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CANDU FUEL:
Evolution towards Optimal Performance

CANDU DEFECT FUEL BUNDLE TRANSFER PLATFORM

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ABSTRACT – Containment of nuclear material in the CANDU design is most effectively achieved by ensuring the integrity of the fuel bundle cladding is maintained. Recent fuel defects experienced at Ontario Power Generation's Pickering station challenged this principle, triggering an investigation into their underlying cause. This effort was hindered by fundamental limitations in defect locating capabilities, resulting in numerous suspect bundles discharged to fuel bay storage baskets incompatible with the existing retrieval tooling. Recovery of these bundles, crucial to the fuel defect causal analysis, was ultimately achieved through the commissioning of a submersible seismically qualified fuel bundle transfer platform capable of both unloading and re-loading bundles from any existing basket position.

Introduction

In support of Ontario Power Generation's (OPG) nuclear fuel performance commitments at Pickering Nuclear Generating Station (PNGS) and a World Association of Nuclear Operators (WANO) Area For Improvement (AFI), long standing limitations and persistent obstacles faced by the fuel defect inspection program are to be addressed through the development and procurement of specialized tooling. A solution was proposed, based on a similar successful implementation at OPG's Darlington Nuclear Generating Station (DNGS), under which a Fuel Bundle Transfer Platform (FBTP) would be installed within the Irradiated Fuel Bay (IFB) to enable the retrieval and subsequent return of 28-element fuel bundles from any standard irradiated fuel storage basket. This then, would make available all previously inaccessible suspect defect bundles to fuel inspectors for in-bay examination; the results of which are crucial to the fuel defect causal analysis effort.

The project was allotted a strict one year timeframe and procured under OPG's Modification process. Compatibility with existing IFB equipment was essential. Provisions were to be made to accommodate: a fully loaded standard fuel basket (dry weight ~864 kg), a fully loaded modified basket (dry weight ~275 kg), and two temporary storage racks capable of holding six fuel bundles each (total dry weight ~300 kg). Having completed a similar project for DNGS in 2015, Burlington, Ontario based CANTECH Associates Ltd. was contracted to supply the necessary solution. This included the services of two of its senior fuel specialists who share between them approximately 75 years of fuel design, performance, assessment and internationally recognized fuel inspection expertise. Equipment design, fabrication and testing was subcontracted to nearby Stern Laboratories Inc., which has been a fully qualified and accredited supplier of testing and equipment to OPG (formerly Ontario Hydro), the full CANDU community and other clients world-wide since 1988.

1. Background

Pickering's 28-element CANDU fuel bundles, as seen in Figure 1, are fabricated to exacting standards that ensure their integrity is maintained under the harsh conditions to which they are subjected (high temperature, coolant flow, radiation and operational cycling of these parameters). Collectively, the six operating units at PNGS contain 27,600 fuel bundles within 2,300 pressurized channels. Though statistically rare, considering over 17,000 bundles are expended annually at the station, fuel defects have occurred. In-bay inspection results indicate debris induced fretting and manufacturing flaws to be the most prominent cause.

Figure 1 Pickering 28-Element CANDU Fuel Bundle

Pickering's reactors are not furnished with systems capable of locating specific channels within which a fuel defect resides. To this end, Bruce and Darlington generating stations, also operating in southern Ontario, are equipped with Delayed Neutron (DN) and Feeder Scanning (FS) systems respectively. Additionally, these stations have on-line Gaseous Fission Product (GFP) monitoring equipment in place that, when operational, has afforded varying levels of success in defect location. Though never commissioned, Pickering's reactors were originally equipped with FS equipment, and additionally, loop-specific GFP systems, on Units 5-8. The methodology by which in-core fuel defects are detected and managed at Pickering remains largely unchanged since commissioning; relying solely on tracking Primary Heat Transport System (PHTS) fission products (principally I-131) via manual grab samples.

When indications characteristic of an in-core defect are observed, the challenge of isolating them to a specific channel location is exacerbated by the combined effect of continuous, and at times increased, on-power refuelling rates and infrequent (while operating without defects) manually obtained PHTS radiochemistry samples. As a result, it is not uncommon for a resultant suspect defect list to exceed 20 channels among the units 390/380 channels (PNGS 1-4 / 5-8). Re-fuelling of suspect defect channels is performed expeditiously, though not consecutively due to the impact on the nominal fuelling strategy required to maintain core balance and ensure compliance with operational safety limits. Fuelling Engineers (FE's) alert

Operations (OPS) and Fuel Handling (FH) that any bundles discharged from these channels exhibiting defect behaviour (e.g. PHTS activity spike/significant drop, gamma alarm on Units 5-8, positive radiation survey on Units 1 and 4, or high Reactor Building (RB) stack monitor activity) are to be set aside for visual inspection within the irradiated fuel bay.

Pickering Units 1 and 4 rely extensively on the results of manually obtained radiation surveys to trigger specific fuel handling actions required to route defective fuel to the IFB inspection facility. These surveys are requisitioned by FEs and are performed within the accessible area of the RB immediately prior to, and following the re-fuelling of suspect channels. A rudimentary comparison of the results confirms or refutes the presence of a defected bundle. Historically, this method has experienced a mixed level of success due to natural mechanisms at work. For example: post-discharge thermal contraction may be sufficient to constrict continued release of fission products from a very small singular sheath penetration. In this way, confirmation of a defect discharge is heavily reliant on tracing downward PHTS activity curves to a preceding re-fuelling run. By this time however, bundles discharged from within this interval would have been sent to the Irradiated Fuel Bay ‘A’ (IFB-A) for storage in standard irradiated fuel baskets.

Fueling machines and associated transfer equipment are used to send fuel originating from Units 1 and 4 in pairs to the receiving area of the IFB-A. Here they are loaded into one of two storage basket designs: standard or modified. The receiving bay cradle is equipped to handle one basket type at a time and must therefore be staged in advance of any arriving fuel.

Figure 2 Standard Pickering Irradiated Fuel Bundle Storage Basket

The standard Pickering fuel basket holds 32 bundles arranged in a 4x4x2 configuration of troughs, as seen in Figure 2. Bundles not scheduled for inspection, which comprise the vast majority, are loaded into this basket type and stored submerged for a minimum of 10 years before they can be transferred to Dry Storage Containers (DSCs). Bundles that *have* been flagged for in-bay inspection must be loaded into the upper level of a modified version of the standard basket. The modification consists of removing several of the upper framing members to allow access by bundle retrieval tooling.

Further challenging the capture of suspected defect bundles has been required or emergent maintenance activities within the bay that have resulted in their diversion to standard storage baskets, making them inaccessible for inspection. The findings of IFB evaluations, and if necessary detailed off-site Post-Irradiation Examinations (PIE) at Chalk River Laboratories (CRL), are vital in determining the root cause of Pickering's fuel defects and subsequently directing the corrective actions necessary to prevent their recurrence.

2. Scope and Design Requirements

The scope of the PNGS IFB-A project was to secure a means by which to transfer fuel bundles from any standard storage basket position to the pre-existing submerged inspection table. The proposed solution included the following items:

- Handling Tools
- Lasso and Miscellaneous Tools
- Submersible Lighting
- Fuel Bundle Pusher
- Ladder Rack
- Fuel Storage Racks
- Fuel Bundle Transfer Platform (FBTP)

The essential design requirements for the equipment included considerations to ensure that: fuel sheath failures do not occur as a result of inadequate cooling or physical damage, continuous fuel monitoring by the International Atomic Energy Agency (IAEA) Safeguards is unimpeded, irradiated fuel remains submerged at a depth of no less than 3.46 m at all times, Foreign Material Exclusion (FME) considerations are made (e.g. use of tethers, no-lubricants), platform strength is designed to support a minimum load of 1587 kg, and submersible equipment is constructed using materials that are radiation resistant and will not corrode under the environmental conditions present in the IFB-A. The table itself is primarily constructed of 304 Stainless Steel, with fixtures and hand tools fabricated from various arrangements of Aluminum (Alloy 6061) and 304, 312, 316, 404, 416, or 17-4 SS.

2.1 Design Considerations

Space available within the IFB-A is limited by physical, thermal and structural considerations. By design, the bay is capable of supporting a fixed number of irradiated fuel bundles within approved configurations (i.e. within storage baskets). The standard irradiated fuel storage baskets are stacked up to 6 high within 2x3 stacking frames (seen empty in the centered-lower portion of Figure 3) that restrict their movement under Design Basis Earthquake (DBE) conditions. Parallel limitations, are imposed to this quantity by the heat removal capacity of the bay and the capability of the physical structure to withstand loading. Furthermore, the bay must be capable of accommodating core fuel dumps following end-of-life station layups in addition to all receipts from daily fuelling runs.

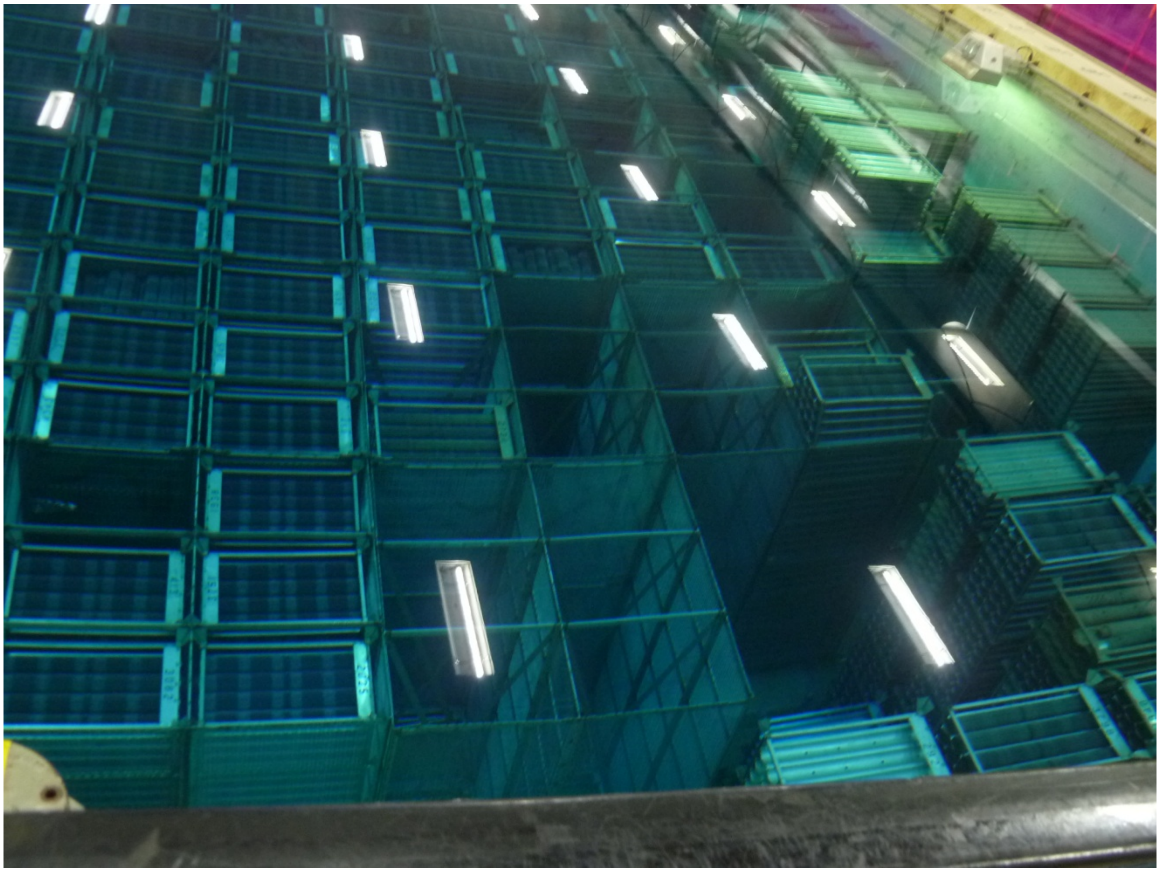

Figure 3 Pickering IFB-A Stacking Frames

Challenged primarily by limited available space, the original Fuel Bundle Transfer Platform (FBTP) design was comprised of a work surface mounted atop the stacking frames. The tool in this configuration would obstruct access, but not circulation, to the cooling irradiated fuel below it and could be moved when required (i.e. end of station service life). Though a seemingly more simplistic solution, the concept was swiftly abandoned following concerns raised by PNGS Civil Design Engineers in completing the necessary seismic analysis, under the Electric Power Research Institute's (EPRI) Seismic Margin Assessment (SMA) [2] methodology, within the stringent schedule allotted to the project. As a result, the design of the FBTP evolved into its final configuration which required both substantial design changes and forfeiture of vacant IFB-A floor space held as a contingency by Fuel Handling Operations to support the project.

Numerous installation-site visits were performed by the OPG/CANTECH team in an effort to optimize the tooling design. Of specific concern was operator burden due to hand tooling length and weight, and interference with routine bay inventory and inspection activities. The updated design saw the platform fitted with supports that raise its operating surface to approximately 3 meters from the bay floor. At this height, the uppermost features of baskets loaded atop the platform would remain below the overall level of the bays frequently traversed stacking frames.

2.2 Seismic Design Considerations and Analysis

Given the sensitivity of its surrounding environment, namely the irradiated fuel bundles, significant deflection, sliding, or overturning of the FBTP could not be afforded. Subsequently, bracing and reinforcements were added to the primary vertical structural supports and the base plates were enlarged to increase floor contact friction, more evenly distribute loading and further inhibit overturning moment.

Finite Element Analysis (FEA) of the table was performed to demonstrate that it will adequately maintain its form and position during and following a DBE event. The analysis was dynamic with results derived by the Square Root of the Sum of Squares (SRSS) method. A digital STEP (STandard of the Exchange of Product model data) model was utilized in ANSYS (ANalysis SYStem) computer software, with non-structural components (full fuel baskets, racks and participating water elements) converted to lump masses; depicted as spheres within Figure 4 below. FEA considerations were made in accordance with Atomic Energy Canada Limited (AECL) PNGS-A Half Review Level Earthquake (RLE) DBE Floor Response Spectra (FRS) [3], an approach that was deemed conservative.

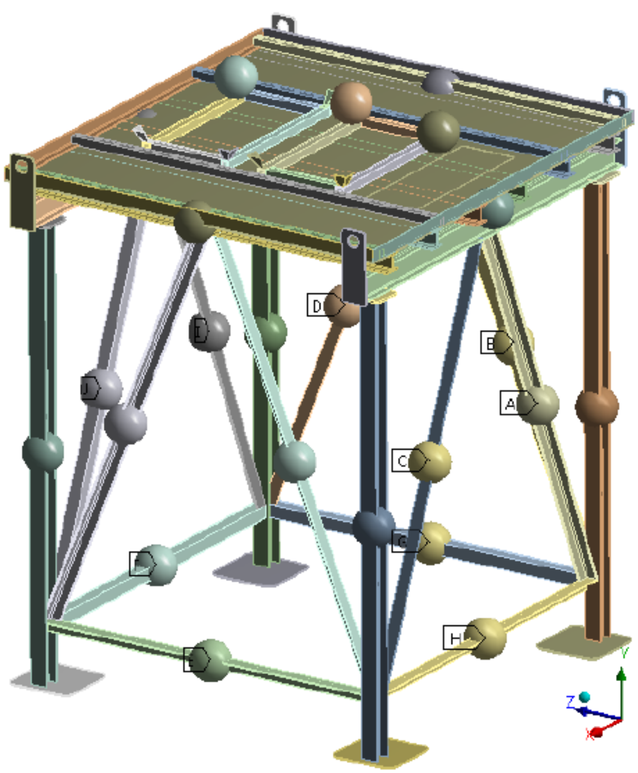

Figure 4 FEA Structural Model of the FBTP [4]

Since penetrations of the IFB-A epoxy coated concrete liner are not permitted, the FBTP structure is not anchored or fastened in any way. Therefore, all forces are transferred through contact between the four base plates of the table and the surface of the bay floor. Significant consideration was given to the selection of frictional coefficients and maximum transferrable horizontal forces. The resulting analysis demonstrated the table design exceeded a Factor of Safety (FOS) of 1.25 against overturning, as required by Canadian Standards Association (CSA) N289.3 Section 4.7.1 [5].

The contribution of hydrodynamic forces resulting from the simulated DBE conditions was investigated, but found to be well within the available margin to critical safety limits accommodating stresses, deformations and overturning forces. Considering all possible field loading configurations of the table, favorable final results of the Response Spectrum Analysis (RSA) were used to seismically qualify the FBTP for use in the PNGS IFB-A.

2.3 Flexibility

The initial concept for the FBTP was to address long standing limitations in the PNGS IFB-A which prevented the retrieval of suspect defect bundles that had been inadvertently diverted to inaccessible storage basket positions. However, the capability of the tooling to also return intact fuel to these baskets, presented a significant cost savings opportunity. Traditionally, bundles that have undergone inspection at PNGS are stored in a third, so-called “scrap,” storage basket. Albeit more simplistic in design, these containers are costly to produce, and further expected to necessitate a substantial expenditure in their eventual DSC qualification. The FBTP allows intact irradiated fuel bundles to once again be configured for eventual DSC loading.

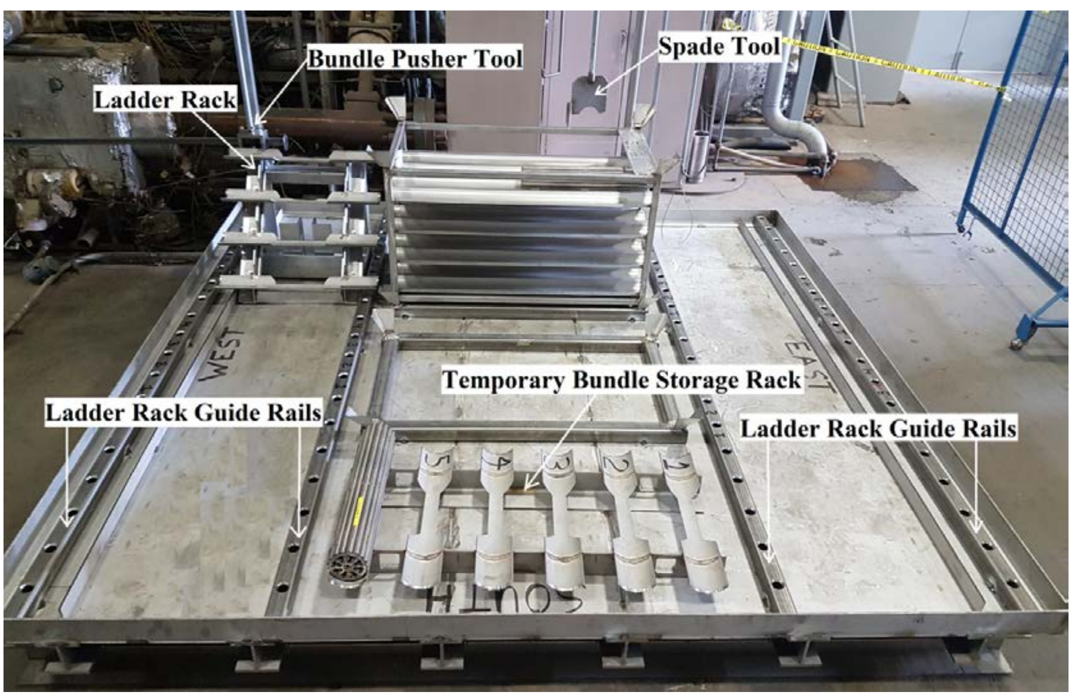

Figure 5 Fuel Bundle Transfer Platform Layout

The overall layout of the FBTP working surface, as seen is Figure 5, consists of two fuel basket storage cradles flanked on either side by guide rails. These rails maintain parallel ladder rack trough alignment with the fuel bundles loaded within the storage basket. Though a single rail system satisfies full functionality of the table, the second was conservatively included to offer additional operational flexibility.

2.4 Functional Description

The following sequence describes the process by which the FBTP is used to retrieve and transfer a fuel bundle from a standard fuel storage basket (bundles inaccessible) to a modified basket (bundles accessible). The re-loading of bundles is in many regards a reversal of the un-loading process and is therefore not detailed in this paper. Once the FBTP is staged with both standard and modified storage baskets, an operator working from the gantry crane above the IFB aligns the ladder rack with the storage basket position from which he/she intends to extract a bundle. This is accomplished manually using a spade tool that pivots from holes in the guide rails to advance the ladder rack. By incrementing its lateral position in this way, the 4 ladder rack troughs can accommodate a bundle expelled from any of the 16 storage basket matrix locations as seen in Figure 6.

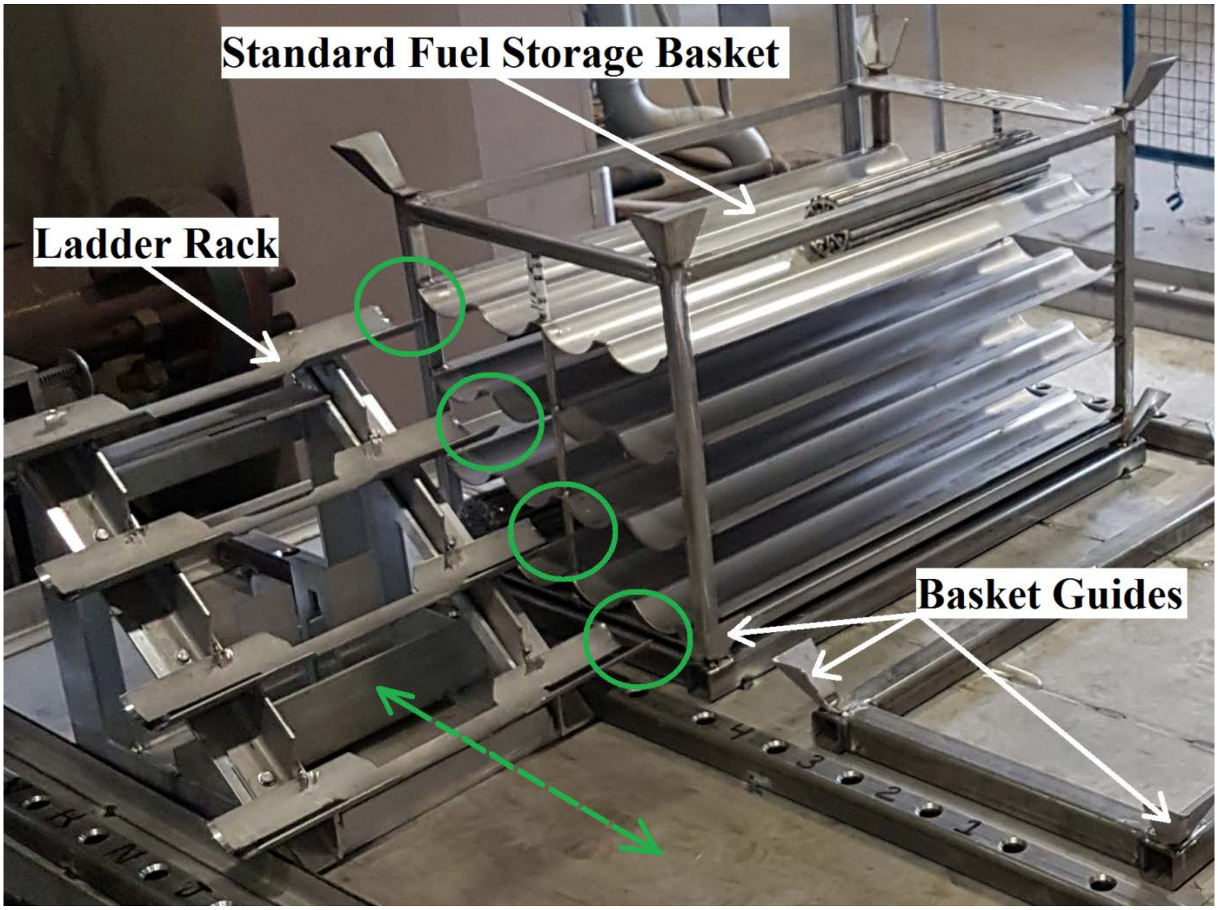

Figure 6 FBTP Ladder Rack Positioning and Alignment

Once the receiving trough is correctly positioned, the operator uses a specially designed tool called a “bundle pusher” to advance fuel bundles one at a time onto the ladder rack from the opposite side of the storage basket. For simplicity, the bundle pusher tool has been equipped with a vertically adjustable, manually-driven, rack and pinion ram assembly with incremental height presets matching those of the storage basket. Parallel alignment of the ram with the longitudinal axis of the bundles is maintained by a locating system that utilizes a series of holes within the platforms guide rails. The ram is subsequently retracted after each individual bundle push. A cross-sectional depiction of the tooling in use within the IFB-A can be observed in Figure 7.

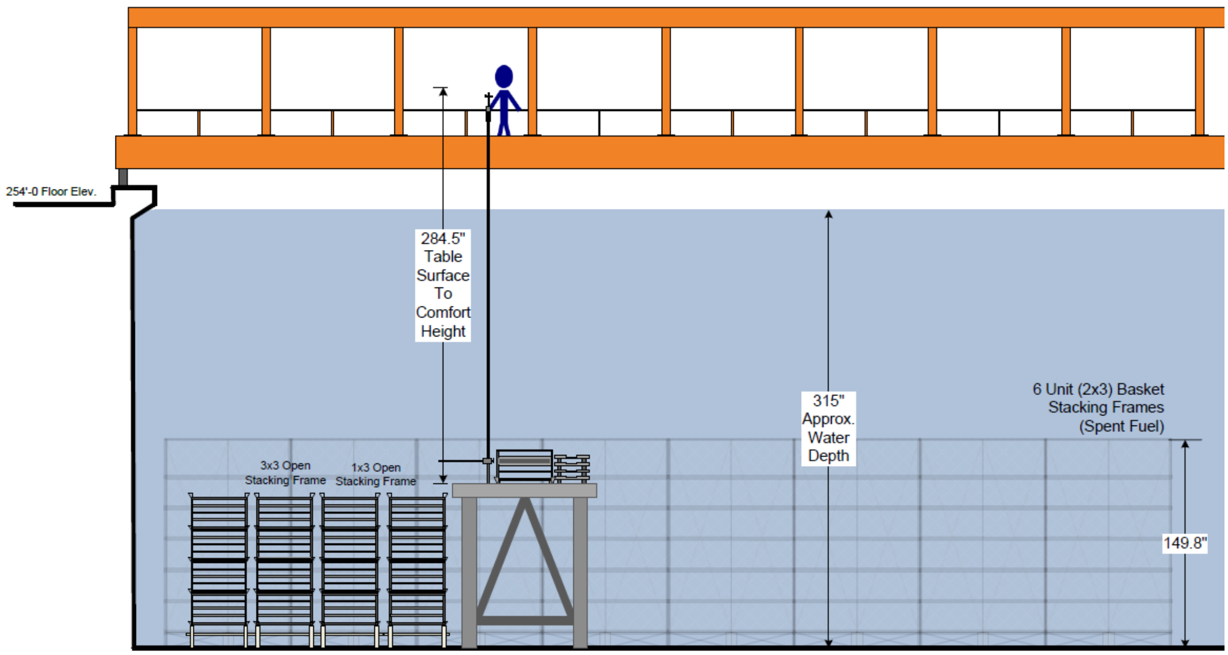

Figure 7 PNGS FBTP IFB-A Cross-Section Arrangement

Once fully supported by the ladder rack, and clear of the storage basket, the discharged fuel bundle is transferred directly to the uppermost level of the modified storage basket using a universal fuel bundle handling tool of Stern Laboratories Inc. design (a seen in Figure 8). This specialized device is capable of securely engaging and releasing the endplates of any CANDU bundle design. As previously stated, only the top rung of the modified basket can be accessed by existing tooling available at the existing IFB-A inspection area. Once bundles are loaded onto the modified basket, they are delivered to the inspection table using the IFB-A gantry-mounted basket handling mechanism (a.k.a. Supertool), where established inspection procedures are employed.

Figure 8 Fuel Bundle Handling Tool (Stern Laboratories Inc. supplied photo)

Figure 9 IFB-A Fuel Basket Transfer Platform (Pre-Delivery)

3 Conclusions

The acquisition of the Fuel Bundle Transfer Platform (seen following chemical passivation and prior to delivery in Figure 9) by OPG PNGS has resolved long standing limitations in the PNGS IFB-A. Suspect defect bundles currently residing in standard fuel storage baskets are now accessible to fuel inspectors for detailed examination. Furthermore, this tool adds the flexibility to both: recover any future suspect defect bundles that have not been loaded into accessible "modified" baskets, and to return intact bundles to their original locations – alleviating challenging IFB space constraints and resources.

4 References

[1] Institure of Nuclear Power Operations, “Guidelines for Achieving Excellence in Nuclear Fuel Performance,” Guideline INPO 07-004, Revision 2, July 2012.

[2] Electric Power Research Institute, "A Methodology for Assessment of Nuclear Power Plant Seismic Margin," Report NP-6041-SL, Revision 1, August 1991.

[3] Atomic Energy Canada Limited Technical Specification 44RS-68000-TS-011, “Seismic Qualification of Instrumentation, Control and Electrical Equipment,” January 2000.

[4] Keewatin Group Ltd, “FEA Report - IFB-A Fuel Bundle Transfer Table,” Project #16522, March 2016.

[5] Canadian Standards Association, “Design Procedures for Seismic Qualification of Nuclear Power Plants,” Standard N289.3-10 (R2015), 2010 (Reaffirmed 2015).

5 Acronyms

AECL – Atomic Energy Canada Limited
AFI – Area For Improvement
ANSYS – Analysis System
CANDU – CANada Deuterium Uranium
CRL – Chalk River Laboratories
CSA – Canadian Standards Association
DBE – Design Basis Earthquake
DN – Delayed Neutron
DNGS – Darlington Nuclear Generating Station
DSC – Dry Storage Container
EPRI – Electric Power Research Institute
FBTP – Fuel Bundle Transfer Table
FE – Fuelling Engineer
FEA – Finite Element Analysis
FH – Fuel Handling
FME – Foreign Material Exclusion
FRS – Floor Response Spectra
FS – Feeder Scan
FOS – Factor of Safety
GFP – Gaseous Fission Product
IAEA – International Atomic Energy Agency
IFB – Irradiated Fuel Bay
IFB-A – Irradiated Fuel Bay A (Pickering Units 1 and 4 – formerly Pickering A)
INPO – Institute of Nuclear Power Operations

OPG – Ontario Power Generation
OPS – Operations (OPG)
PHTS – Primary Heat Transport System
PIE – Post Irradiation Examination
PNGS – Pickering Nuclear Generating Station
RB – Reactor Building
RLE – Review Level Earthquake
RSA – Response Spectrum Analysis
SRSS – Square Root of the Sum of Squares
STEP – Standard of the Exchange Product
WANO – World Association of Nuclear Operators