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Maintaining Continuity of Knowledge over Spent Fuel Pools- IR Imaging

September 2017

MR MacDougall
JM Benz

U.S. DEPARTMENT OF ENERGY

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

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Richland, Washington 99352

Abstract

This report highlights the experiments performed by Pacific Northwest National Laboratory and Oregon State University at their Testing, Research, Isotope, and General Atomic (TRIGA) test reactor. The objective of these experiments correspond to the broader project objectives to evaluate technologies to supplement current IAEA Containment/Surveillance (C/S) measures to maintain Continuity of Knowledge (CoK) over a spent fuel pool in low or no light conditions. As part of this effort, PNNL was tasked with evaluating ex-pool solutions to maintain CoK, e.g. externally mounted cameras. Sandia National Laboratories is a joint collaborator on this project and is focused on in-pool solution to maintain CoK, e.g. ultrasound imaging sonar.

Preliminary analysis in FY16 identified IR and UV as potential solutions to provide surveillance in low and no light conditions. Additional investigations led the project team to select two cameras that operate in the UV-VIS and VIS – IR spectral regions. The experimental results documented in this report highlight the capabilities of these cameras under variable testing conditions at the OSU TRIGA reactor. Specifically the test variables included varying lighting conditions to simulate normal, low, and no light conditions, and varying power levels to simulate spent fuel at multiple burn-up levels to identify thresholds and minimum detectable thermal output detectable by the cameras. The presented results successfully highlight the camera capabilities to meet project objectives.

Contents

Figures

1.0 Project Objectives

To detect and deter the diversion of nuclear material and to maintain confidence in the integrity of previous accountancy measures, the International Atomic Energy Agency (IAEA) applies a variety of techniques to maintain Continuity of Knowledge (CoK) of nuclear materials, equipment, and facilities. For safeguards at power reactors, it is especially important to have effective containment and surveillance (C/S) measures for fuel assemblies within the spent fuel pool. Current IAEA practices rely heavily on visible-range surveillance cameras to monitor the contents of the spent fuel pool; however, these cameras are rendered ineffective if there is a loss of facility lighting. If this occurs, the Agency must engage in a costly process of re-verifying the inventory of spent fuel to ensure that no illicit changes occurred.

2.0 Test Objectives

The purpose of the field test was to evaluate the performance of the COTS SWIR cameras for safeguards applications—specifically, maintaining CoK over spent fuel in poorly illuminated conditions. Conducting such tests was a critical step in determining the usefulness of the COTS technology for maintaining CoK and identifying undeclared changes to the fuel inventory. Testing the technologies in a reactor setting was important for identifying challenges or limitations that may require safeguards-specific adaptations.

3.0 Overview of Test

PNNL evaluated the OWL VIS SWIR and Hawk-216 UV-VIS cameras, and conducted an extensive series of tests. The purpose of the tests was to evaluate the cameras' ability to maintain CoK under varying lighting conditions in an environment that reflects realistic IAEA requirements. Lessons learned in FY16 demonstrated that SWIR alone was not adequate for imaging in-pool due to the high absorption cross section of SWIR wavelengths in water. Therefore, the OWL and Hawk cameras were identified to include visible and ultraviolet, as well as SWIR, sensitivity to overcome the deficiencies seen in FY16. Additionally, the cameras are not ITAR controlled, which was a significant issue identified in FY16.

Building on the high level project objectives, the key indicators of success for these tests include: (1) the ability to detect gross inventory changes, (2) the ability to count assemblies in the pool, and (3) the ability to identify individual assemblies, all in low or no light conditions.

4.0 Expected Outcome

The outcome of the tests were to collect three broad types of data:

- Digital images from the cameras that record relevant information for maintaining CoK (e.g., images that confirm the correct presence of the fuel or reveal signs of diversion). These images will be used to evaluate device performance under different lighting, operational, or installation conditions.
- Observations about challenges, limitations, or implementation issues relating to deployment in a reactor/spent fuel pool setting.
- Evaluation of alternatives to visible-only camera images to record relevant information for maintaining CoK.

From analyzing this information, PNNL expected to be able to measure the camera's suitability for safeguards application and develop and improved idea of what types of factors might affect its successful implementation as a safeguards instrument.

5.0 SWIR Test Equipment

OWL VIS SWIR (OW1.7-VS-AC s/n 10007)- The OWL SW1.7 CL-640 is a rugged, high sensitivity digital VIS-SWIR camera. Using a 640 x 512 InGaAs sensor from SCD the OWL enables high sensitivity imaging from 0.4µm to 1.7µm. The 15µm x 15µm pixel pitch enables highest resolution VIS-SWIR image and with less than 50 electrons readout noise the OWL 640 enables the highest VIS-SWIR detection limit. The full QE curve is shown below in Figure 1.

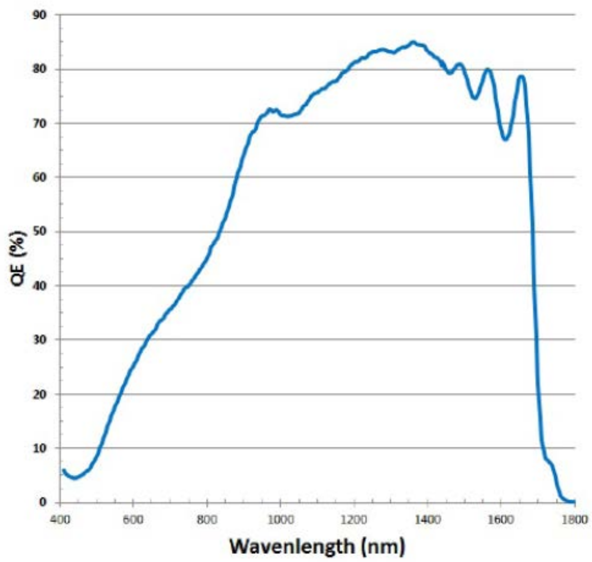

Figure 1: OWL 640 and QE Curve

Hawk-216 (HK216-AN s/n 20004). This device offers comparable performance to Gen III Image Intensifier cameras. Using a back-illuminated sensor from e2v, this 2/3″ full frame transfer camera offers a resolution of 625 TV lines, a frame rate up to 30 Hz and a dynamic range of 55 dB. It enables high sensitivity imaging (<50 flux), using smaller pixels for improved image resolution. With a peak QE of 90% (at 500 nm) it also offers enhanced UV response from 180nm. The full QE curve is shown below in Figure 2.

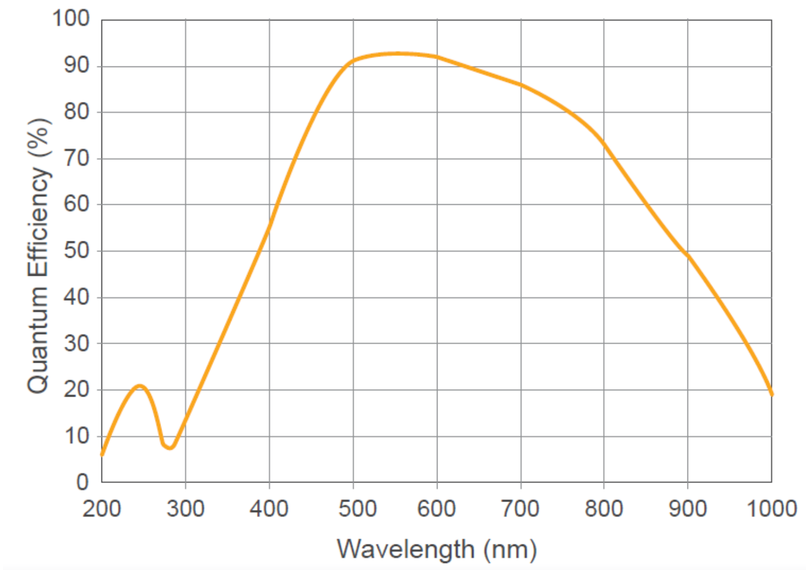

Figure 2: Hawk 216 and QE Curve

Describe the equipment purchased or rented, and any other relevant test equipment.

In conjunction with the cameras, one varifocal lens will be used: the Kowa 9-90mm varifocal F1.8 DC D/N Lens. This lens enables the camera to have a variable zoom and focus such that the bottom of the reactor pool can be focused on.

Lastly, as the cameras are operated in an analog matter, they will be connected to a laptop with an analog video/picture capture frame grabber to record images while the experiments are taking place.

6.0 OSU TRIGA Facility Information and Test Equipment Layout

The tests will occur at the reactor core and the irradiation facility of the Oregon State University TRIGA Reactor (OSTR), depicted in the images below.

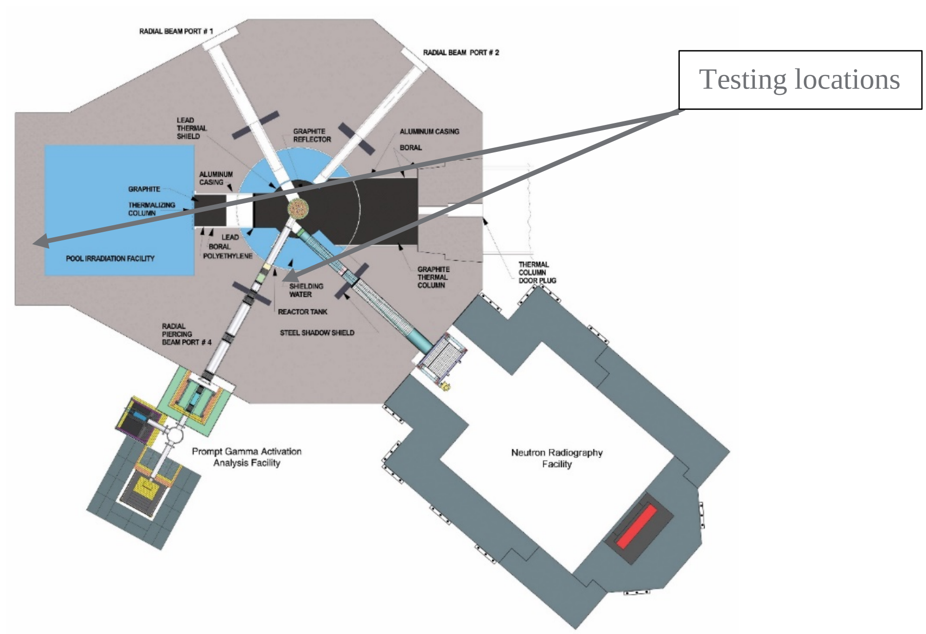

Figure 3: Diagram of the Oregon State TRIGA Reactor.

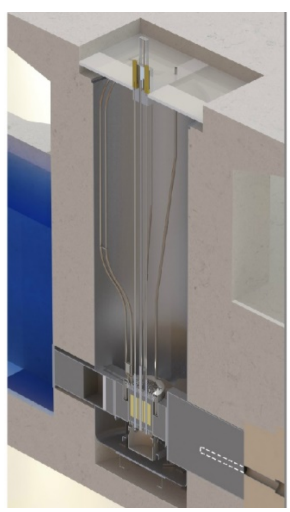

Figure 4: Horizontal Cut of the Reactor Core

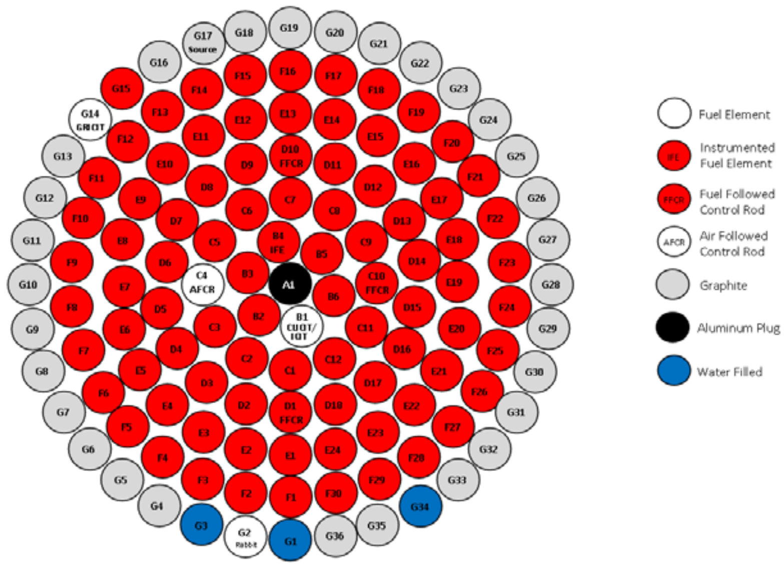

Figure 5: OSU TRIGA Core Grid

The OSTR is a water-cooled, pool-type research reactor that uses uranium/zirconium hydride fuel elements in a circular grid array. The reactor is licensed by the USNRC to operate at a maximum steady state power of 1.1 MW and can also be pulsed up to a peak power of about 2000 MW. The most important responsibility of the OSTR is to support Oregon State University's academic programs. Representative neutron flux values for different energy ranges are described in the table below.

OSTR Irradiation Facility Neutron Flux ($cm^{-2} s^{-1}$)

	Rotating Rack (Lazy Susan)	ICIT	CLICIT	Pneumatic Transfer (Rabbit)	GRICIT (CLICIT Core)	GRICIT (ICIT Core)	Thermal Column	Neutron Radiography Facility
Thermal (<0.5 eV)	3.85E12 ± 4.89E11	9.96E12 ± 1.95E12	4.81E09 ± 3.42E09	1.73E13 ± 3.03E12	7.08E12 ± 1.37E12	9.10E12 ± 1.54E12	2.51E11 ± 3.26E10	4.41E06 ± 2.90E03
Epithermal (0.5 eV to 100 KeV)	1.95E12 ± 6.78E11	2.23E13 ± 8.11E12	2.17E13 ± 6.44E12	5.91E12 ± 2.03E12	5.22E12 ± 1.70E12	6.74E12 ± 2.23E12	5.62E08 ± 2.03E08	6.77E04 ± 3.60E02
Fast (w00 keV to 10 MeV)	1.90E12 ± 3.97E11	2.51E13 ± 4.75E12	2.47E13 ± 4.63E12	5.37E12 ± 9.52E11	6.34E12 ± 1.17E12	6.84E12 ± 1.30E12	2.47E08 ± 5.56E07	—
Corrected values (11/7/14)								

7.0 Test Activities and Results

The data presented represents the results of a number of different OSU reactor and reactor bay configurations meant to simulate a variety of real-world conditions which may pose a challenge to maintaining CoK over a spent fuel pool. These configurations vary lighting, core configuration, and power level.

- Lighting: Full lights (both bay and core), bay lights on and core lights off, bay lights off and core lights on (infrequently used), and all lights off.
- Core configurations: standard operating configuration and a modified core configuration where one element (G12) was moved to an exterior rack (X rack), See Fig. 5.
- The power levels: Initial start-up (15W), 10% power (100 kW), 50% power (500 kW), and 100% power (1 MW). Additionally, the transitions between these levels were recorded. The cameras used within this experiment were the HAWK (UV-IR spectrum) and the OWL (VIS-IR spectrum).

The results below are organized via power level.

7.1 Standard Operating Configuration

7.1.1 Initial Reactor Startup Power (15 W)

The first configuration was the very lower core power scenario. As this was the absolute lowest power the core could maintain, it was expected that the cameras would see very little if any signal at all. Additionally, as the TRIGA core uses a U-Zr fuel around 20%, the heat signature was expected to be quite low.

7.1.1.1 All Lights On

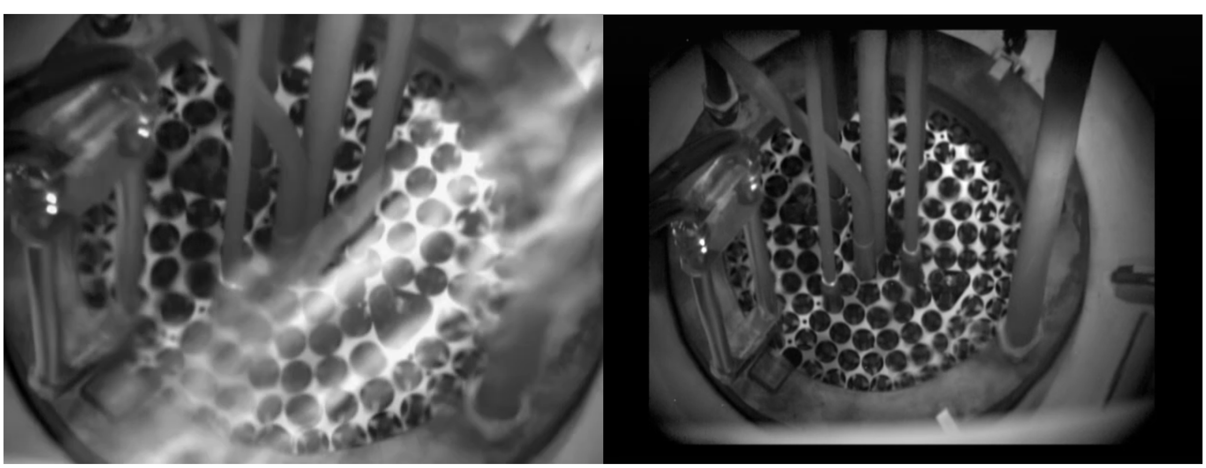

Figure 6: HAWK (Left) and OWL (Right)

7.1.1.2 No lights

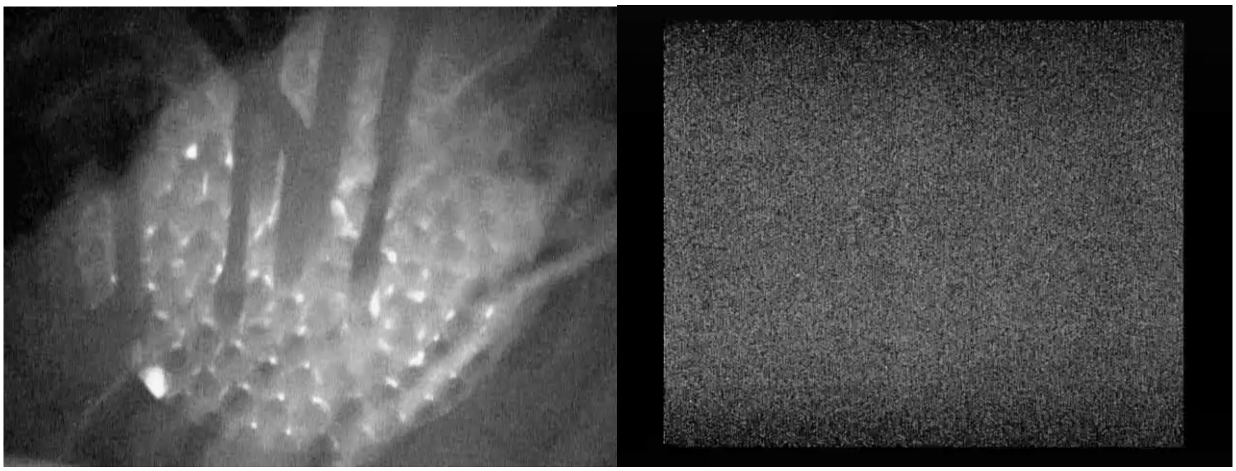

Figure 7: HAWK (Left) and OWL (Right).

7.1.2 Low Power (10%, 100 kW)

7.1.2.1 All Lights On

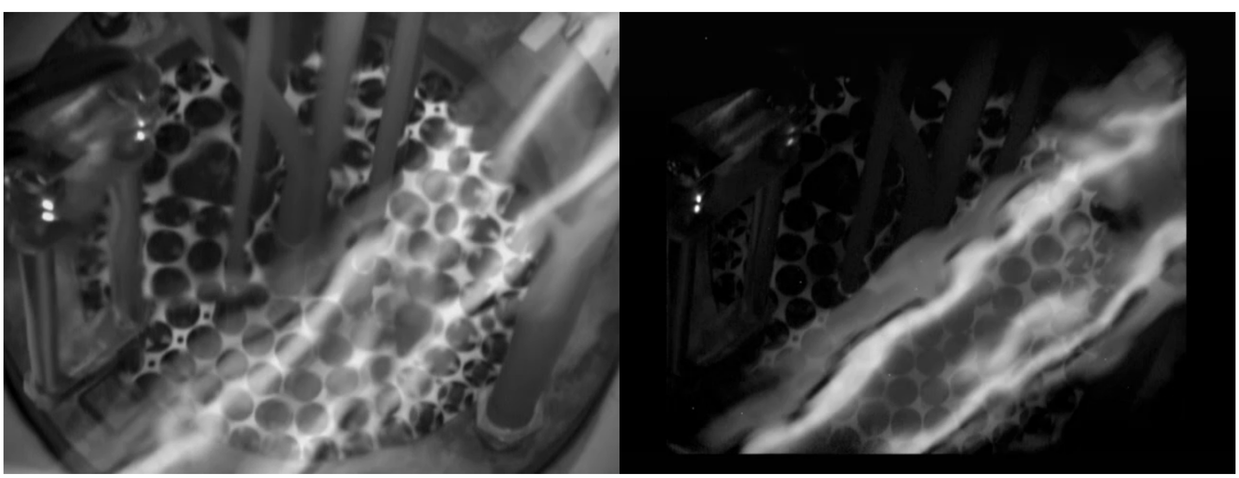

Figure 8: HAWK (Left) and OWL (Right)

7.1.2.2 Bay Lights On Only

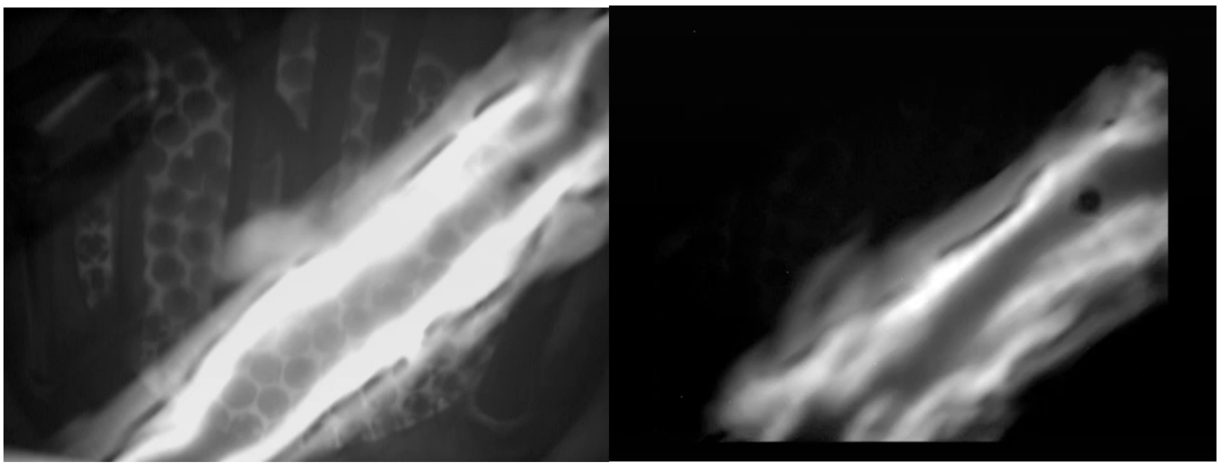

Figure 9: HAWK (Left) and OWL (Right)

7.1.2.3 No Lights

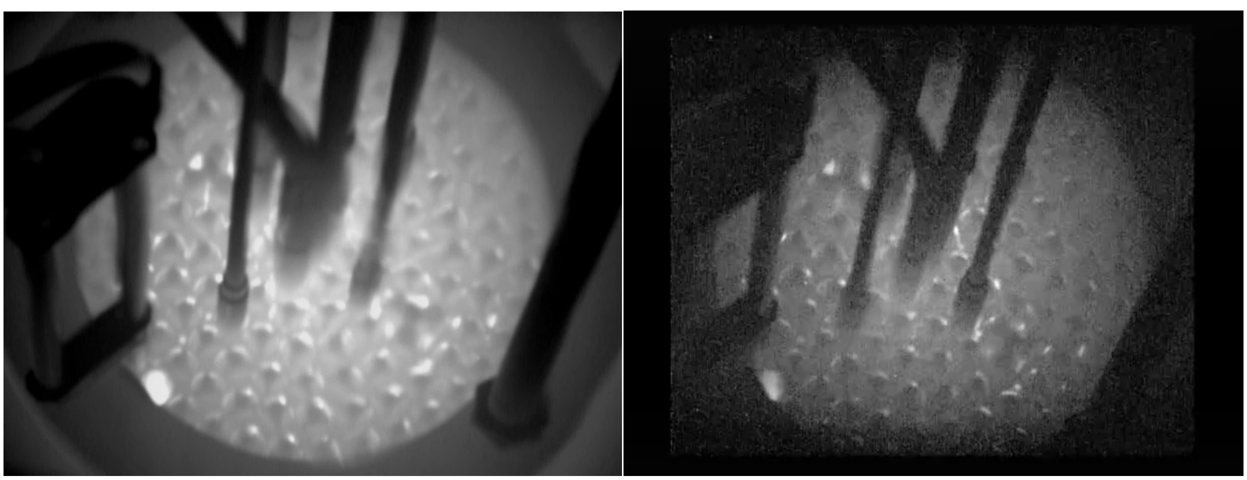

Figure 10: HAWK (Left) and OWL (Right)

7.1.3 Medium Power (50%, 500 kW)

7.1.3.1 All Lights On

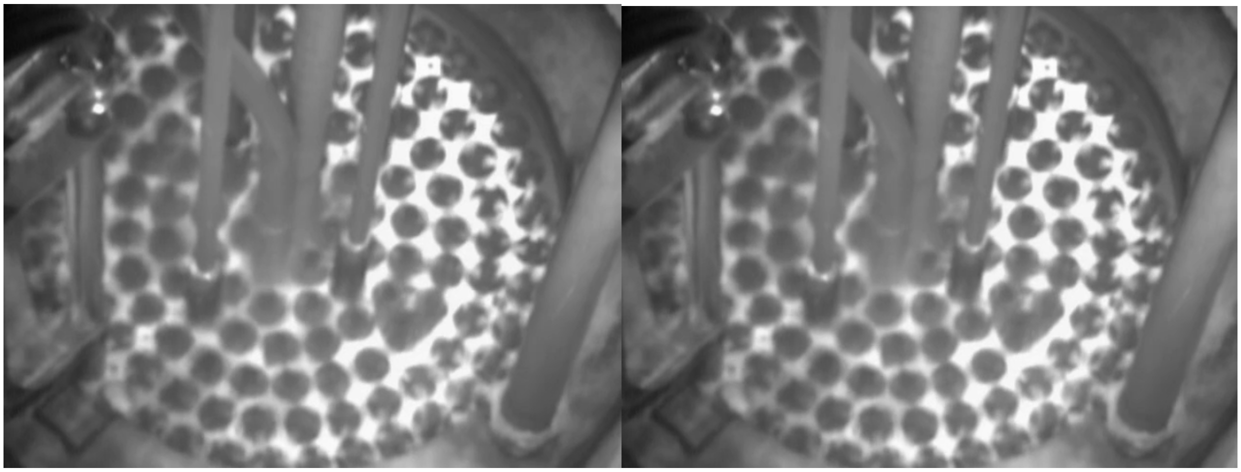

Figure 11: HAWK (Left) and OWL (Right)

7.1.3.2 Bay Lights On Only

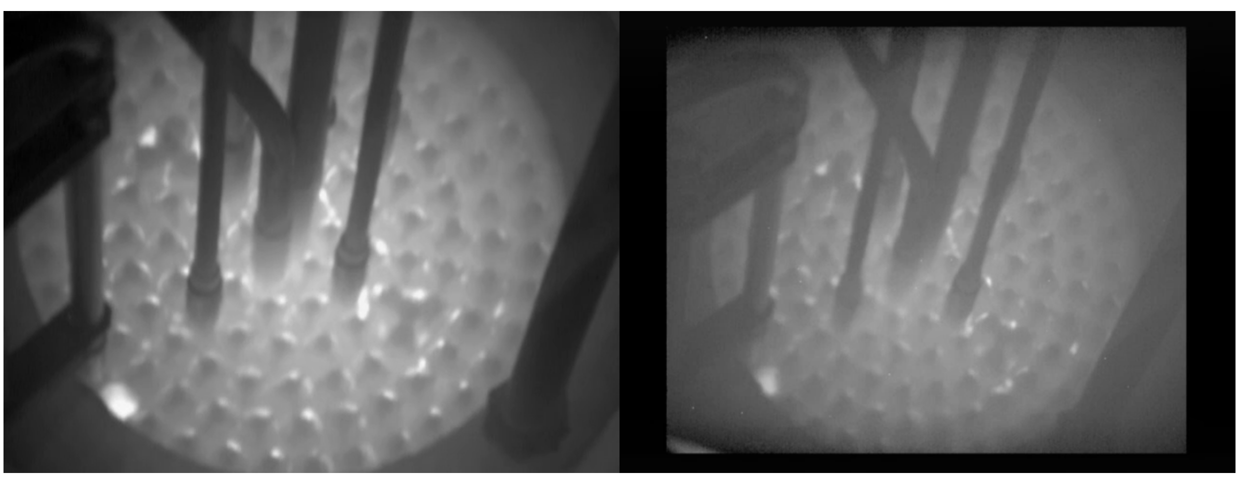

Figure 12: HAWK (Left) and OWL (Right)

7.1.3.3 No Lights

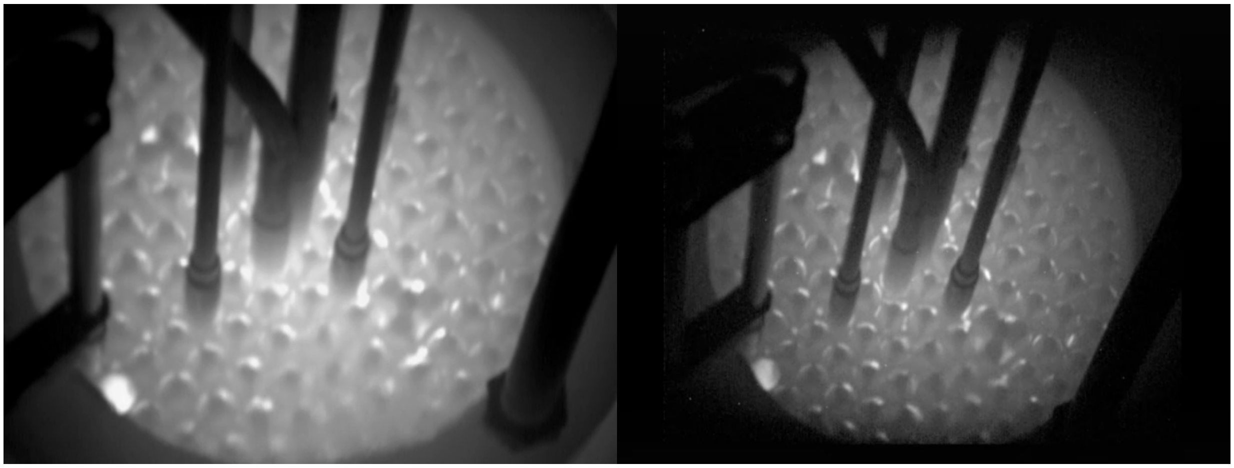

Figure 13: HAWK (Left) and OWL (Right)

7.1.4 Full Power (100%, 1 MW)

7.1.4.1 All Lights On

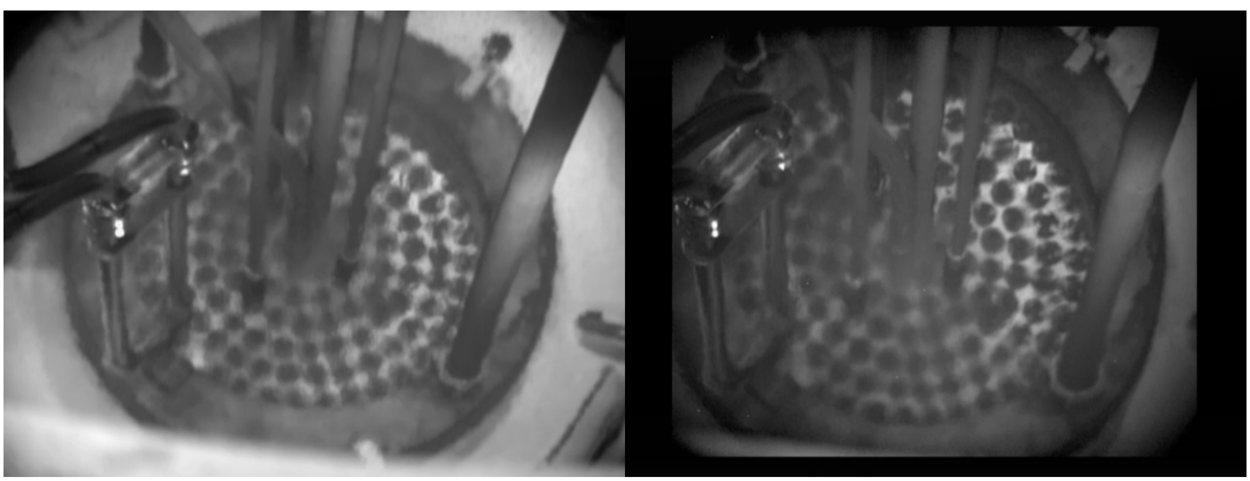

Figure 14: HAWK (Left) and OWL (Right)

7.1.4.2 Bay Lights On Only

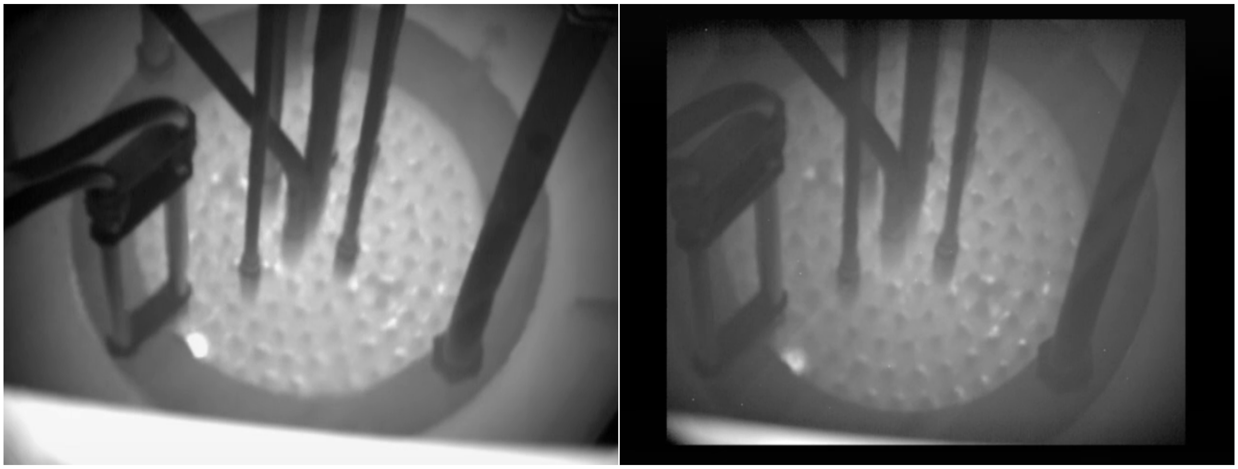

Figure 15: HAWK (Left) and OWL (Right)

7.1.4.3 No Lights

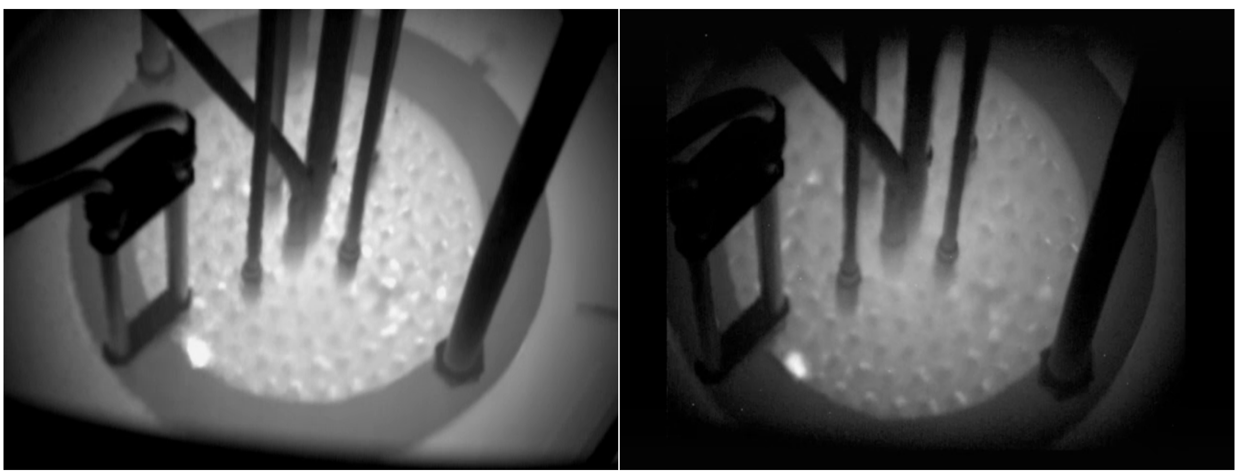

Figure 16: HAWK (Left) and OWL (Right)

7.2 Modified Core Configuration

7.2.1 15 kW

7.2.1.1 All lights on

Figure 17: 15 kW HAWK Zoomed Out with all lights on

7.2.1.2 Bay Lights on

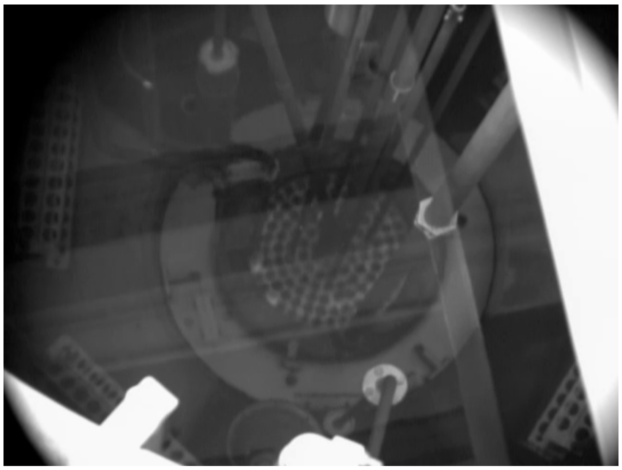

Figure 18: 15 kW HAWK Zoomed out with Bay lights on

7.2.1.3 All Lights Off

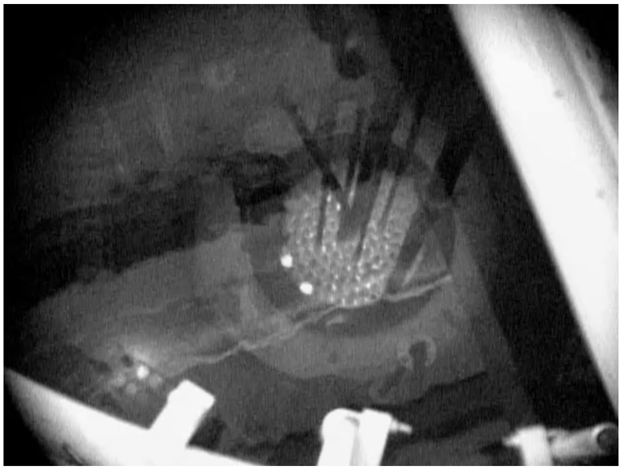

Figure 19: 15 kW HAWK Zoomed Out with all lights off.

7.2.2 100 kW

7.2.2.1 Bay Lights On

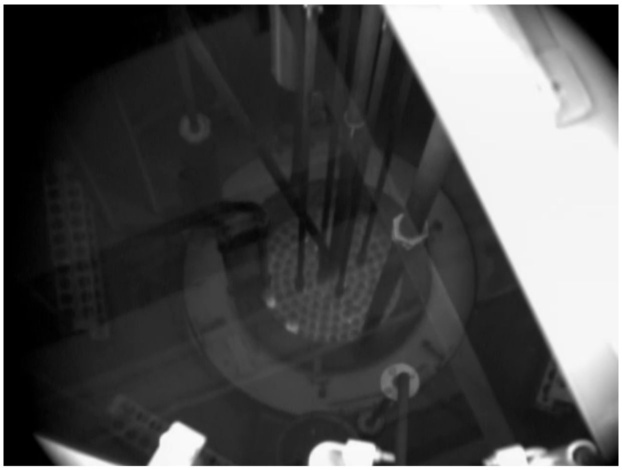

Figure 20: HAWK Zoomed out with Bay lights on.

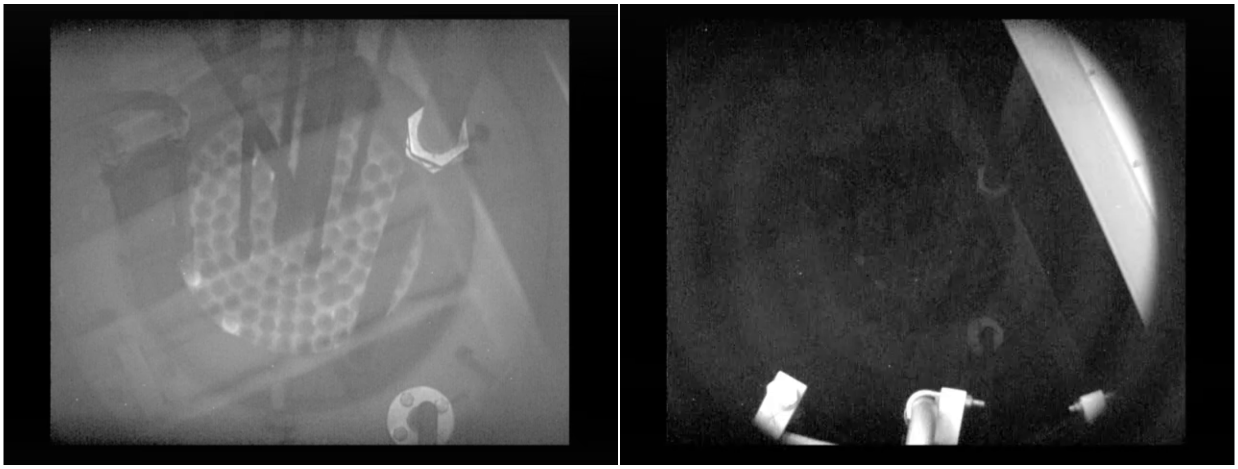

Figure 21: OWL Zoomed In (left) and Zoomed out (right)

7.2.2.2 All Lights Off

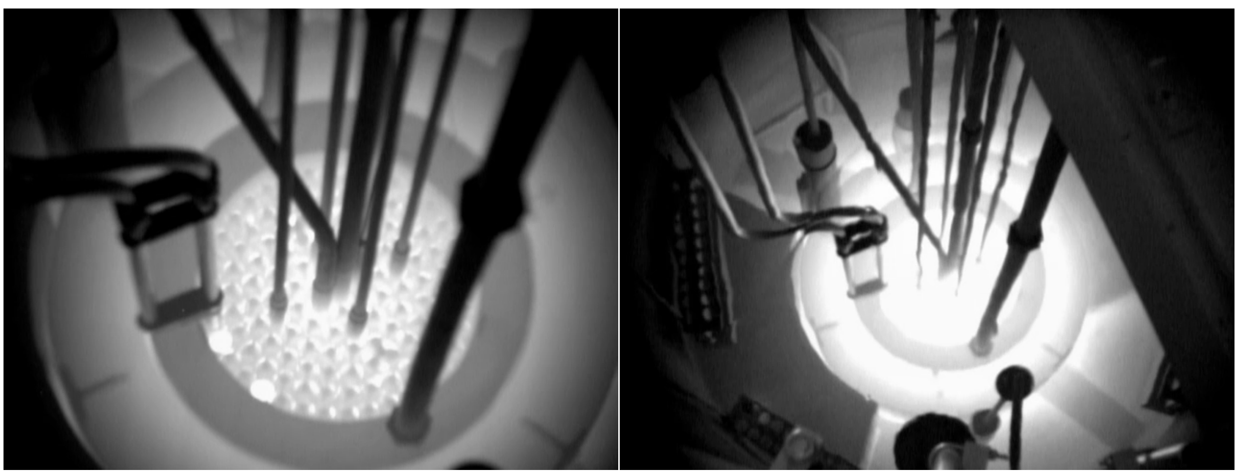

Figure 22: HAWK Zoomed In (left) and Zoomed Out (right)

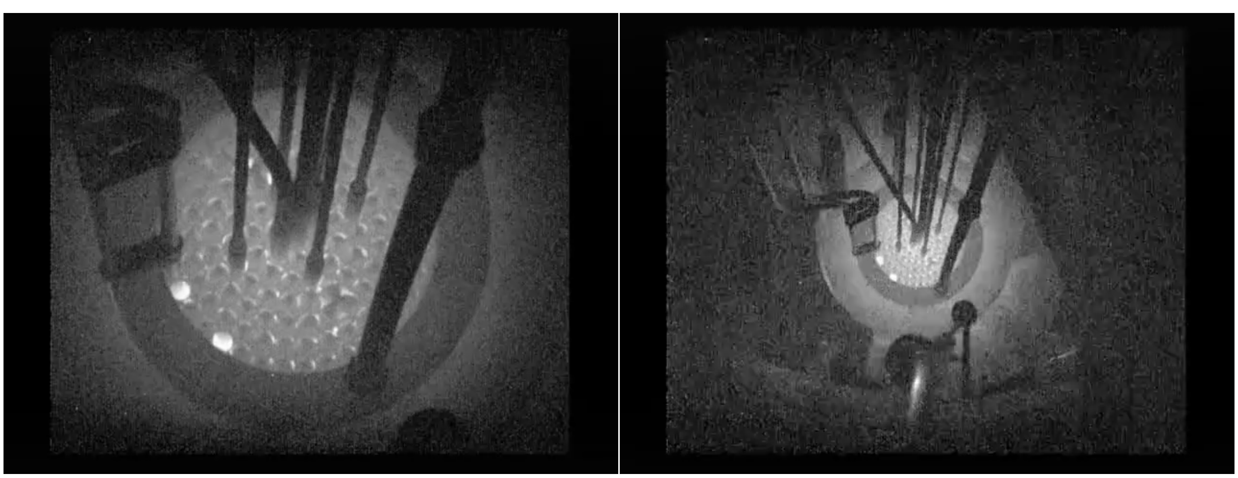

Figure 23: OWL Zoomed In (left) and Zoomed Out (right)

7.2.3 500 kW – No Pictures Due to time limitations

7.2.4 1 MW

7.2.4.1 Bay Lights On

Figure 24: HAWK Zoomed In (left) Zoomed Out (right)

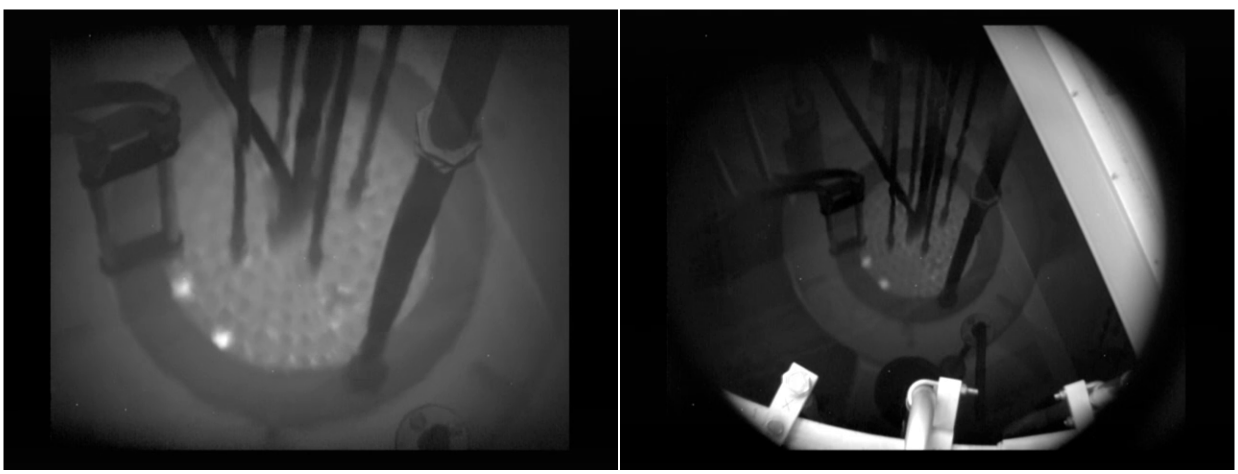

Figure 25: 1 MW OWL Zoomed In (left) Zoomed Out (right)

7.2.4.2 All Lights Off

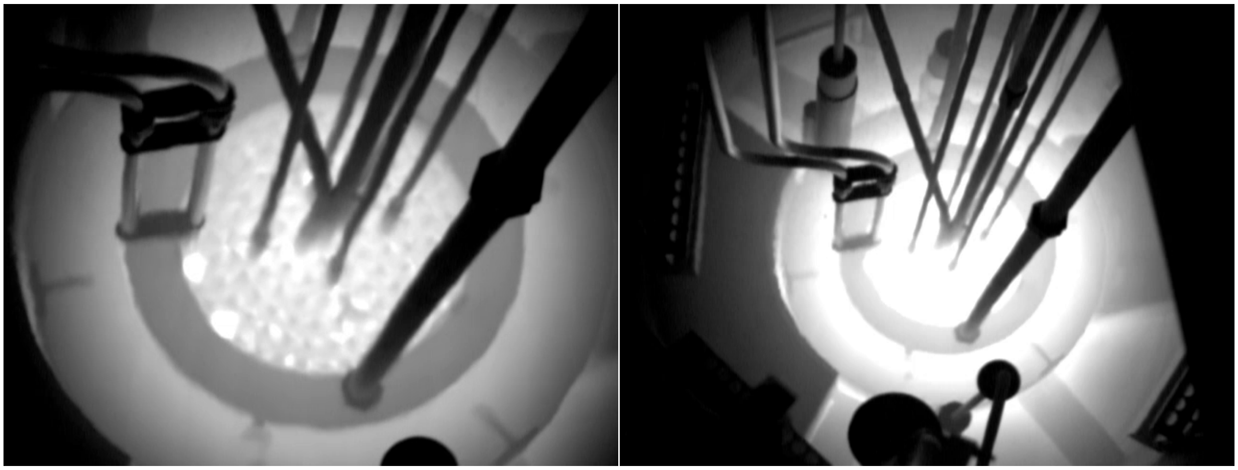

Figure 26: HAWK Zoomed In (left) Zoomed Out (right)

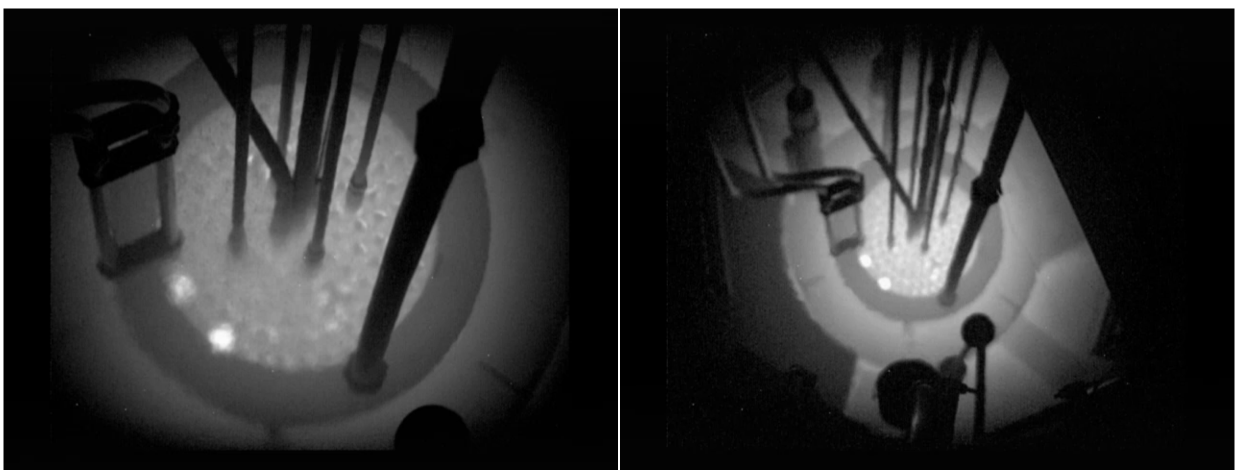

Figure 27: OWL Zoomed In (left) Zoomed Out (right)

8.0 Conclusions and Next Steps

- Both HAWK and OWL cameras performed well and were able to distinguish and count individual fuel elements and detect removal of an element at very low power levels and across a wide range of power levels. To tie this to monitoring a spent fuel pool, the sensitivity and resolution of the cameras should be adequate to count spent fuel assemblies in the pool in all lighting conditions and detect the removal of as few as one assembly over a wide range of potential spent fuel burn-ups and/or in the presence of multiple burn-up fuel assemblies.
- The OWL camera was better able to resolve images of core elements when the TRIGA was operated at high power levels. When monitoring a spent fuel pool, this capability may allow the OWL to maintain continuity of knowledge over a wider variety of conditions and pool configurations that the IAEA may encounter.
- At the lowest power level, the HAWK was able to resolve the core elements and clearly capture difference between an element in-core and removed with the lights off.
- The sensitivity of the cameras in the UV or IR as well as in the VIS portion of the spectrum provides a unique ability to maintain surveillance in both normal and off-normal lighting conditions.
- The cameras only stream video. Capturing images required a separate tool, COTS piece of software, and a laptop. There is no camera-specific software. This presented challenges to capturing data.
- The lighting reflections off of the pool created unexpected challenges for the cameras. This would need to be taken into consideration for future experiments or field-testing.
- The test results demonstrate the capability to successfully achieve 2 of the 3 project objectives – detect gross diversion of fuel assemblies and count fuel assemblies in a spent fuel pool.
- Given the out of pool location of the cameras, it would be impossible to uniquely identify fuel assemblies. Therefore, this particular type of technology cannot perform assembly accounting within a spent fuel pool.
- Given the success of the test at OSU, future work should include a field test at an operating spent fuel pool to perform in-situ monitoring of actual fuel assemblies to validate the results presented here.
- Future work should also include the development of an image capture and data authentication program to convert the camera output video to something useful for international safeguards.

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