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Review of NWMO Spent Fuel Delayed Hydride Cracking (DHC) Program

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1. Introduction

In South Korea, spent nuclear fuel from CANDU reactors at the Wolsong Nuclear Power Plant is stored using dry storage methods. Dry storage is a key strategy for ensuring the long-term safety of spent nuclear fuel, and maintaining the structural integrity of fuel cladding and associated components during storage is essential. In particular, Delayed Hydride Cracking (DHC) is a major degradation mechanism that can cause cracking and reduce mechanical strength, posing a significant challenge to the long-term integrity of spent fuel assemblies.

As part of its research on the long-term management of spent nuclear fuel, Canada's Nuclear Waste Management Organization (NWMO) has investigated the DHC behavior in the weld regions of spent fuel endplates. Endplates play a critical role in maintaining the structural stability of fuel assemblies, and the potential for hydrogen-induced cracking in weld regions is an important factor in assessing fuel integrity during extended storage periods. This paper reviews the studies conducted by NWMO on DHC behavior in endplate welds and discusses their implications for the management of spent nuclear fuel in South Korea.

2. Delayed Hydride Cracking (DHC) Program

The Delayed Hydride Cracking (DHC) Program aimed to assess the susceptibility of CANDU fuel bundle endplate and endcap welds to DHC by providing fundamental material properties data. To determine whether DHC occurs at endplate welds during dry storage, key material properties such as the stress intensity factor (K_{IH}) for DHC initiation and the delayed hydride crack velocity (DHCV) were measured.

A test apparatus was developed to conduct DHC tests on fuel element welds within a fuel bundle, along with experimental procedures for measuring K_{IH} and DHCV. Additionally, a finite-element stress analysis methodology was established to calculate the applied stress intensity factor at the weld discontinuity under experimental loading conditions. In 2008, this apparatus, test procedure, and stress analysis methodology were applied to two General Electric (GE) 37-element unirradiated fuel bundles, enabling the determination of K_{IH} and DHCV.

2.1 Test Equipment and Test Methodology

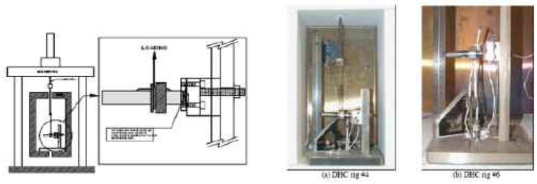

Fig. 1. Equipment Schematic & Load Testing Equipment

The two devices in Figure 1 were designed to operate in a hot cell to test the end plate/end cap welds of irradiated fuel. However, all tests within the program were conducted on non-irradiated fuel assemblies.

2.2 Test Specimen and Load Application Method

The test specimens consisted of a section of a fuel element (without fuel pellets) with a portion of the endplate still attached. The test was conducted by firmly securing the endplate between custom-designed stainless steel (SS) solid blocks and applying a load to the fuel element end, thereby acting as a cantilever. The torque generated from this setup acted on the weld and provided the required energy to fracture it. Most tests were performed at 150°C, which represents the nominal maximum fuel temperature expected during dry storage in Dry Storage Containers (DSCs) (actual temperatures being significantly lower). As shown in Figure 1, the specimen was loaded by pulling upward on the fuel element through a steel cable placed around a groove in an aluminum collar attached to the fuel element. This setup induced tensile bending stress in the lower part of the weld. The pull rod was connected to a load cell and an actuator, which was controlled by a stepper motor. In an alternative setup shown in Figure 9, the fuel element was pulled downward, resulting in tensile bending stress on the upper part of the weld.

2.3 Crack Detection and Monitoring System

Heating was provided by a programmable temperature-controlled furnace, with an allowable temperature fluctuation of ±2°C during isothermal K_{IH} or DHCV tests. Crack initiation and propagation were monitored simultaneously using acoustic emission (AE) and direct current potential drop (DC-PD) techniques. A wave guide was used to transmit AE signals to an external transducer located outside the furnace.

For the PD crack detection and monitoring system, microvolt resolution was required to detect cracking, and a constant current of 3–4 A was used. The AE system was capable of detecting the breaking of a 0.5 mm H pencil lead when background noise was minimal. The test procedure was designed to allow continuous crack growth after initiation, making it easier to detect than crack initiation alone.

2.4 Specimen Preparation & Crack Measurement Method

The tested CANDU fuel bundles were manufactured without UO_2 pellets. Before testing, they were hydrided to a specified hydrogen concentration of 40 ppm using the electrolytic/thermal diffusion hydriding technique. After electrolytic hydriding, a 75 mm section of the bundle was cut using wire electrical discharge machining (WEDM). The test was conducted using a single fuel element with a portion of the endplate still attached. The endplate was firmly secured in the test apparatus, and a gradually increasing load was applied to the fuel element at a distance of approximately 75 mm from the endplate.

As the load increased, torque was applied to the endplate/endcap weld, leading to fracture initiation once the critical load was exceeded. The voltage differential across the crack was monitored throughout the loading process. Once crack initiation occurred, the voltage differential increased linearly over time, allowing for the estimation of crack velocity.

After sufficient crack growth, the cracking process was arrested by increasing the test temperature by 50°C for a short interval, causing hydrides at the crack tip to re-dissolve. While the cracking was halted, the fractured surfaces were oxidized (tinting method) to measure crack length. Since the elapsed time from crack initiation to arrest could be determined, the crack velocity (DHCV) was estimated. Once tinting was completed, the test specimen was returned to the original test temperature, and testing resumed. As is characteristic of DHC, crack propagation resumed after tinting, but the crack velocity after tinting was observed to be higher than before.

2.5 CANDU Spent Fuel Testing

Fig. 2. The empty fuel bundle elements

Following the successful development of the Delayed Hydride Cracking (DHC) test apparatus for CANDU fuel bundle endplate/endcap welds, the preliminary database was expanded to include other fuel bundle types and manufacturers.

The initial database included test results from two General Electric (GE) 37-element unirradiated fuel bundles tested in 2008 (Shek & Wasiluk, 2009). A total of five endplate welds were tested at 130°C and 150°C, with four welds exhibiting K_{IH} values ranging from 7.6 to 8.3 $MPa\sqrt{m}$. However, one sample showed a higher K_{IH} value of 13.6 $MPa\sqrt{m}$.

For the additional tests, three unirradiated fuel bundles without fuel pellets were used:

- GE 28 fuel : 1EA
- GE 37 fuel : 1EA
- CAMECO 37 fuel : 1EA

These fuel bundles were manufactured using standard fabrication and welding processes and did not have serial numbers.

After electrolytic hydriding, a 75 mm-long section was cut from each of the three fuel bundles using wire electrical discharge machining (WEDM) (Figure 16). It was observed that the fuel elements in all three cut sections sprang out after cutting, likely due to the presence of residual stresses in the endplate assembly.

The three cut-off end sections were then annealed at 266°C for 47 hours in a large oven to allow hydrogen diffusion from the surface hydride layer into the bulk metal, achieving the target hydrogen concentration of 40 ppm. After diffusion annealing, it was noted that the oxide color of the CAMECO bundle differed from that of the GE bundles.

A coupon was taken from the endplate weld of each bundle for hydrogen concentration measurements. The process involved:

1. Removing the remaining hydride layer from the coupon by pickling and grinding.
2. Measuring the Terminal Solid Solubility for hydride dissolution (TSSD) temperature using Differential Scanning Calorimetry (DSC).
3. Sending the coupons to Nu-Tech for hot extraction inert gas fusion analysis using a LECO instrument to determine hydrogen concentration.

2.6 Results

The DHC experimental program aimed to establish a database of K_{IH} and DHCV values by testing the endplate welds of different fuel bundle designs (GE 37-element, GE 28-element, and CAMECO 37-element).

- 2008 Tests (GE 37-element, unirradiated, 2 bundles, 5 welds)
  - 130°C (10 ppm H_2): K_{IH} = 8.3 MPa√ m
  - 150°C (40 ppm H_2): K_{IH} = 7.6–13.6 MPa√ m, DHCV = 10^{-9} m/s
- 2009 Tests (additional GE and CAMECO bundles)

➔ Comparison of K_{IH} and DHCV

The key results and conclusions are as follows.

First, a comparison of weld differences among fuels showed that the CAMECO 37 welds had a larger notch radius and fewer discontinuities, making them less susceptible to Delayed Hydride Cracking (DHC). Additionally, the welds of the GE 28 and CAMECO 37 were located on the outer diameter (OD) side, whereas the welds of the GE 37 were positioned centrally.

Second, an analysis of DHC crack initiation locations revealed that GE 37 and CAMECO 37 exhibited cracks at a 45° offset from the loading direction. In contrast, the GE 28 developed cracks at the topmost region of the weld, showing a trend similar to that observed in the 2008 GE 37.

Third, an evaluation of bending stress differences during DHC initiation indicated that the bending stress followed the order GE 37 > CAMECO 37 > GE 28. Additionally, the 2009 fuel exhibited higher bending stress than the 2008 GE 37. It was also confirmed that higher bending stress was required on the OD side compared to the ID (inner diameter) side under loading conditions.

Fourth, a comparison of K_{IH} values (Threshold Stress Intensity for Hydrogen-induced Cracking) showed that the K_{IH} value of the 2009 fuel was higher than that of the 2008 GE 37. However, the difference in K_{IH} values between OD and ID loading conditions was not significant.

Finally, a comparison of DHCV (Delayed Hydride Cracking Velocity) revealed that the DHCV value at 150°C for the 2009 fuel was lower than that of the 2008 GE 37.

Table.1 Summary of the 2009 DHC Tests on Endplate/ Endcap Welds (Shek et al., 2010, and, Shek, 2011)

Test #	Bundle type	Element #	DHC rig	Tensile stress on ID or OD side	DHC initiation load (N)	Bending stress for DHC initiation (MPa)	K_{IH} MPa√m	DHCV at 150°C prior to heat tinting (m/sec)	DHCV at 150°C after heat tinting (m/sec	Postulated location for DHC initiation based on fracture surface examination
09-106	GE 37-element	2	4	ID	64	282	11.2	6.12 E-10	1.33 E-9	~45° from top
09-120	GE 37-element	5	6	ID	63	282	10.7	4.46 E-10	1.54 E-9	~45° from top
09-136	GE 37-element	8	4	ID	72	334	11.1	5.01 E-10	1.56 E-9	~45° from top
09-148	GE 37-element	15	4	ID	76	367	13.1	8.57 E-10	2.93 E-9	~45° from top
09-124	GE 37-element	17	4	OD	83	346	12.2	1.23 E-9	2.31 E-9	~45° from top
09-125	GE 28-element	2	6	ID	53	227	10.1	1.29 E-9	NA	Top of weld
09-130	GE 28-element	4	6	ID	53	214	10.0	1.45 E-9	2.55 E-9	Top of weld
09-144	GE 28-element	15	6	ID	56	220	13.6	1.41E-9	3.26 E-9	Top of weld
09-172	GE 28-element	6	6	ID	53	225	9.4	1.20 E-9	5.05 E-9	Top of weld
09-182	GE 28-element	8	6	OD	67	285	11.6	4.46 E-10	2.17 E-9	~45° from top
09-135	CAMECO	6	6	ID	73*	253	NA	NA	NA	~45° from top
09-186	CAMECO	18	4	ID	85	277	12.2	NA	NA	~45° from top
09-204	CAMECO	5	4	ID	80	255	12.1	8.41 E-10	1.78 E-9	~45° from top
09-208	CAMECO	16	6	ID	80	325	NA	7.0 E-10	NA	~45° from top
10-16	CAMECO	9	4	ID	93*	324	13.5	NA	NA	~45° from top

*based on estimated cracking time; NA: Not Available

Table.2 Summary of the 2008 Tests on Endplate/ Endcap Welds (Shek et al., 2008, and, Shek and Wasiluk, 2009)

Test ID	Bundle type	Type of Test	H concen-tration (ppm)	Test Temp. (°C)	Maximum nominal bending stress at crack initiation (MPa)	K_I for DHCV test or K_{IH} (MPa√m)	DHCV (m/sec)		Postulated location for DHC initiation based on fracture surface examination
							Before heat-tinting	After heat-ting	
07_09	GE-37	K_{IH} test	10	130	184	8.3	4.7E-10	5.4E-10	Top of weld
07_67	GE-37	K_{IH} test	40	150	163	7.7	2.5E-10	NA	Top of weld
07_104	GE-37	K_{IH} test	40	150	167	7.9	6.8E-10	2.3E-09	Top of weld
07_140	GE-37	K_{IH} test	40	150	170	7.6	2.1E-10	4.0E-10	Uncertain
07_164	GE-37	K_{IH} test	40	150	155	13.6	6.6E-10	2.1E-9	Top of weld
07_78	GE-37	DHCV	40	150	214	11.8	2.1E-9	4.0E-9	Top of weld
07_79	GE-37	DHCV	40	150	209	12.2	1.8E-9	5.5E-9	Top of weld

3. Conclusions

The NWMO's spent fuel integrity program evaluated the potential for Delayed Hydride Cracking (DHC) in CANDU spent fuel during dry storage for up to 100 years. Experimental DHC studies and finite element stress modeling confirmed that DHC is unlikely to occur, providing meaningful experimental results to support the long-term integrity of domestic CANDU spent fuel. The study focused on 28-unit CANDU fuel stored in Dry Storage Containers (DSCs) at 130–150°C. Stress analysis showed minimal deformation, with mid-section bending limited to 1 mm, while the stress intensity factors (SIF) at weld discontinuities remained below 3 MPa√ m. These calculations were based on conservative models, excluding the stiffening effect of UO_2 fuel. To assess whether these stresses could initiate DHC, K_{IH} values were experimentally determined for Zircaloy-4 welds, revealing that unirradiated welds had K_{IH} values between 7.6 and 13.6 MPa√ m, regardless of manufacturer. Irradiation effects on K_{IH} were not directly tested, but a slight reduction of a few MPa√ m is expected. Additionally, CAMECO CANDU 6 fuel exhibited no weld discontinuities, indicating lower susceptibility to DHC. These findings provide crucial scientific evidence to assess the safety of dry storage for domestic CANDU spent fuel and to ensure its long-term structural integrity.

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