application. Accelerometer sensors have been used in many applications like freefall detection, activity monitoring, and motion sensing. There are two types – analog and digital. The analog version generates an electrical signal that is proportional to acceleration. The digital version can be set up to have preset thresholds and only when a threshold is crossed will it output an electrical signal known as an interrupt. Load cells are transducers that generate a measureable electrical signal with the change of force. A tension-based load cell can easily be implemented to detect the presence of a load on a crane.

3.5.5 Swimming Pool Safety Systems

Passive sonar systems are available commercially for the purpose of managing the safety of swimming pools. These consist of a hydrophone (underwater microphone) with wireless communication to a monitoring station [21]. The concept is that if a child falls into a swimming pool, the hydrophone will detect the sound and alarm. Software analyzes the sounds and distinguishes between a child falling into the pool and other situations such as toys and debris. Although not exactly the same concept as we are researching, the software could be modified to detect the sounds associated with movement of spent fuel assemblies within the pool and trigger the imaging systems. Authentication would have to be added to this technology as well.

A different swimming pool safety technology that could possibly be adapted for spent fuel pools is buoy alarms that detect water motion. Diversion could be detected by deploying these buoy alarms throughout the pool – alarms would be sent if waves were detected and trigger initiated. One example is the Pool Patrol PA-30 [22] – sensitivity can be adjusted to higher or lower levels and the sensor covers 20x40 feet. Again, authentication would have to be added.

Table 6: Technical considerations and evaluation criteria for other out-of-pool technologies

TECH CONSIDERATIONS	BMS/Seals	Laser Breakbeam or Microwave	Load Sensor or Accelerometer	Pool Safety
Operate within radiation environment	N/A (outside pool)	N/A (outside pool)	N/A (outside pool)	Unknown
Operate within expected temperatures and humidity	Yes	Yes	Yes	Unknown (pool is warmer than commercial swimming pool)
Robust against power fluctuations	Battery powered	Battery powered	Battery powered	Battery powered
Robust against mechanical shocks and vibration	Unknown	Likely	Yes	Yes (floating)
Not interfere with crane movements	Concept is to prevent undetected crane movement	Will not	Concept is to prevent undetected crane movement	Will not
Not interfere with spent fuel bundle transfers	Will not	Will not	Will not	As floating, would have to ensure not in path of handling equipment
Not interfere with equipment maintenance	Will not	Will not	Will not	Unknown
Possess the ability to be installed with minimal impact to facility ops	Yes	Yes	Yes	Yes
Meet facility safety requirements - electrical	Likely	Likely	Likely	Likely
Meet facility safety requirements - fire	Likely	Likely	Likely	Likely
Meet facility safety requirements – criticality	Likely	Likely	Likely	Likely

Waterproof	N/A (outside of pool)	N/A (outside of pool)	N/A (outside of pool)	Yes
Must not corrode or release material into the pool	N/A (outside of pool)	N/A (outside of pool)	N/A (outside of pool)	Yes
Ability to be sealed or secured in a tamper indicating enclosure (TIE)	Yes	Likely	Likely	Unknown
Ability to authenticate (digitally sign) and/or encrypt data collected	Yes	No	No	No
Ability to store data for extended periods of time	Yes	No	No	No
Have a high mean time between failure (MTBF) of parts	Yes	Unknown	Yes	Unknown
Have redundant or back-up power to prevent loss of data	Yes	Unknown. Type dependent	Unknown	Unknown
Require minimal maintenance over operational lifetime	Yes	Likely	Likely	Unknown
Have sufficient resolution to confirm spent fuel bundle IDs	No	No	No	No
Have sufficient resolution/sensitivity to provide an inspector the ability to count spent fuel bundles and distinguish normal and off-normal operations	No	No	No	No
Have sufficient resolution/sensitivity to provide an inspector the ability to distinguish normal and off-normal operations	Yes (trigger) and detection of undeclared movements	Yes (trigger) and detection of undeclared movements	Yes (trigger) and detection of undeclared movements	Yes (trigger)
EVALUATION CRITERA				
Safety: can the equipment be installed without introducing additional hazards to the facility?	Yes	Yes	Yes	Yes
Timeliness: Will the time required to install and maintain the equipment require extensive facility personnel time to accommodate?	No	No	No	No

Resource Intensiveness: Does the equipment require extensive facility modifications to allow it to operate within the facility?	No	No	No	No
Footprint: Does the space and infrastructure required to install and operate the equipment impact facility operations?	No	No	No	No
Operational Security: Does the equipment capture sensitive or proprietary activities which must be protected?	No	No	No	No
Equipment: Is the cost of the equipment reasonable?	Yes	Yes	Yes	Yes
Lifecycle: Is the lifetime cost (parts, installation, and maintenance) reasonable?	Yes	Yes	No	Yes
Equipment Functionality: Is the equipment able to achieve the required monitoring objectives?	Partial	Partial	Partial	Partial
Integrity: Can the equipment be easily accessed to allow for verification of integrity during inspections?	Yes	Yes	Yes	Yes
Reliability: Can the equipment operate for its expected lifetime with minimal maintenance or failures?	Yes	Likely	Yes	Unknown

4. Technology Testing and Results

4.1. Testbed Results

A selected set of technologies were deployed for testing at the Oregon State University (OSU) TRIGA reactor (OSTR). The OSU spent fuel pool is approximately 9’x9’x10’. Any monitoring equipment installed at the top of the pool will remain 8’-10’ away from the spent fuel element. There is only one fuel element in the pool, but there are other items that are highly radioactive with dose levels between 80 and 100 R/hr. The OSU spent fuel pool has dose rates on the order of 100 mR/hr when the reactor is running, and approximately 1 – 10 mR/hr when the reactor is shutdown. These dose rates are measured in the pool, a few feet below the surface. The dose rate is at or less than 1 mR/hr at and above the surface.

We chose technologies based on availability for testing, and promising performance for achieving the stated monitoring objectives. We intended to test one in-pool and one or two out-of-pool imaging systems. However, due to the radiation environment inside the pool, we were unable to test the in-pool imaging sonar as they are not qualified for this environment. The out-of-pool technologies tested were the InGaAs SWIR camera and a FujiFilm IS Pro camera with visible, UV, and IR filters. The IS Pro camera is based on a CCD detector which is sensitive to wavelengths between 380 nm and 1000 nm. By swapping filters, it has the capability to image across varying spectrums within and just outside the visible region. The specific filters used during the experiments are shown below in Figures 16 and 17. The PECA 904 IR filter, shown in Figure 16, highlights the near IR spectrum and the PECA 908 UV/IR filter, shown in Figure 17, highlights the UV and near IR spectra available to the IS Pro. This camera was tested as a pseudo-baseline instrument to compare against the InGaAs SWIR camera.

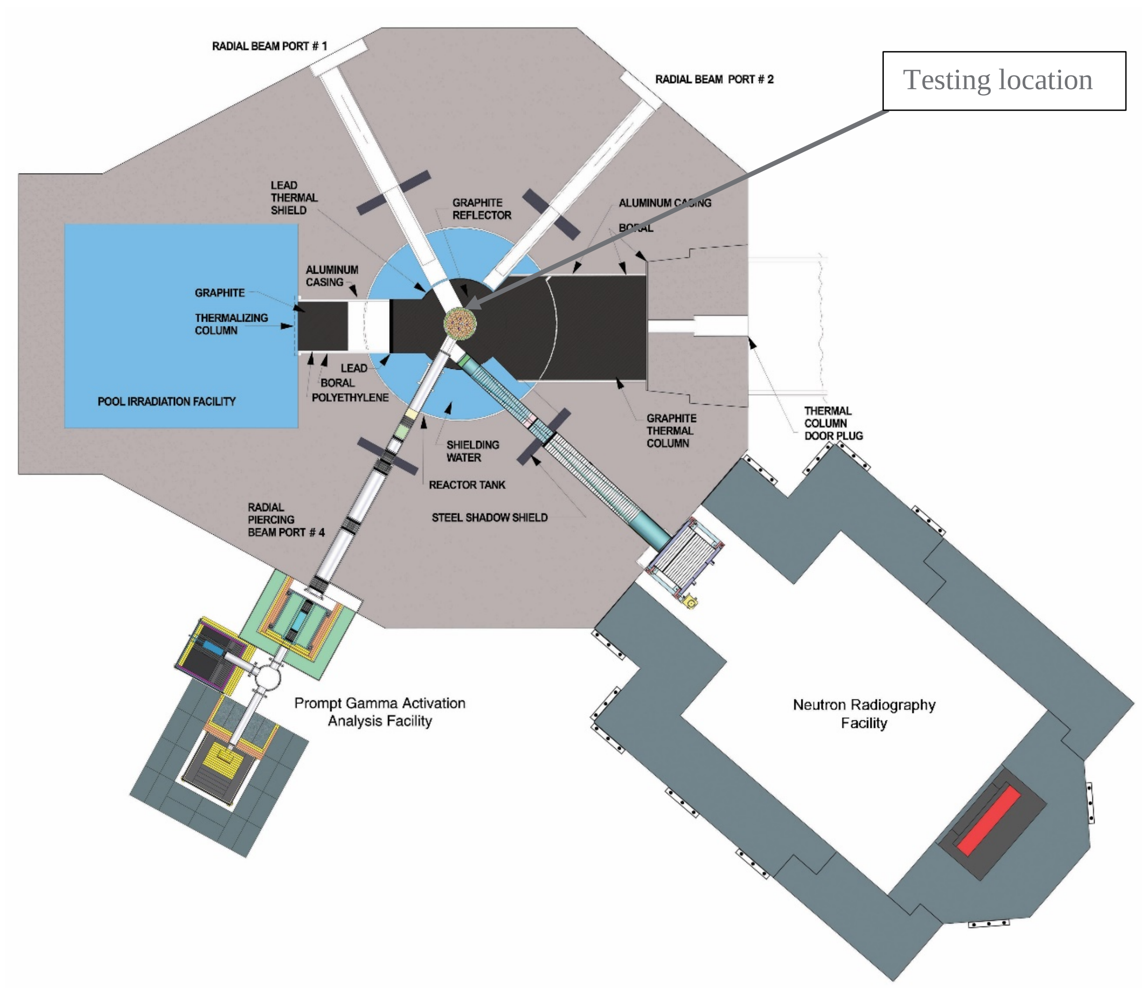

Figure 15: Diagram of the Oregon State TRIGA Reactor [24].

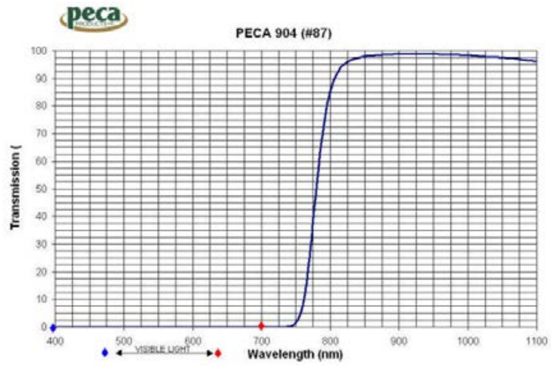

Figure 16: Near IR PECA 904 Filter Used to Capture Only Near IR Spectrum on IS Pro

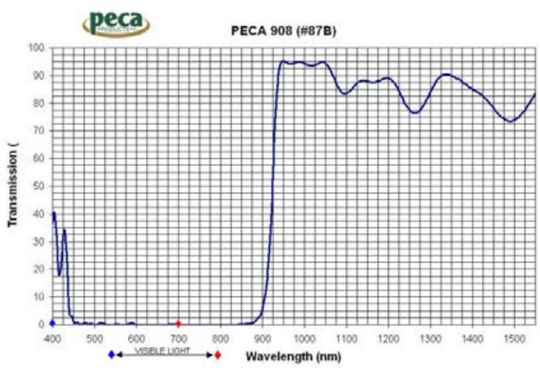

Figure 17: PECA 908 UV/IR Filter Used to Capture Only UV and Near IR Spectrum on IS Pro

The purpose of these experiments was to test equipment against the three scenarios; diversion, gross item counting, and unique identification within a spent fuel pool in varying light scenarios. As the spent fuel pool at Oregon State University's TRIGA reactor did not contain any spent fuel at the time of testing, testing occurred on the fuel pins within the reactor. This was possible due to the open pool design and flexibility of the TRIGA reactor. From atop the pool, directly above the reactor core (see Figure 18), the following tests occurred:

- Utilized the InGaAs SWIR Camera in variable lighting situations to identify individual fuel pins at varying temperature/power levels. The objective of this was to determine if the InGaAs SWIR camera could count the fuel pins, thus meeting the requirements of both the first and second scenarios.
- Utilized a FujiFilm Camera with UV, IR, and visible light filters to supplement the InGaAs Camera results to identify individual fuel elements at varying temperature/power levels. The objective of this was to include an alternative and complementary technology.

The reactor was operated in three power modes: 1 MW, 10 kW, and No Power to create different temperature signatures from the fuel elements. The reactor was operated in regular core configuration as well as with two pins removed and put in holding racks external to the reactor core. In this altered configuration, two different orientations were tested: pins located in the same rack and pins located in separate racks. The objective of this setup was to simulate a spent fuel pool with spent fuel elements of varying burn-up.

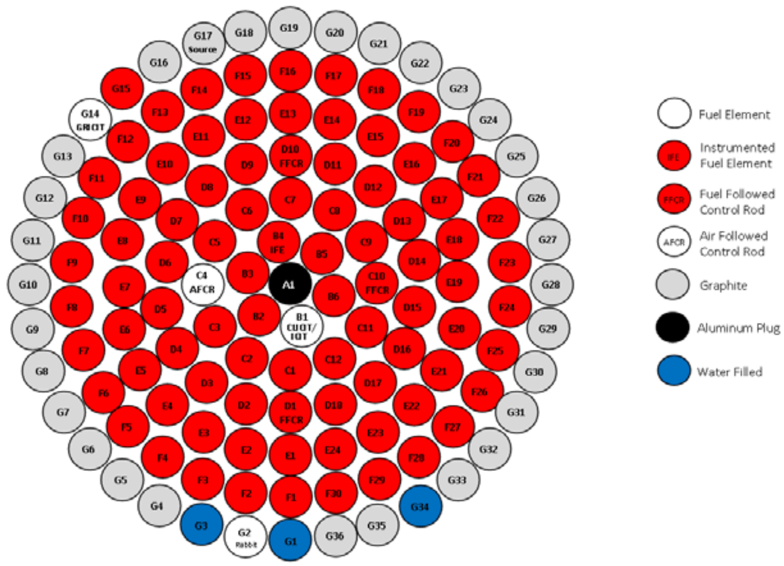

Figure 18: OSU TRIGA Core Grid

Table 7: Experiment Setup and Results at OSU TRIGA Reactor

OSU Experiment			
Thursday			
Equipment	Situation	Variations	Comments
SWIR InGaAs	Set up on reactor top		Although the tripod and all other components were set up properly, it looks as though the camera may not be able to focus on the core due to an extended distance from the core (16-20 ft.). Possible issue with IR absorption in water? Will take photos to determine if distance or medium issue.
FujiFilm IS Pro	Set up on reactor top		Appears to be able to be functioning properly. Utilize Filter 908 for UV and 904 for IR. Control pictures in visible light spectrum will be taken as well
Friday			
SWIR InGaAs	Reactor Full Power	Light Levels	Not able to view core
FujiFilm IS Pro (UV/IR)	Reactor Full power	Light Levels UV/IR/Visible Filters	
SWIR InGaAs	Reactor Low Power	Light Levels	Not able to view core
FujiFilm IS Pro (UV/IR)	Reactor Low power	Light Levels UV/IR/Visible Filters	

SWIR InGaAs	Reactor No Power	Light Levels	Not able to view core
FujiFilm IS Pro (UV/IR)	Reactor No Power	Light Levels UV/IR/Visible Filters	
SWIR InGaAs	Pins shifted to rack	Light Levels	Not able to view core
FujiFilm IS Pro (UV/IR)	Pins shifted to Rack	Light Levels UV/IR/Visible Filters	
SWIR InGaAs	Spent Fuel Pool	Light Levels	Not able to view core
FujiFilm IS Pro (UV/IR)	Spent Fuel Pool	Light Levels UV/IR/Visible Filters	

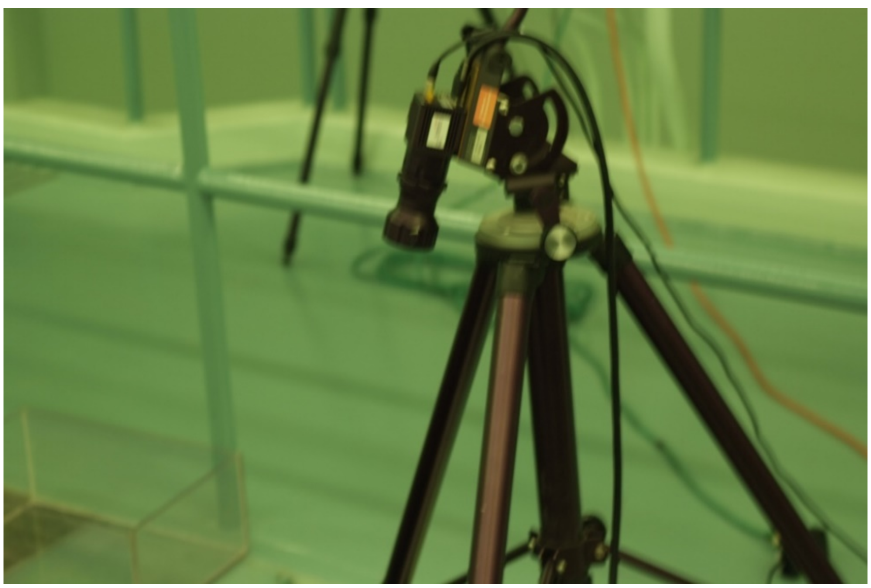

Figure 19: InGaAs Camera Setup

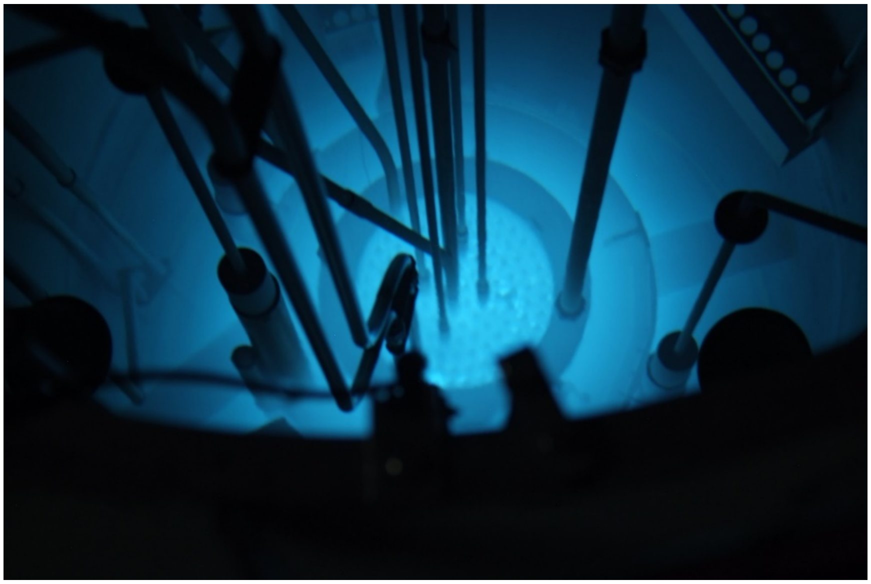

Figure 20: Reactor Operating at 1 MW

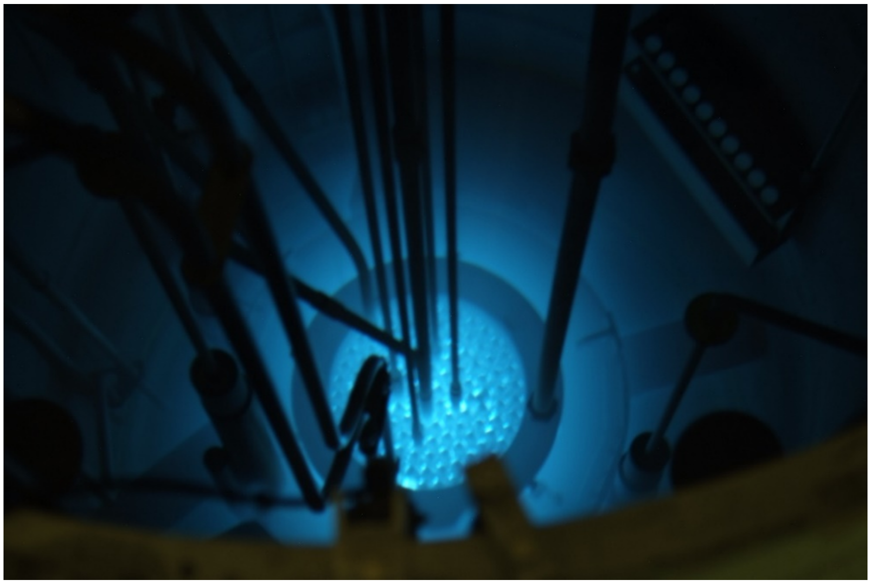

Figure 21: Reactor Operating at 10 kW

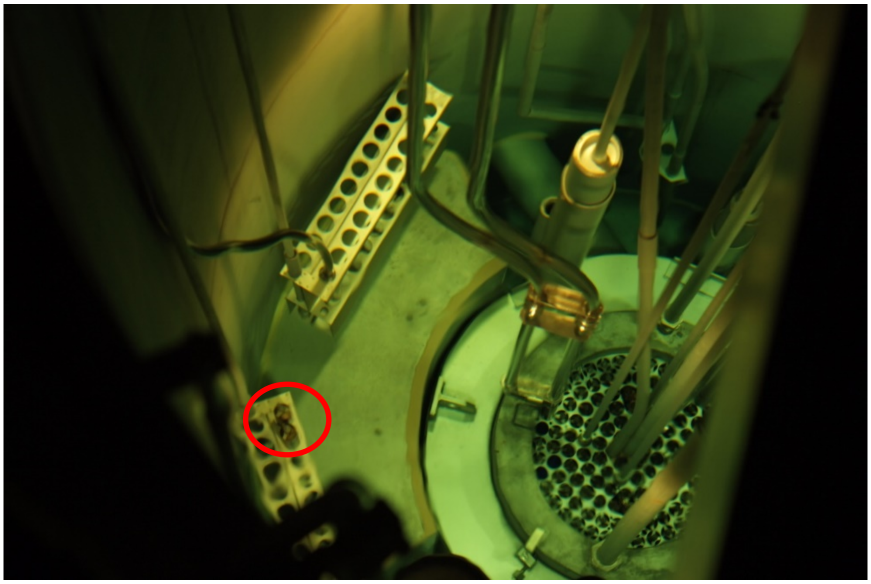

Figure 22: Reactor operating at zero power and 2 fuel elements collocated in the same storage rack

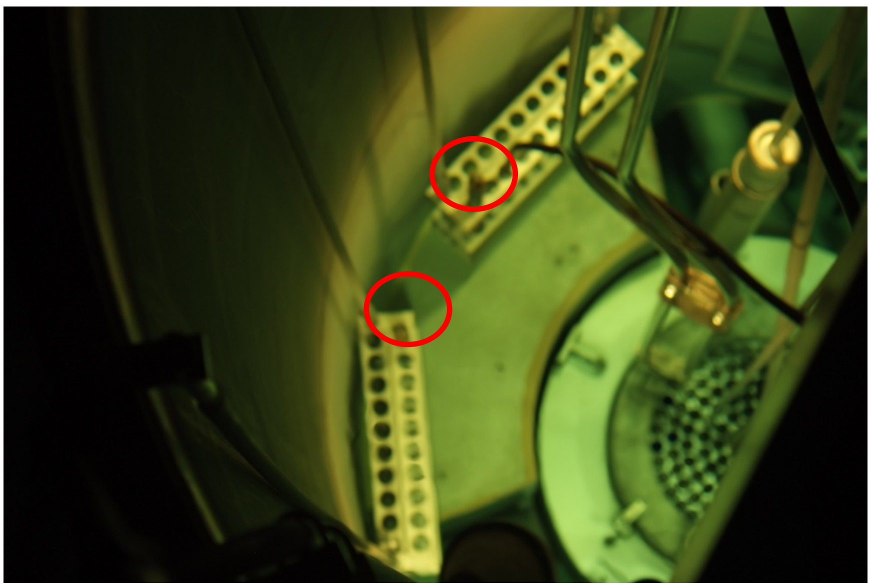

Figure 23: Reactor operating at zero power and fuel elements in separate storage racks

4.2 Conclusions

The SWIR InGaAs camera should be able to achieve the objectives of detecting diversion from the spent fuel pool. Initial testing indicates that the camera may have difficulty performing gross item counting in the pool, but further testing should be performed before a final conclusion is drawn.

The IR spectrum's absorption through water is significantly higher than that of visible light as shown in Figure 24. Due to this absorption increase, imaging through large bodies of water results in distortion and poor resolution within the IR spectrum. This is shown in Figure 25 and Figure 26 where Figure 25 shows a reference resolution for the camera at a distance of 30 ft through air. Within this image, one can clearly view the textbooks within the office. Within Figure 26, no image is able to be identified due to the large absorption or scatter of IR light in water. This same poor image resolution occurred for all power levels and additionally occurred when utilizing the UV and IR filters for the FujiFilm camera. Further testing and analysis is required to identify a path forward to utilize UV or IR options for out-of-pool spent fuel verification. Potential solutions include image processing, such as that requested in a recent IAEA challenge to enhance ICVD images of spent fuel in pools. Another option may be to increase sensitivity in the IR region. This could be through increased camera sensitivity, such as increasing gain, or by identifying a more sensitive camera. It is recommended that this be included in any future research.

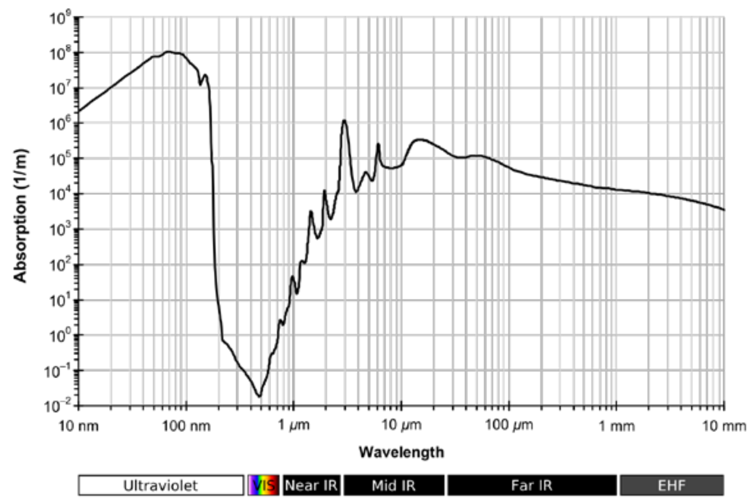

Figure 24: Light absorption as a function of wavelength

Figure 25: Reference Resolution

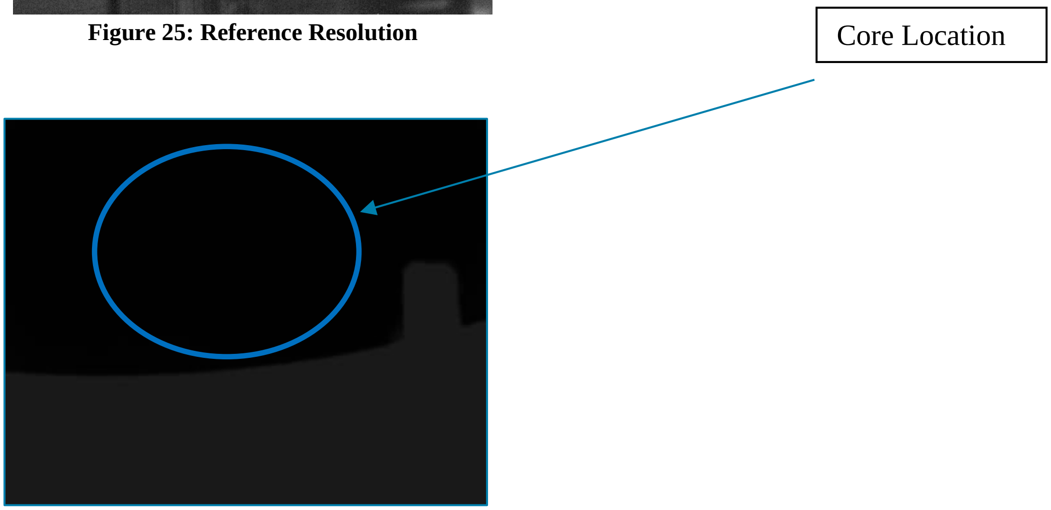

Figure 26: Core Image

5. Recommendations and Next Steps

The technologies represented in this survey range from requiring minimal adaptation to significant adaptation for international safeguards use. There are currently no plug and play technologies identified for international safeguards use. The imaging sonar requires the most adaptation, but provides the most capability in terms of supplemental C/S measures and improvements to effectiveness and efficiency. The SWIR imaging system may require the least amount of adaptation for international safeguards use, but does not provide the ability to item count, and it is unknown at this time if aggregate counting is possible.

While we performed limited testing at the OSU TRIGA research reactor, further analysis and testing is recommended based on the results of this study. In particular, we recommend further testing of the imaging sonar and an exportable SWIR imaging camera. The imaging sonar may require initial testing in non-radioactive environments with mockup fuel assemblies. Based on the results of this testing, considerations can be given to radiation protection for the imaging sonar. All three scenarios should be tested for the imaging sonar, while gross change detection and aggregate counting should be further tested for SWIR imaging cameras.

Table 8: Technologies requiring minimal adaptation, by scenario.

Scenarios/Technologies	Comments
Gross Change Detection	
1. SWIR Imaging	• Requires adequate tamper-indication • Requires data authentication between the camera and a data acquisition system • Requires confirmation of meeting facility safety requirements and negotiation of equipment placement to minimize impact to normal operations • Requires hardware or software trigger to reduce data • Requires additional testing to address IR absorption issue
2. USSB	• Requires design of fixture to secure fuel assemblies into storage racks
3. Thermal Imaging	• Requires adequate tamper-indication • Requires data authentication between the camera and a data acquisition system • Requires implementation of trigger: can be built-in intelligent motion detection or integration of a hardware trigger • Requires confirmation of meeting facility safety requirements and negotiation of equipment placement to minimize impact to normal operations • Requires additional testing to address IR absorption issue
Aggregate Counting	
1. SWIR Imaging	• Requires further analysis or testing to determine if a SWIR camera can view and discern fuel assemblies and at what depth • Requires adequate tamper-indication • Requires data authentication between the camera and a data acquisition system • Requires confirmation of meeting facility safety requirements and negotiation of equipment placement to minimize impact to normal operations • Requires hardware or software trigger to reduce data • Requires additional testing to address IR absorption issue
Unique Identification	
1. None identified	

Table 9: Technologies requiring moderate to significant adaptation, by scenario.

Scenarios/Technologies	Comments
Gross Change Detection	
1. Imaging Sonar	• Requires adequate tamper-indication • Requires data authentication between the imaging sonar system and a data acquisition system • Requires testing or modification for radiation environment (shielded enclosure or separation of components out of pool) • Requires confirmation of meeting facility safety requirements and negotiation of placement to minimize impact to normal operations • Requires procedures/consideration for maintenance due to submersion in spent fuel pool • Requires hardware or software trigger to reduce data • Requires continued discussions with vendor to acquire more information

	(temperature ranges, environmental factors)
Aggregate Counting	
1. Imaging Sonar	• Requires adequate tamper-indication • Requires data authentication between the imaging sonar system and a data acquisition system • Requires testing or modification for radiation environment (shielded enclosure or separation of components out of pool) • Requires confirmation of meeting facility safety requirements and negotiation of placement to minimize impact to normal operations • Requires procedures/consideration for maintenance due to submersion in spent fuel pool • Requires hardware or software trigger to reduce data • Requires continued discussions with vendor to acquire more information (temperature ranges, environmental factors) • Requires further analysis or testing for this scenario
Unique Identification	
1. Imaging Sonar	• Requires adequate tamper-indication • Requires data authentication between the imaging sonar system and a data acquisition system • Requires testing or modification for radiation environment (shielded enclosure or separation of components out of pool) • Requires confirmation of meeting facility safety requirements and negotiation of placement to minimize impact to normal operations • Requires procedures/consideration for maintenance due to submersion in spent fuel pool • Requires hardware or software trigger to reduce data • Requires continued discussions with vendor to acquire more information (temperature ranges, environmental factors) • Requires more information concerning fuel assembly IDs – size, depth of ID features; testing of sonar with ID mockups and various ranges and angles

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