DYNAMIC THERMO-CHEMO-MECHANICAL STRAIN OF ZIRCALOY-4 SLOTTED RINGS FOR EVALUATING STRATEGIES THAT MITIGATE STRESS CORROSION CRACKING

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Abstract
Stress corrosion cracking (SCC) in Zircaloy-4 fuel sheaths has been investigated by static loading of slotted ring samples under hot and corrosive conditions. However, in nuclear reactors, power ramps can have short (e.g., 10-20 minutes) and recurring timeframes due to dynamic processes such as on-power refuelling, adjuster rod manoeuvres, and load following. Therefore, to enable out-reactor dynamic testing, an apparatus was designed to dynamically strain slotted ring samples under SCC conditions. This apparatus can additionally be used to test fatigue properties. Unique capabilities of this apparatus and preliminary results obtained from static and dynamic tests are presented.

Introduction
A thin (~ 0.45 mm) collapsible sheath made from Zircaloy-4 is designed to contain the fission products emitted from nuclear fuel (UO₂) during normal operation in the CANDU® nuclear reactor. During a power ramp, radiation-induced swelling and thermal expansion of fuel pellets may strain the sheath. In combination with exposure to corrosive fission products (e.g., iodine), the induced stress and strain could potentially initiate stress corrosion cracking (SCC) in the sheath, which can permit the undesirable release of fission products into the primary heat transport system.

CANDU nuclear reactors generally operate consistently at base-load power to take advantage of low fuel cost and ease of fuel management [1,2]. However, as nuclear power occupies a higher percentage (currently 50% in Ontario, Canada) of the power grid, there is a trend toward periodic variations in load power (load following). In France, for example, nuclear power has occupied 74-79% of the power grid from 2002-2012, and nuclear reactors are operating with load-following capability [3].

All Ontario CANDUs, including the units at the newest stations (Darlington and Bruce B), were designed for some load-cycling without using turbine steam bypass [4]. CANDU load-following testing performed in the 1980s in research and commercial reactors was generally encouraging. For instance, operational feedback from 3 Bruce B reactors showed no evidence of fuel failure from stress corrosion fatigue (SCF) for up to 3 reactor power manoeuvres per week for 9 months [5]. At that time, Hastings et al. reported that the data showed no discernable difference between base-load and load following operation, the fuel-bundle defect rate remained below 0.1%, and that activity burdens in heat-transport and purification systems remained at low levels [6]. However, the cycling tests of the time were limited to less than
100 cycles. Since the residence time of Zircaloy bundles in-reactor averages about 250-300 days, daily load-following would generate hundreds of strain cycles. Tayal et al. demonstrated through initial analytical assessments for SCF that fuel would survive more frequent load-following operation, albeit with reduced margins to failure [5]. The CANDU designs for new-builds, such as EC6 and ACR-1000, will be capable of deep, planned load-following, which involves cycling down from 100% to 60% (EC6) or 75% (ACR-1000) power and back. For both designs, 50% power can be achieved by passing excess steam directly to the condensers.

Dynamic operations can cause considerable strains in CANDU fuel sheaths. For instance, the minimum strain predicted to initiate stress corrosion cracking (0.1-0.5% [7]) is generally exceeded during power ramping in CANDU fuel, wherein the hoop strain in the sheath can reach values of 0.8-1.3%, and drop by 0.6% during a shutdown condition. Furthermore, the highest strains occur at fast ramp rates (1 kW·m⁻¹·min⁻¹), because they reduce the time available for fuel densification (FD) [6]. Note that FD occurs in the early stages of irradiation and that modern day fuel begins at a high density (i.e., 98% of theoretical UO₂ density) to reduce in-reactor densification.

Stress corrosion cracking (SCC) in Zircaloy-4 fuel sheaths has previously been investigated by static loading of slotted ring samples [8]. At 300°C, Wood found that slotted Zircaloy rings crack in iodine vapour at applied hoop stresses greater than 217 MPa, where the failure time depends critically on whether the iodine concentration exceeds 3 mg I₂ per cm² of Zircaloy material. Above this threshold iodine concentration, results by Quastel et al. suggest that the corrosion resistance of Zircaloy-4 slotted rings can be improved by directly (pure O₂) or indirectly (hyperstoichiometric UO₂ plus dried graphite) adding oxygen to the system [9].

However, in static loading tests, the stress must be applied before the slotted ring is raised to the test temperature in a corrosive environment. In addition, the applied stress continuously relaxes during the test, which means that the stress could decay below the threshold stress for SCC during a long incubation period. These are disadvantages that make interpreting results difficult [10]. To overcome this, Cox developed an apparatus for remotely stressing intact (not slotted) Zircaloy rings in either tension or compression, allowing stress to be applied after the environment reaches the test temperature. In this way, the stress can remain constant throughout the test [11].

In a non-corrosive environment, Waheed et al. conducted fatigue cycling tests on Zircaloy tubes for a load-following program [12]. Slotted Zircaloy-4 sheath rings were heat-treated to simulate heat-affected and transition zones, while the stress-relieved condition was obtained from as-received sheathing. Due to the high strain rates (3-5 Hz) used, plastic strains dominated the fatigue life of Zircaloy-4 and that temperature (up to 300°C) played an insignificant role. In addition, microstructural differences significantly varied the fatigue life, with the transition zone having the longest fatigue life.

Hosbongs demonstrated that a corrosive environment reduces the fatigue life of annealed Zircaloy [13]. At 300°C, specimens were subjected to repeated reverse-bending strain cycles at a 0.01667 Hz cycling frequency. Control specimens were tested in air, and other specimens were tested in air containing 0.03 mg·cm⁻³ of iodine. In the iodine atmosphere, the fatigue life
of annealed Zircaloy-4 (with no hold-time at a total plastic strain of 6%) decreased by approximately 40%, from 212 to 136 cycles.

In our experimental study, a unique dynamic loading apparatus (DLA) is designed to apply static or dynamic strains externally on slotted ring samples in an argon-filled environment containing iodine. Dynamic loading allows stresses to be applied after the environment reaches the test temperature. In addition, the DLA enables simultaneous real-time measurements of ring loads and strains, as well as chamber pressure and temperature.

1. Dynamic loading apparatus

A dynamic loading apparatus (DLA) has been designed to investigate the behaviour of Zircaloy-4 ring specimens under dynamic stresses in hot and corrosive environments (Figure 1). It is made almost exclusively of 316 stainless steel to accommodate high temperatures (up to 300°C) and offer resistance to iodine corrosion. The overall cylindrical design fits into a 55 mm inner diameter quartz tube within a 60 mm diameter tube furnace.

Figure 1: Components of the DLA prototype. A programmable linear actuator cycles a cylindrical rod through four ring holders. Within a given ring holder, the adjustable support (labelled “A”) is attached to the rod, and the stationary support (labelled “B”) is welded to the apparatus. Consequently, a slotted ring fastened across “A” and “B” will stretch further open when the cylindrical rod moves in the direction of the yellow arrow.
Within the apparatus, dynamic ring deflection is achieved using a programmable linear actuator, which cycles a cylindrical rod through four ring holders at an adjustable speed. Each ring holder has an adjustable support attached to the rod (labelled “A”, Figure 1), and a stationary support welded to the apparatus (labelled “B”, Figure 1). Consequently, a slotted ring fastened across “A” and “B” will cyclically open and close as the rod cycles back and forth. The strain amplitudes experienced by fastened rings can be increased by manually increasing the distance between the adjustable and stationary supports, and by pre-programming the slot displacements using a LabVIEW interface (Section 1.2).

Once the slotted rings are loaded on their respective ring holders (Figure 1), the chamber is closed (Figure 2a). Optionally, for corrosion experiments, an iodine-filled glass vial may be placed into a specially designed holder (Figure 2b) within the chamber before its closure. Adjacent to the vial holder is a screw that translates into the holder and breaks the iodine vial at an appropriate time by rotating a dial at the far end of the apparatus (Figure 2a).

Three equidistant pipes (three black arrows, Figure 2a and 2c) directed into the chamber accommodate the thermocouple rod, inlet gas flow, and the outlet gas flow. The pipe for inlet gas flow extends nearly completely into the chamber to ensure turbulent gas flow. The pipe for the thermocouple rod extends midway into the chamber within close proximity to the ring holders, where it is closed off to isolate the metal thermocouple from direct contact with the iodine environment.

A load cell monitors the force exerted by the rings on the rod. A transient force measured by the load cell indicates the sudden failure of at least one of the rings. A pressure transducer and K-type thermocouple monitor the pressure and temperature in the chamber, and strain gauges monitor stress relaxation and calibrate the strain response to a given slot displacement.

### 1.1 Sample preparation

Zircaloy-4 tubes were sectioned into slotted Zircaloy-4 rings using a Buehler Isomet 1000 precision saw containing a circular diamond blade (151-mm-diameter). The process involved low-deformation radial cutting of narrow rings (5.00 ± 0.07 mm), followed by longitudinal cutting of the slot openings (2.30 ± 0.07 mm). The slotted rings were sequentially polished using 320 and 600 grit silicon carbide paper, and then cleaned ultrasonically in ethanol for 20 minutes to eliminate metal shavings and dust.

#### 1.1.1 Corrosion testing

For corrosion testing, a glass vial is loaded with crystalline iodine (900 ± 10 mg) and subsequently weighed while attached to a vacuum system. Three freeze-pump-thaw cycles ensure that the iodine resides in an oxygen-free environment in the glass vial. Finally, trace argon is introduced before sealing the vial.

Once the iodine vial is prepared, the cleaned rings are loaded on the DLA ring holders, the ring holder openings are recorded, the iodine vial is placed into its holder within the DLA chamber, and the DLA chamber is closed. Using metal/tygon tubing, the DLA input and output gas flow pipes are connected to a pressurized argon tank and fume hood, respectively.
Figure 2: (a) Fully assembled dynamic loading apparatus. The enclosed sample chamber (red dashed line) contains the ring holders, and an iodine vial holder (b). In addition, three equidistant gas/thermocouple pipes (three black arrows) directed into the chamber are used to accommodate the thermocouple rod, inlet gas flow, and outlet gas flow, respectively. (c) The pipe for inlet gas flow extends nearly completely into the chamber to ensure turbulent gas flow. The pipe for the thermocouple rod extends midway into the chamber within close proximity to the ring holders, where it is closed off to isolate the metal thermocouple from direct contact with the iodine environment. (d) Fully assembled chamber without cover.
While argon gas flows through the DLA at 200 ml min\(^{-1}\) to purge air from the DLA chamber, the furnace temperature is ramped from room temperature to 300°C in 1.5 h. After holding the temperature for an additional 1.0 h, the thermocouple rod measures a chamber temperature of 300°C, after which the argon tank is turned off, and the ball valves located near the DLA input and output pipes are subsequently closed to isolate argon within the DLA chamber. At this point, the iodine vial is broken by translating a metal screw into the vial by turning a dial on the DLA outside the furnace (Figure 2a). Finally, a programmed cycling sequence is initiated using the LabVIEW interface.

1.2 LabVIEW interface

A LabVIEW interface (Figure 3) records and enables the real-time visualization of temperature, pressure, load force, and strain. Four windows plot the real-time chamber pressure (panel A), load force (panel B), and measured strains from up to four strain gauges simultaneously. Panels C and D track the strains from 120 Ω and 350 Ω gauges, respectively.

Figure 3: LabVIEW interface: Panel A – Chamber pressure; Panel B – Force on load cell; Panel C – 120 Ω strain gauges (up to 4 gauges); and Panel D – 350 Ω strain gauges (up to 4 gauges).

The interface permits manual and automatic operation, where the manual mode permits sporadic loading (e.g., a power ramp) and the automatic mode permits continuous cycling (e.g., fatigue testing). All data are recorded automatically at a user-specified frequency. Abnormal occurrences (e.g., when a ring fails) are indicated when user-specified thresholds for pressure and force are exceeded. For example, the amplitude of the loading cycles decreases dramatically when a ring is dislodged from the apparatus during cycling (Figure 4).
Figure 4: An example cycling trace (6 min-cycle\(^{-1}\)) where a ring fell from its ring holder after approximately 200 min. The load exerted by slotted rings on the cylindrical rod is plotted versus time. The mechanical resistance of the Huntington bellows provides a baseline load on the cylindrical rod when cycling occurs without rings.

In Figure 4, the ring likely fell from its holder because some strain cycling occurred during the controlled temperature ramp, when the DLA components (Huntington bellows and cylindrical rod) are sensitive to the periodic overshooting and undershooting of the temperature controller. Such temperature-slope fluctuations can change the ring holder displacements beyond their programmed values. For example, a ring holder displacement that becomes too narrow permits the ring to slip from its holder. Therefore, in subsequent experiments, the strain cycling began when the temperature reached 300°C.

Stress relaxation of a slotted ring can be measured by a strain gauge (Figure 1 and Figure 5). For this test, the gauge is installed on the top surface of the slotted ring, and therefore measures compressive (negative) strain. The initial slot opening (2.3 mm) is stretched to 5.3 mm, and held for 2 days at room temperature. During this time, the stress relaxed and the magnitude of the compression stress therefore decreased. The relatively short duration, low initial stress, and low temperature relaxed the stress minimally (~30 \(\mu\varepsilon\) (Figure 5) corresponds to ~ 3 MPa). To verify that strain gauges are measuring strains accurately, we will now outline the theory of elastic deformation of the uniform-width slotted ring.
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Figure 5: Stress relaxation of a slotted ring as measured by a strain gauge. The initial slot opening (2.3 mm) was stretched to a fixed 5.3 mm slot opening, which was held for 2 days at room temperature. The gauge measures compressive (negative) strain because it is installed on the top surface of the slotted ring. Points were recorded every 30 minutes.

2. Elastic stress and strain in a slotted ring

Stress corrosion cracking occurs beyond a threshold stress, and most likely initiates in regions of maximum stress. For the slotted ring geometry (Figure 6), the maximum stress occurs on the inner surface directly above the slot (i.e., point A, Figure 6). When the slot is stretched from its initial opening ($w_0$) to a final opening ($w$), the analytical formula for maximum stress vs. the half-angle ($\alpha$, see Figure 6a) is [14]:

$$
\sigma_A = \frac{Et(w - w_0)(1 + \cos \alpha)}{2R^2\left((\pi - \alpha)(1 + 2\cos^2\alpha) + 1.5\sin 2\alpha\right)}
$$  \hspace{1cm} (1)

This formula for bending stress applies when the ring is elastically loaded. The ring has a radius ($R = 6.55 \text{ mm}$), thickness ($t = 0.4 \text{ mm}$), and a Young’s modulus (of as-received Zircaloy-4 fuel sheath) given by [15]:

$$
E = 97.83 - 0.0657(T - 273)
$$  \hspace{1cm} (2)

At room temperature ($T = 296 K$), the Young's modulus is 96.3 GPa. Typically, the half-angle is approximately 11° (=0.19 rad), corresponding to $w_0 = 2.3 \text{ mm}$ (initial slot opening). As the half-angle approaches zero, Equation 1 simplifies to [16]:
For the practical range of $\alpha$ values, the maximum elastic stress calculated in a COMSOL Multiphysics (version 4.4) finite element analysis model shows excellent agreement with Eq. 1. In addition, the COMSOL model calculates the distribution of horizontal stress in the ring (Figure 6b), and helps to determine when shape variations cause Eq. 1 to deviate from the true stresses in the ring. Furthermore, the COMSOL model can be modified to accommodate inevitable plastic and thermal stresses. Moreover, it can predict the surface strains ($\varepsilon_s = \sigma_s/E$) caused by increasing the total gap deflection ($TGD = w - w_0$).

\[ \sigma_A = \frac{Et(w - w_0)}{3\pi R^2} \]  

(3)

Good agreement was achieved between predicted values and strains measured by attached strain gauges (Figure 7). Strain Gauge #1 measured the strain on a freshly prepared slotted ring, while Strain Gauge #2 measured a ring that previously endured repeated cycling at random intervals over approximately six months. Since the latter condition likely induces stress relaxation and/or fatigue, the strains measured from SG #2 were lower in magnitude than those from SG #1.

For a 1 mm $TGD$ increase, the COMSOL model predicts maximum strain and stress increases by approximately 1014 $\mu$e and 104 MPa, respectively. Since the yield strength for non-irradiated, stress-relieved Zircaloy-4 cladding lies within 414-565 MPa (at room temperature), depending on metallurgical conditions [12], purely elastic deflection of rings is expected only up to 300 MPa (approximately 3 mm of ring deflection) [17]. Beyond 300 MPa, plastic stress will begin contributing to the overall stress. In addition, at higher temperatures (400°C), the yield strength falls by nearly 245 MPa and the elastic stress range correspondingly narrows [12]. Consequently, preliminary static and dynamic tests were conducted with stresses applied around 300 MPa.
3. Preliminary testing

A series of preliminary static and dynamic loading tests were performed on slotted rings to investigate the effect of temperature, initial strain, and iodine on stress relaxation and ring deflection. Structural performance (strength) of the slotted rings was evaluated by measuring the initial and final slot openings and by subjecting the rings to various mass-loads (15, 45, and 95 g) after which the corresponding slot deflections were measured. The deflection testing apparatus and procedure are outlined by Quastel et al. [9], and the preliminary test results are shown in Table 1.

In the first test, slotted rings experienced a static strain ($w = 4.5 \text{ mm}$) for three days. Two rings were strained at room temperature and two rings were strained at 300°C. Since stress relaxation is enhanced at higher temperatures, the slot openings expectedly relaxed a bit more at the higher temperature (0.23 ± 0.06 mm vs. 0.13 ± 0.03 mm), whereas the deflections were basically equivalent (0.85 ± 0.02 mm vs. 0.83 ± 0.03 mm for a 95 g mass-load).

The next three-day test involved daily cycling of four slotted rings at 300°C. Two rings were initially strained at a 4.5 mm slot opening, and two rings were initially strained at a 6.5 mm slot opening. The cycling step involved increasing the slot displacement of all rings by 1 mm once every 24 h. This involved a 3-minute rise-time (up to 5.5 and 7.5 mm), a one-hour hold, and a 3-minute fall-time (back to 4.5 and 6.5 mm). Again, the deflection measurements yield no discernable differences among the four rings (Table 1), but the slot openings relaxed considerably more at higher initial strains (1.3 ± 0.1 mm vs. 0.3 ± 0.1 mm). The former result suggests that structural integrity is preserved even after a 6.5 mm displacement (~406 MPa maximum stress), and the latter result is expected because stress relaxation is enhanced at higher initial strains.
Table 1: Average *deflection* and *relaxation in slot size* values are shown for each test condition. Uncertainty values represent one standard deviation. The *deflection measurement* represents the increase in slot size due to a given mass-load, which is measured at room temperature and after the thermo-mechanical stress regimen is complete. The *relaxation in slot size* value is the difference between the unloaded slot openings measured before and after the cycling tests. Equation 1 was used to calculate the maximum stress at Point A (Figure 6a) on the ring ($\sigma_A$) at room temperature and at 300°C, where Young’s modulus is a function of temperature.

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Deflection Measurements (mm)</th>
<th>Relaxation in Slot Size (mm)</th>
<th>$\sigma_A$ at 23°C (MPa)</th>
<th>$\sigma_A$ at 300°C (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 g</td>
<td>45 g</td>
<td>95 g</td>
<td></td>
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<tr>
<td><strong>Static measurements</strong></td>
<td></td>
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<tr>
<td>Room temperature - 4.5 mm wedge</td>
<td>0.133 ± 0.008</td>
<td>0.403 ± 0.001</td>
<td>0.85 ± 0.02</td>
<td>0.13 ± 0.03</td>
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<tr>
<td>300°C - 4.5 mm</td>
<td>0.122 ± 0.005</td>
<td>0.40 ± 0.03</td>
<td>0.83 ± 0.03</td>
<td>0.23 ± 0.06</td>
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<tr>
<td><strong>Daily cycling</strong></td>
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<tr>
<td>300°C - 4.5 mm (1 h at 5.5 mm daily)</td>
<td>0.159 ± 0.008</td>
<td>0.442 ± 0.001</td>
<td>0.89 ± 0.02</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>300°C - 6.5 mm (1 h at 7.5 mm daily)</td>
<td>0.15 ± 0.02</td>
<td>0.435 ± 0.001</td>
<td>0.89 ± 0.03</td>
<td>1.3 ± 0.1</td>
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<tr>
<td><strong>Continuous cycling</strong></td>
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<tr>
<td>300°C - 6 min-cycle$^{-1}$ (4.0 to 5.0 mm)</td>
<td>0.12 ± 0.01</td>
<td>0.39 ± 0.01</td>
<td>0.80 ± 0.02</td>
<td>0.22 ± 0.08</td>
</tr>
<tr>
<td>300°C - 6 s-cycle$^{-1}$ (3.4 to 5.4 mm)</td>
<td>0.117 ± 0.007</td>
<td>0.377 ± 0.009</td>
<td>0.78 ± 0.01</td>
<td>0.19 ± 0.02</td>
</tr>
<tr>
<td><strong>Continuous cycling with iodine</strong></td>
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<tr>
<td>300°C - 6 s-cycle$^{-1}$ (3.4 to 5.4 mm)</td>
<td>0.114 ± 0.009</td>
<td>0.36 ± 0.02</td>
<td>0.78 ± 0.02</td>
<td>0.36 ± 0.08</td>
</tr>
</tbody>
</table>
At 300°C, the 4.5 mm to 5.5 mm daily cycling test yielded larger ring deflections and slot openings compared to those from the 4.5 mm static test. Although the daily one-hour holds at 5.5 mm ($\sigma_A \approx 310 \, MPa$) appeared to marginally increase slot size, a larger sample size is required for confirmation.

Continuous cycling was completed in three tests, where each test strained three rings over three days. Test 1 involved oscillating the displacement about 4.5 mm (from 4 to 5 mm) using a 6-minute strain cycle. Compared to the static 4.5 mm test at 300°C, little difference was observed. Clearly, larger dynamic strains would be required to yield a noticeable difference. Test 2 involved a bigger range of slot displacements (3.5 – 5.5 mm) and faster cycling rate (6 s strain cycle). The differences in cycling rate and strain were insufficient to change the deflection measurements significantly. Test 3 replicates Test 2, but the rings are exposed to 900 mg of iodine vapour. The iodine test produced essentially equivalent deflection measurements, because the iodine concentration per unit area of metal was low, and because iodine was permitted to settle outside the chamber. Consequently, the next design iteration will be modified to incorporate valves closer to the chamber.

Clearly, the sample sizes in these preliminary tests will need to be increased to draw stronger conclusions. However, it appears that the stresses corresponding to a 4.5-7.5 mm slot displacement are low enough that dynamic cycling bears little effect. Therefore, we will continue experimentation over larger strain cycles, higher initial strains, and longer cycling times.

4. Summary and future work

A dynamic loading apparatus has been designed to exert static and dynamic strains on slotted Zircaloy-4 rings in hot and corrosive environments. As load cell measurements were found to be sensitive to temperature ramping, strain cycling was completed only at the test temperature. Strain gauges measured accurate strains, which are in good agreement with COMSOL modelling and the elastic strain formula for slotted rings (Eq. 1). Strain cycles were executed safely in both corrosive and non-corrosive environments. For low initial strains, preliminary results from deflection testing suggest that deflection resistance and stress relaxation are uncorrelated. Deflection measurements at the 45 g mass-load ($0.40 \pm 0.04 \, mm$) are somewhat lower than those reported by Quastel et al. ($0.46 \pm 0.02 \, mm$) [9], most likely because Quastel et al. used higher stresses.

More testing is underway to improve the statistics and to collect data at higher initial strains. In addition, strain gauge readings will be collected at high temperatures, and efforts are underway to characterize plastic and thermal strains. The DLA will be used to investigate ongoing SCC mitigation strategies at the Royal Military College of Canada including the characterization of alternative fuel sheath coatings, the doping of coatings with alkaline additives (such as Na$_2$O) for scavenging iodine species, and implementing oxidized UO$_2$ as a potential remedy for repairing oxide cracks in the fuel sheath.

5. Acknowledgements

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6. References


11. B. Cox and R. Haddad, “Recent studies of crack initiation during stress corrosion cracking of zirconium alloys”, AECL-8104 (October 1983) and in: Proc. 7$^{th}$ Int. Symp.


