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OPTIMIZING IN-BAY FUEL INSPECTION CAPABILITY TO MEET THE NEEDS OF TODAY'S CANDU FLEET

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ABSTRACT – With the recent return to service of many CANDU units, aging of all others, increasingly competitive energy market and aging hot cell infrastructure – there exists now a greater need for timely, cost-effective and reliable collection of irradiated fuel performance information from fuel bay inspections. The recent development of simple in-bay tools, used in combination with standardized technical specifications, inspection databases and assessment techniques, allows utilities to characterize the condition of irradiated fuel and any debris lodged in the bundle in a more timely fashion and more economically than ever. Use of these tools and "advanced" techniques permits timely engineering review and disposition of emerging issues to support reliable operation of the CANDU fleet.

Introduction

CANDU utilities typically complete in-bay inspections to characterize the condition of fuel on anywhere from 20 to 500 bundles in a year. Bundles are selected for inspection for any number of reasons – with general surveillance, monitoring compliance with the operating envelope, and follow-up on any operational events or conditions being typical motives for most stations. The in-bay inspection processes employed by many CANDU utilities to complete these inspections have been presented in previous proceedings [1], [2]. The intent of this paper is to elaborate on a few specialized techniques developed across the industry to allow for a more detailed underwater inspection of irradiated CANDU fuel and highlight the benefits this provides to those groups tasked with fuel performance assessments.

1. Selecting bundles for inspection

According to local governance requirements, at the beginning of each year operating stations develop an annual plan which specifies a range of inspection objectives with known criteria for choosing bundles for inspection. Typically, utilities will select bundles for inspection if they meet certain criteria:

- Generic surveillance (random sampling of irradiated bundles)
- Operating close to the allowable envelope of in-core conditions
- Bundle is suspected of containing a defected element (based on ^{131}I releases in th PHTS)
- Bundle is related to an operational or manufacturing event

The majority of bundle inspections tend to be completed mainly for surveillance purposes, however the inspection plans also include allowances for investigative-type inspections. Depending on the nature of a defect or operational event, the scope of inspections to be done for any channel or unit can increase quickly. Figure 1 below demonstrates how a well-planned inspection strategy will be balanced between sampling bundles which have experienced bounding conditions (e.g., power & burnup) and accounting for a complementary random sample in any given CANDU unit.

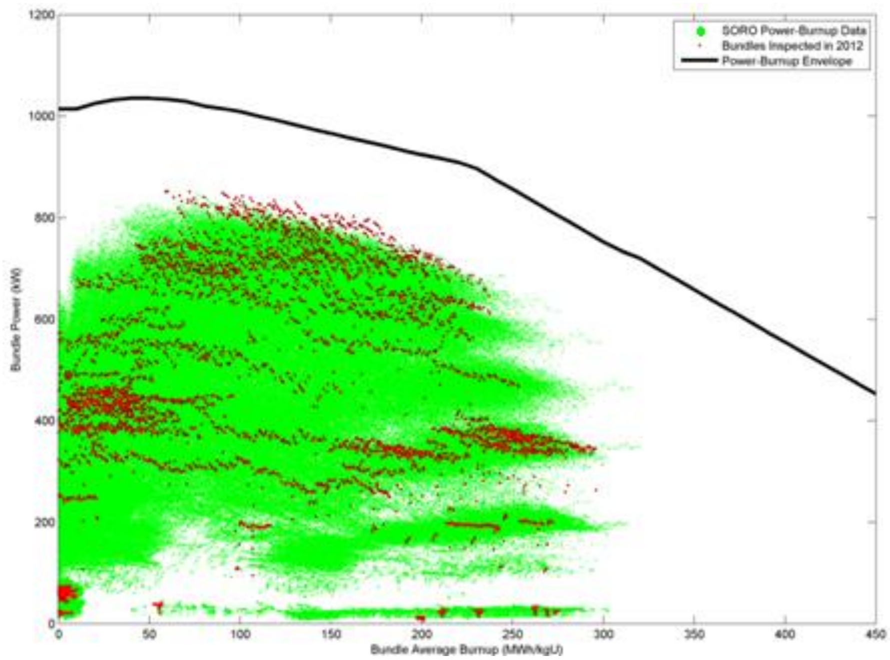

Figure 1 – An Example of Power-Burnup Data Relating the Distribution of Bundles Inspected during the Year (Red) to the Total Population of Bundles Irradiated during the Year (Green) for a Given CANDU Unit. Each data point represents one SORO state for an individual bundle.

Irradiated fuel inspection is a process whereby trained technologists provide consistent and prescribed sets of observations on the post-irradiation condition of the fuel bundles using visual benchmarks and techniques. This generates semi-quantitative data, which is calibrated and verified by quantitative measurements in hot cells (on a small selection of inspected bundles). The inspections provide information on the condition of the bundles during in-core service, which lends itself to several purposes:

- Verifies that fuel operating conditions are within the design basis limits
- Provides indirect information on the condition of the heat transport system, fuel channels, and fuel handling system
- Provides a statistical measure of the condition of fuel in the core to verify that it is within the range assumed by safety analysis at the start of an accident
- Provides information to support incident investigations
- Provides information to determine the root cause of fuel defects
- Provides input for fuel channel selection for pressure tube inspections

2. The underwater fuel inspection process

Fuel inspection technologists monitor the movement of a fuel bundle to and from the inspection platform (also known as the bundle manipulator, or rotator, Figure 2). The inspection then consists of the following sequential steps [1]:

- recording (with a photo) of the bundle serial number
- determining and recording the direction of coolant flow along the bundle (if possible)
- detailed inspection (and mapping as required) of both endplates and visible endcap surfaces
- detailed inspection of all visible surfaces of each fuel element (element-by-element)
- inspection and recording of any features, as required:

  - assembly weld integrity
  - debris fret marks
  - bearing pad wear
  - bearing pad crevice corrosion
  - spacer pad interlocking
  - mechanical interaction marks
  - element sheath integrity
  - spacer pad wear
  - endplate integrity
  - endplate wear
  - local sheath collapse
  - sheath corrosion
  - deposits
  - spacer sleeve / burnish mark interactions

Inspection observations are recorded on inspection sheets, which include hand drawn sketches of artifacts selected from a pick list, accompanied by written comments and photographs of key observations.

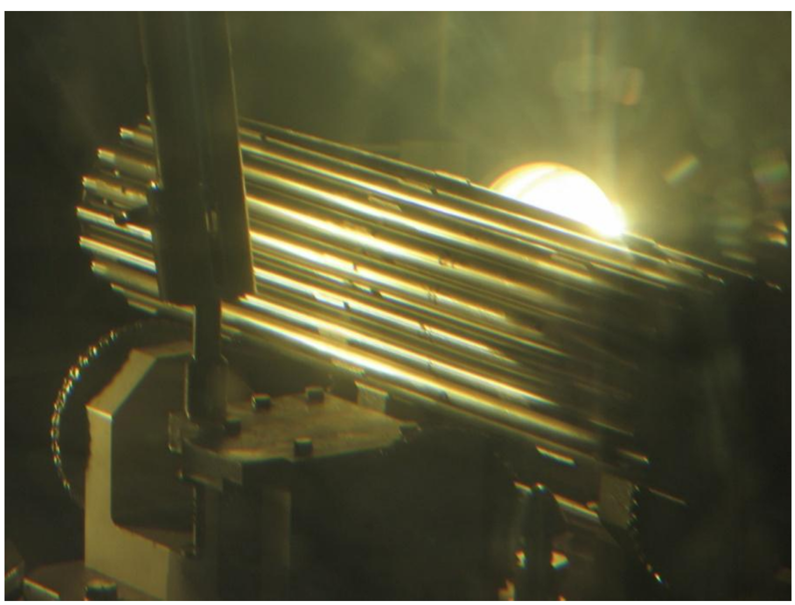

Figure 2 – A CANDU Fuel Bundle on the Underwater Inspection Platform

3. More recent, "advanced", techniques

The above summary describes the process that is followed to complete inspections on the vast majority of fuel bundles inspected in any given year. However, there are circumstances where engineering and safety groups require additional information – necessitating the use of some "advanced" techniques. A few of these advanced techniques, some of which inspectors have perfected over time, and others which have only been used in mock-up trials to date, are summarized below.

3.1 Viewing the interior of the bundle – no disassembly required

The 'standard' underwater fuel inspection provides a view of the bundle's outer envelope (i.e., the bundle's outer elements and end plates); however, limited information can be obtained about the condition of the bundle's insides. Granted, a partial view of most intermediate elements is available – however, the inner ring and centre element are essentially out of view. This becomes problematic when analysts and engineers are interested in collecting data which pertains to the bundle's cricitcal (i.e., CHF) inner subchannels, for example:

- determining whether inner spacer pads are interlocked
- determing the extent of wear on inner spacer pads
- determining whether inner subchannels contain debris

Obtaining such information has traditionally required that a bundle be disassembled in the irradiated fuel bay (Figure 3). While these disassemblies are usually possible, they are labor intensive and time intensive and challenging, as elements are removed one-by-one. The work requires the utmost dexterity, as hand tools are handled using a 20' pole. Further complicating the matter are the material properties of irradiated fuel – often rendering the response of the elements / bundles somewhat unpredictable upon the application of force when torquing the welds to free individual elements. Furthermore, for safeguards purposes, regulatory requirements stipulate that regulatory agencies are to be notified when bundles are disassembled. As such, disassembly of a bundle generally becomes a significant undertaking.

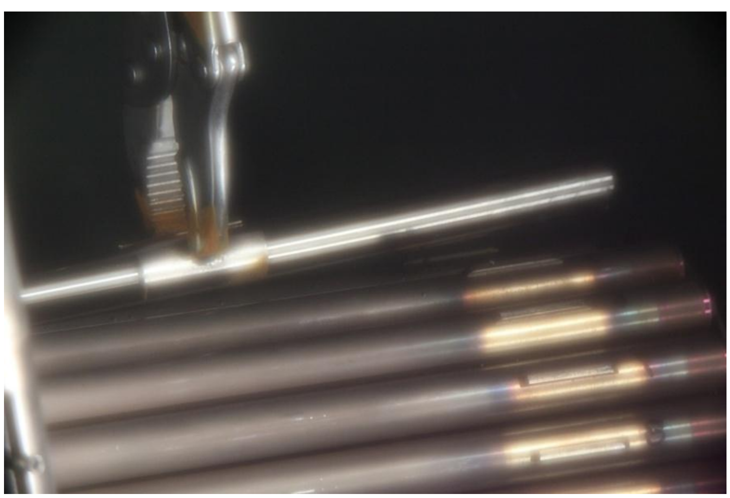

Figure 3 – Irradiated Fuel Disassembly

Luckily, for occasions when the motives for an 'inside view' might not justify the resources associated with disassembly of the bundle, the configuration of the equipment and lighting at the bottom of most irradiated fuel bays allows a glimpse into the insides of the bundle via much easier means. 'Back-lit' inspections simply require that a source of underwater lighting be placed in alignment with the end of the bundle and the viewing device (periscope or underwater camera). Depending on the inspection requirements, inspectors can obtain full views of the bundle (as shown in Figure 4), or zoom in the field of view to characterize any given subchannel with greater precision. While relatively simplisitic, the technique offers a quick and easy way of gaining insight into the behaviour of the bundle's inner regions, and can greatly facilitate decision making during an investigation.

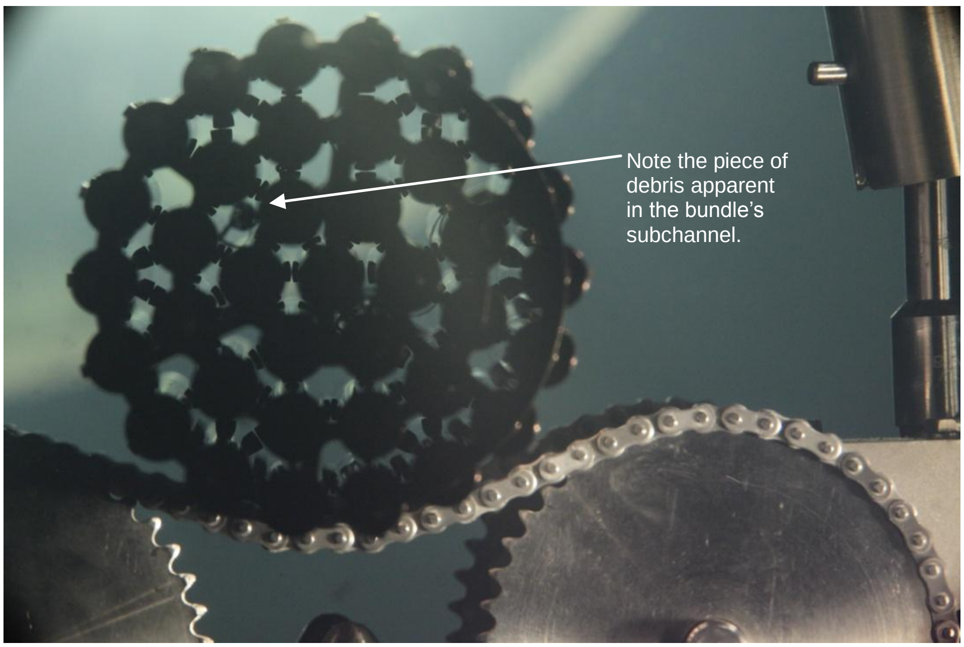

Figure 4 – An Example of a Back-Lit Fuel Inspection Photograph

3.2 Collecting foreign material – an exhibition in dexterity

Debris circulating in the primary heat transport system has been recognized as a threat to many interfacing systems since the early days of CANDU operation. The list of affected areas includes (but is not necessarily limited to):

- fuel – as fretting damage leads to fuel failures
- pressure tubes – as fretting damage can lead to PT flaws
- worker dose – as debris can become activated
- closure plug seals – as debris can become jammed during closure
- fuel handling equipment – as accumulation of debris can cause increased ram drive resistance, leading to increased axial loading required to perform normal functions
- interference with the operation of valves in the heat transport system such as loop isolation valves or emergency core cooling injection valves

As such, the need to mitigate the presence of debris in the primary heat transport system is obvious, and utilities make concerted efforts to sustain highly effective foreign material exclusion (FME) programs. Nonetheless, no prevention effort is perfect. The design of the fuel bundle lends itself to act as a filter in the primary heat transport system for catching this foreign material, and the debris often lodges itself into the fuel bundles. Over the years, the list of items that has been recovered from the coolant (either in fuel bundles or other PHTS locations) has grown, and includes items that would surprise most people. A few of the more common pieces of foreign material observed and/or retrieved from irradiated fuel bundles during inspection include:

- welding slag
- machine turnings (Figure 5)
- wire brush bristles

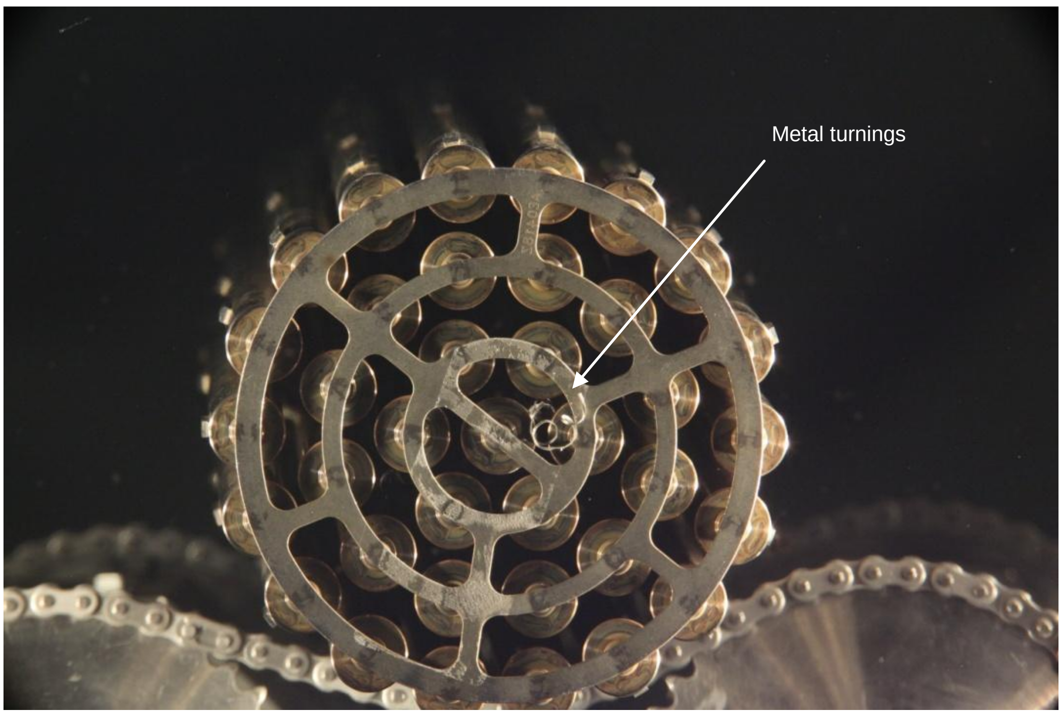

Figure 5 –Debris Caught in a CANDU Fuel Bundle

In some cases, the debris is readily identifiable by visual identification alone. However, in many cases, collection of the debris is critical to its identification, as the debris must be sent to a laboratory for material identification. Stern Laboratories has recently devised a simple basket with a container that is compatible with the existing bundle rotator setup to ensure that debris from the bundles can be collected. By using this, debris that might have otherwise fallen to the bottom of the bay can be collected using tweezers (Figure 6, left). The tools are designed to be used on the ends of manually controlled poles stretching down to the bottom of the bay. The storage container (Figure 6, right) allows for collection of the debris, and makes further inspection possible at a later time if required.

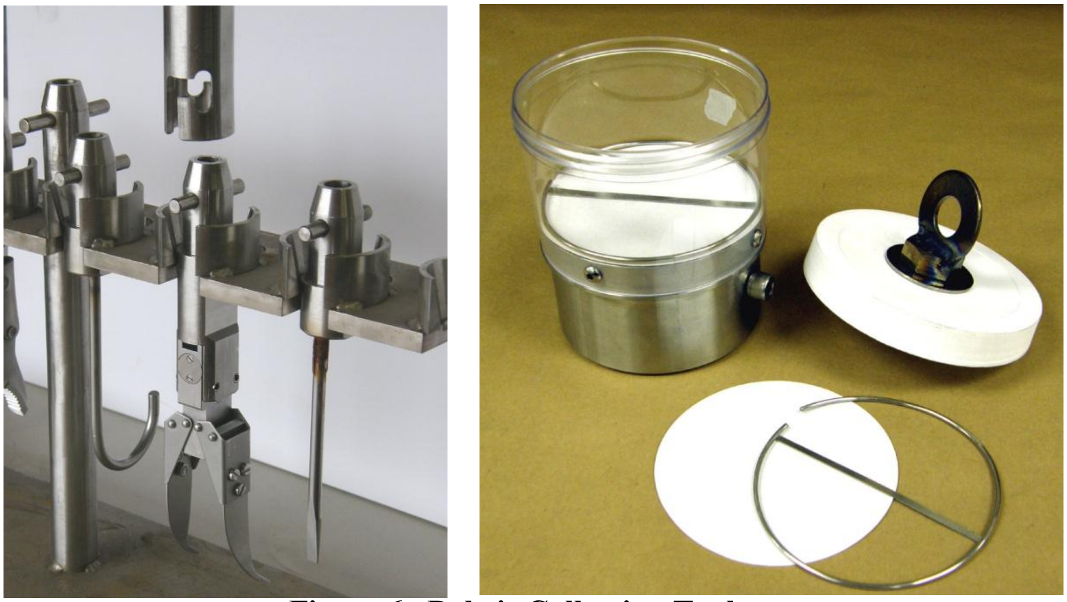

Figure 6 –Debris Collection Toolset
Tweezers (left) and Debris Collection Bottle (Right)

3.3 Unique techniques for atypical PIE shipments

Given the investigative nature of PIE work, and the challenges that accompany handling and transportation of irradiated fuel, it should come as no surprise that some PIE shipments can pose unique challenges. This is particularly the case when it comes to shipping defective irradiated fuel. Defective fuel is usually embrittled, due to secondary deuteriding degradation. If degradation is sufficient, the integrity of the defective elements can be reduced sufficiently to allow elements to break free from the bundle during in-bay inspection or handling. Figure 7 below demonstrates how simple solutions can be used to mitigate such problems and temporarily ‘restore’ a bundle’s geometry.

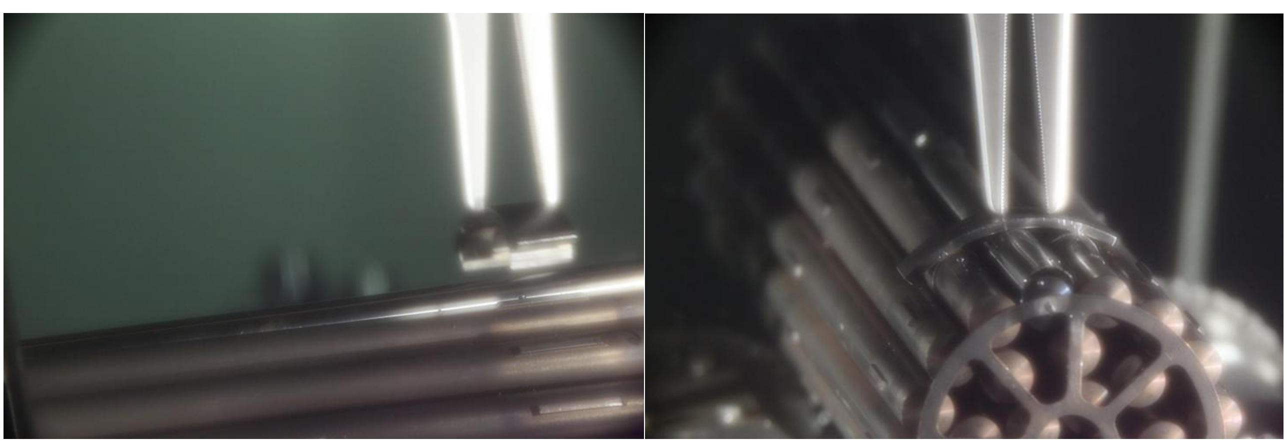

Figure 7 – Application of clips to restrain a defected element into position
for transit to a hot cell facility

The stainless steel clip device shown above is quite simple in design – it is simply two element identification clips welded to a stainless steel band. The clips are spaced apart such that they can be clipped onto the intact elements that neighbour a defective element, and the stainless steel band ensures that the defective elements is restrained in place. The technique allows normal handling and loading of a bundle into the shipping can and irradiated material transport flask used to transport bundles from the irradiated fuel bays to hot cell facilities. One should note that the technique can not only be used in cases where an element has come free from the bundle needing shipment, but also as a preventatory measure, in cases where defective elements remain attached to the bundle but degradation is sufficient to warrant concerns that transit conditions may jeopardize element integrity.

3.4 Characterizing the bundle's geometry – FEMER

Another recent development has been the design and fabrication of FEMER, or the Fuel Envelope MEasuring Rig (Figure 8). As part of industry-sponsored projects, Stern Laboratories has developed this tool, capable of measuring the outer dimensions of irradiated fuel bundles in the bays at the stations - a task which had previously been possible using hot cell profilometry equipment. The tool is capable of measuring:

- Bundle diameter
- Element spacing (radial & transverse bow)
- Element diameter
- Bearing & spacer pad height (wear)
- Bearing pad angular position
- Bundle length
- End plate profiles (parallelograming, doming, broken or cracked webs)

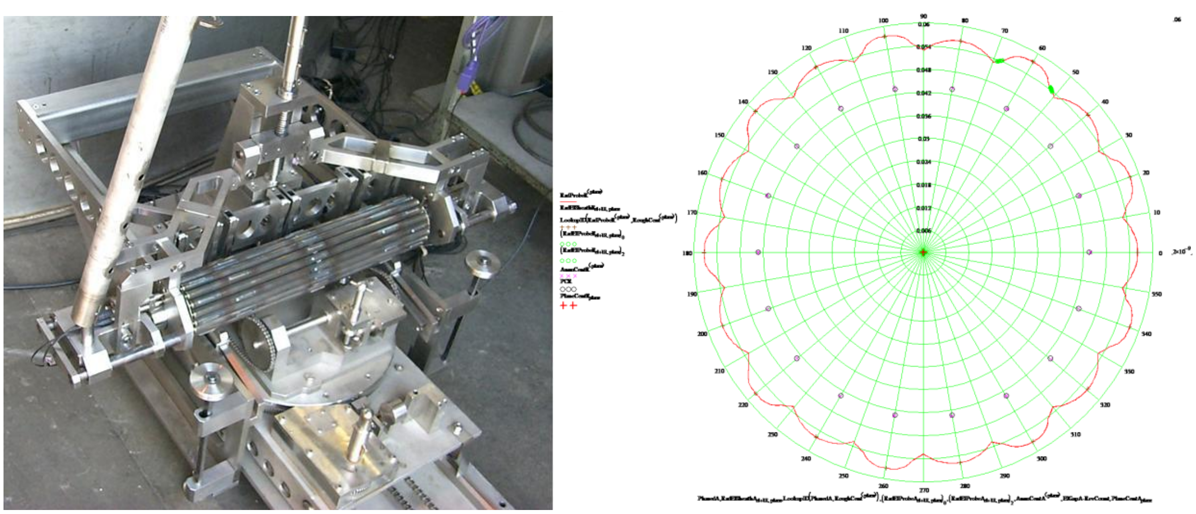

Figure 8 –FEMER Attachment to the Fuel Inspection Platform (left) and Sample Measurment Output (right)

The data that FEMER is capable of providing would help quantify fuel bundle creep behaviour – data which lends itself to multiple purposes:

- accident scenario analysis,
- understanding of long-term-storage behaviour,
- assessment of incidents (axial loading of bundles, etc)
- core aging assessments

FEMER is fully automated, and completes a full bundle scan in approximately two minutes. Stern Laboratories has successfully used FEMER scans during out-reactor testing campaigns to support the qualification of new fuel designs.

Eventual use of this tool would allow CANDU utilities to collect more data in the irradiated fuel bays to determine the operating condition of the fuel. It would also ultimately reduce the work load on the hot cell facilities - in turn enabling hot cells to conduct more quantitative verification through the completion of destructive testing on fuel shipments.

3.5 Improvements in imaging techniques and visual inspection quality

Underwater fuel inspections are completed in what has been called by some – 'the worst possible place to take a picture'. Bundles are inspected on a platform, under approximately 20' of water, under relatively dark conditions. However, given that the photographs taken by inspectors often offer the only glimpse that analysts or engineers will have of the bundle, the importance of obtaining quality photographs cannot be underestimated. Recent advancements in the field have allowed continued improvements in the quality of underwater inspection photography.

Stern Laboratories has developed a Light Pipe (Figure 9), which consists of a tube with a mirror on the bottom, and a camera with a long telephoto lens mounted at the top, aimed directly down at the mirror. The mirror is remotely actuated, with three degrees of freedom (pan, tilt and lift). The system allows inspectors to perform their work from any location on the platform, instead of being arched over the periscope or camera mast handles. As listed below, the design leads to many obvious added benefits:

- With the camera being mounted on the assembly above the water level in the fuel bay, the longevity and interchangability of the camera is greatly enhanced. Picture quality is only limited by the quality of camera one wishes to utilize. With the use of a modern, computer-connected camera, the Light Pipe allows users to benefit from advanced imaging techniques, such as:
    - High Dynamic Range (HDR)
    - Automatic Focus Stacking
    - 'Unrolling' of video into images (see Figure 10), which can be used to replace inspection sheets, which are currently completed 'by hand'

- The degrees of freedom to manipulate the mirror at the bottom of the assembly greatly enhances the field of view.

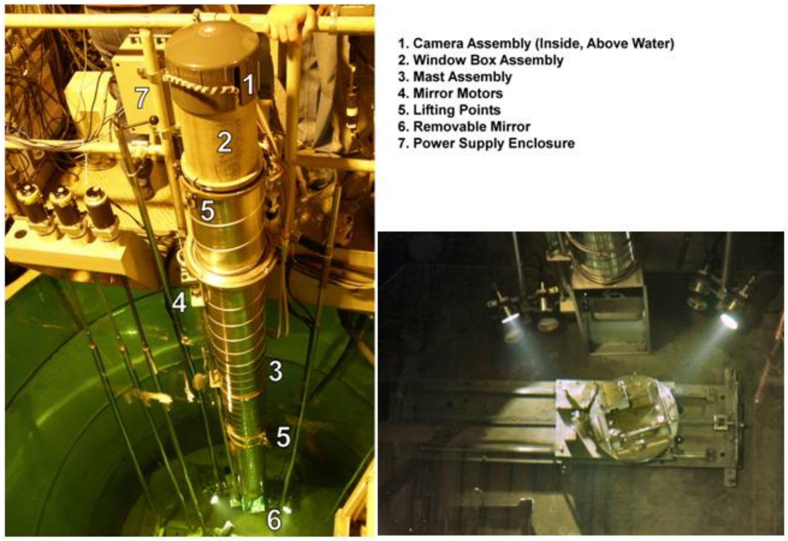

Figure 9 – The Light Pipe

Figure 10 – An Example of the 'Unrolling' of the Video Taken During a Fuel Bundle Inspection. Provides full view of all outer elements.

The light pipe design offers an inexpensive alternative to periscope or underwater camera designs. The light pipe prototype is currently installed in the Fuel Bay Simulator Tank at Stern Laboratories, and has been successfully used in the training of irradiated fuel inspectors and rehearsal mock-ups over the past 5 years.

3.6 Improvements in inspection capacity

One issue that tends to present challenges for inspectors when it comes to achieving annual inspection targets is the availability of fuel handling operators. Fuel inspectors require fuel handling operators to load bundles onto the inspection platform for inspection, and subsequently move them back onto the storage trays afterwards. Depending on site priorities, fuel handling operators are not always available when needed by the inspectors. Therefore, a mini gantry system (Figure 11) was developed at Stern Laboratories to allow fuel inspectors to work more independently, and inspect a larger number of bundles with less frequent need for fuel handling operator support. The system allows fuel handling operators to load the mini gantry with 16 bundles at a time, from which the fuel inspector can transfer bundles to and from the rotator independently - significantly increasing the efficiency of the process. The automated design of the system allows operators to shuffle bundles remotely from their inspection station.

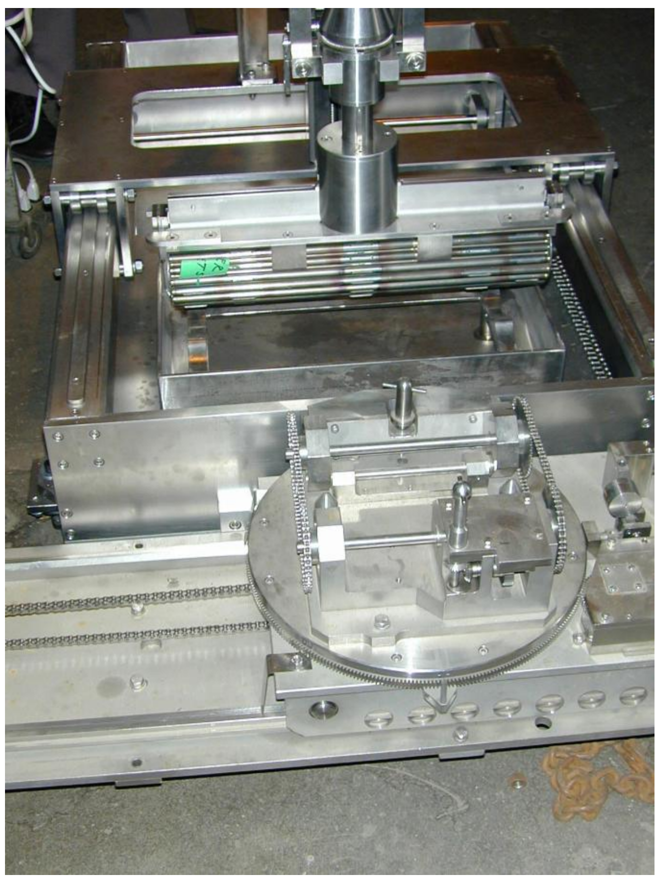

Figure 11 – The Mini Gantry Attachment to the Fuel Inspection Platform

The design also opens up a number of possibilities to increase the complexity and variety of tasks which can be completed under water. The modularized attachment design was developed to allow the use of fine motor control attachments on the mechanism used to transport bundles to and from the rotator. The concept is similar to the robotic arm design used in hot cell facilities. The introduction of such dexterity at the bottom of the irradiated fuel bay opens up a number of possibilities for:

- debris collection
- end plate cutting (for controlled bundle disassembly)
- brushing / scraping of deposits in a more controlled fashion
- hardness testing
- physical dimensioning

4. Benefit to the engineer / analyst

The working environment in the irradiated fuel bays tends to ensure that inspection techniques and equipment are limited to those which are simple and straightforward. Nonetheless, recent advancements in the field, combined with the use of standardized technical specifications, inspection databases and assessment techniques, have enabled stations to characterize the condition of irradiated fuel in greater detail than had previously been possible in-bay. In addition to the 'standard' visual inspection, engineers and analysts can now obtain information on the bundle's inner subchannels, identify foreign material, and characterize a bundle's geometry in-bay – all of which are critical inputs to engineering response to emerging operational events.

5. In conclusion

This paper has briefly summarized CANDU practices in the field of underwater fuel inspection, and communicated a few examples of more recent "advanced" techniques which have proven to be useful and effective. While it is true that 'necessity is the mother of all invention', readers are cautioned to remember that irradiated fuel is to be handled and inspected with care at all times, as the inherent risks require our constant respect and attention. That being said, relatively simple solutions have proven effective.

Please feel free to contact the authors at any time if you would like to know more about how any of the above solutions may be put to work in your fuel bay to meet the needs of your CANDU utility. Thanks for reading.

6. References

[1] Q. Jacobs, "In-Bay Fuel Inspection Processes and Techniques", Proceedings of the 10th International Conference on CANDU Fuel, Ottawa, Ontario, Canada, 2008.

[2] Q. Jacobs, "In-Bay Fuel Inspection Processes and Techniques", Proceedings of the 2010 International Youth Nuclear Congress, Cape Town, South Africa, 2010.