Hotcell Examinations of In-core Inconel X-750 spacers removed from CANDU Reactors for Surveillance

Kris Dunn and Grant A. Bickel

Canadian Nuclear Laboratories (CNL), Ontario, Canada
Corresponding author: Kris Dunn <kris.dunn@cnl.ca>

Life cycle management programs require periodic removal of core components from CANDU reactors. One of these components is the Inconel X-750 spacers that serve to prevent contact between the cold calandria tube and the hot pressure tube in the CANDU Heavy Water Reactor design (Figure 41). While serving only a support function, the Inconel X-750 spacer is subject to significant metallurgical transformations in core with the most significant being from the thermal neutron transmutation of nickel leading to high levels of alpha particle production and retention in the form of helium bubbles (up to 3 atomic percent He per the bulk). Surveillance spacers require hotcell examination and testing to ensure that they continue to meet their design requirement. These activities are integral to the overall Inconel X-750 spacer management program (Griffiths, 2013; Judge et al., 2014). The examination and testing activities carried out in the CNL hotcell facilities, equipment used and general findings are discussed.

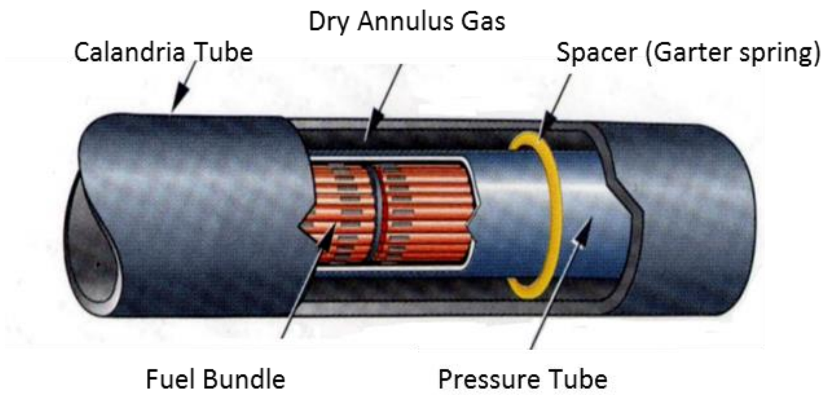

Figure 41: CANDU Fuel Channel schematic cut away showing the key components.

The spacers in a CANDU reactor fuel channel are of a helical spring design (Figure 42). The spacer service life may exceed 25 calendar years in core and hence spacers are highly activated at the time of removal. The most significant activation product is ^{60}Co with levels of up to 3 Ci ^{60}Co per gram material (roughly 30 - 50 curies of ^{60}Co per spacer). The gamma fields of a single spacer at 1 meter would be as high as 65 R/hour. A single coil from that spacer could have a field as high as 4000 R/hr near contact (1 cm). These radiation fields require that all handling takes place within a hotcell until they are sub-sampled to microscopic sizes.

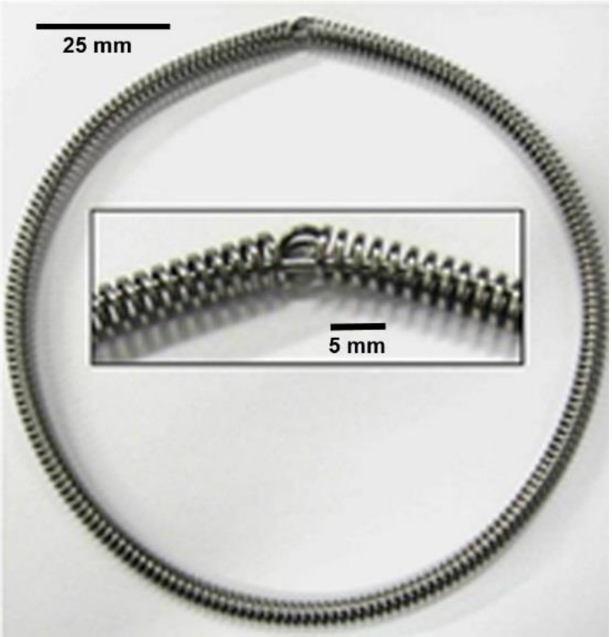

Figure 42: Inconel X-750 spacer and close-up showing attachment hooks and individual coils.

Examination of these spacers begins with an assignment or verification of their in-service location and orientation. The concentric pressure tube and calandria tube lie horizontal in a CANDU reactor so that the bottom portion of the spacer is in contact between the hot pressure tube and the cold calandria tube. As such, the bottom pinched portion experiences much cooler service temperatures than the portion that is only in contact with the hot pressure tube. Since examination and testing requires knowledge of the in-service conditions (temperature and neutron fluence), the orientation and axial location must be determined; information that can only be assumed from the blind removal process. The axial location is determined based on a measurement of the spacer diameter. Since the spacer is conformal to the pressure tube, its inner diameter can be matched to the known outer diameter of the pressure tube usually removed at the same time as the spacers. A calibrated tapered cylinder (Figure 43) enables a simple yet accurate diameter measurement. The pitch of the helical spring also varies around the spacer in ways that reveal the contact region at the bottom of the fuel channel. A rotational indexing stage provides a platform for the spacer and a high resolution video camera provides images for an accurate coil-by-coil measurement of the pitch. These images also provide for a closer examination of the spacer condition after removal from the core.

Once the provenance of the spacer material is established, sectioning for subsequent testing can proceed. Sections are taken for mechanical testing (crush testing, endurance/fatigue testing, micro and nano-indentation (Figure 44), and small-scale micro-mechanical testing), metallographic examinations (optical metallography, post mechanical testing fractography, and high resolution transmission electron microscopy), density determination via immersion techniques, and measurement of the bulk He content with hot vacuum extraction mass spectrometry.

The majority of the mechanical testing requires bulk material, and thus the work is performed exclusively within the hotcells using specially designed tooling. Nano-indentation, small-scale micromechanical testing, and transmission electron microscopy must be performed out-of-cell, and therefore techniques for sectioning and thinning material were developed to reduce the volume of the material down to masses of ~ 2 mg. Samples are then electro-polished to less than 100 microns thick. The fields are then reduced to the levels acceptable for out-of-cell handling. Specimens are first introduced to an active focused ion beam (FIB) for TEM preparation, and small-scale micromechanical testing using an in-situ PI88 Hysitron indenter (Howard et al., 2018). Once prepared in the FIB, the fields have immeasurable activity levels (too low for ordinary radiation protection equipment to measure) to be used for a suite of microscopic analyses. All this surveillance data contributes to a better understanding of the spacer condition and its fitness for continued service.

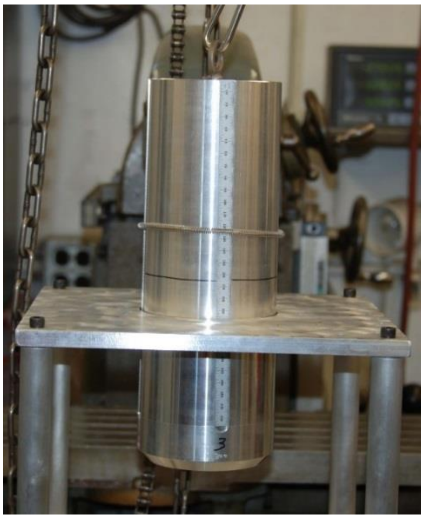

Figure 43: Calibrated tapered cylinder set up for measuring spacer diameter.

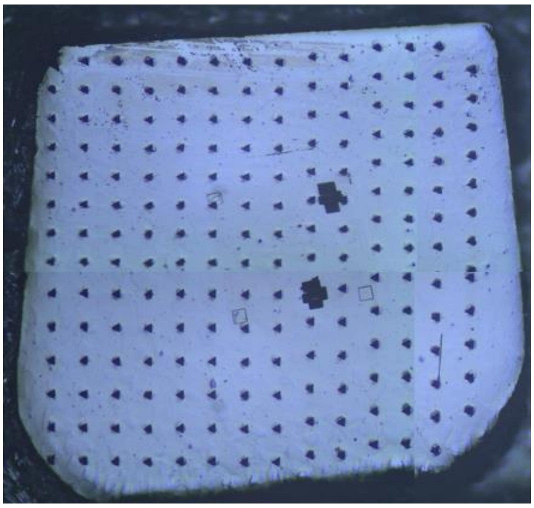

Figure 44: Example of the nano-indentation pattern used on the spacer wire cross section.

References

Griffiths, M. (2014). The effect of irradiation on Ni-containing components in CANDU® reactor cores: a review. *Nuclear Review*, *2*(1), 1-16.

Howard, C., Judge, C., Bhakhri, V., Dixon, C., Rajakumar, H., Mayhew, C. (2018). Using Novel Small Scale Mechanical Testing (SSMT) to Link the Mechanical Properties and Deformation Mechanisms of High Dose Inconel X-750 Core Material, *Submitted to the proceedings of the 55th Annual Meeting - HOTLAB 2018*.

Judge, C. D., Gauquelin, N., Walters, L., Wright, M., Cole, J. I., Madden, J., ... & Griffiths, M. (2015). Intergranular fracture in irradiated Inconel X-750 containing very high concentrations of helium and hydrogen. *Journal of Nuclear Materials*, *457*, 165-172.