Development of a Dynamic Loading Apparatus for Investigating Strategies that Mitigate Stress Corrosion Cracking in Nuclear Fuel Elements

D. Pierce*, G.A. Ferrier, P.K. Chan, and E.C. Corcoran
Royal Military College of Canada, Kingston, Ontario, Canada
*9dp18@queensu.ca

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Abstract

Iodine-induced stress corrosion cracking (I-SCC) is a dynamic process that can initiate the structural failure of fuel elements in a nuclear reactor. Consequently, as an affordable way to investigate I-SCC in the laboratory, a dynamic loading apparatus was designed to realistically reproduce the chemical and mechanical conditions during a fuel power-ramp operation in a nuclear reactor. This apparatus will significantly improve upon established C-ring SCC tests and will be a valuable tool for developing novel SCC mitigation strategies. This paper outlines the design and development of the dynamic loading SCC testing apparatus at the Royal Military College of Canada.

1.0 Introduction

In the CANDU® nuclear reactor, stress corrosion cracking (SCC) may compromise the Zircaloy-4 cladding, which normally shields the uranium dioxide fuel pellets and efficiently transfers their heat to an external coolant. Stress corrosion cracking begins when a large stress field and corrosive fission products (e.g., I and Cs) are present. Initially, while the reactor is on-power, the cladding contracts under a compressive force applied by the coolant. Shortly afterward, fission-induced thermal expansion causes the cladding and fuel pellets to expand radially. Since the fuel expands more rapidly than the cladding, and because the cladding continues to creep down, the interfaces will eventually make direct contact. Eventually, additional fuel expansion beyond the initial contact will generate stress and strain fields in the cladding.

It was believed that the application of a thin graphite-based layer (CANLUB) to the inner surface of the cladding reduces these stress and strain fields, thereby reducing the probability of SCC occurring [1]. Although the protection mechanism of CANLUB may be related to mechanical lubricating properties, it is more likely because of chemical properties [2]. In fact, the specific working mechanism of CANLUB remains unclear despite several SCC studies [1,3,4]. Consequently, further experimentation with specialized experimental equipment is necessary to better understand SCC-related phenomena and to develop new SCC mitigation strategies.

Compared with previous C-ring SCC tests [5], the dynamic loading apparatus (DLA) described here will create more realistic and dynamic stress-strain fields, which are comparable to those created in CANDU nuclear fuel during power ramps. In addition, this apparatus will likely be a valuable tool in the development of novel SCC mitigation strategies.

2.0 Structural Design of the Dynamic Loading Apparatus (DLA)

To facilitate the structural design of the DLA, previous experience will be drawn from SCC testing equipment developed by Atomic Energy of Canada Limited at Chalk River (AECL-CRL) [6]. The DLA (Figure 1) is a sectioned stainless steel cylinder containing four 6.45 cm diameter disks (three stainless steel disks and one ceramic disk). The cylindrical structure allows samples to be heated to 350°C in a standard tube furnace. The stainless steel disks provide structural support for the DLA while the ceramic disk provides heat shielding for instruments outside the furnace. The electronics and control mechanisms are located well outside the heating area generated by the tube furnace.

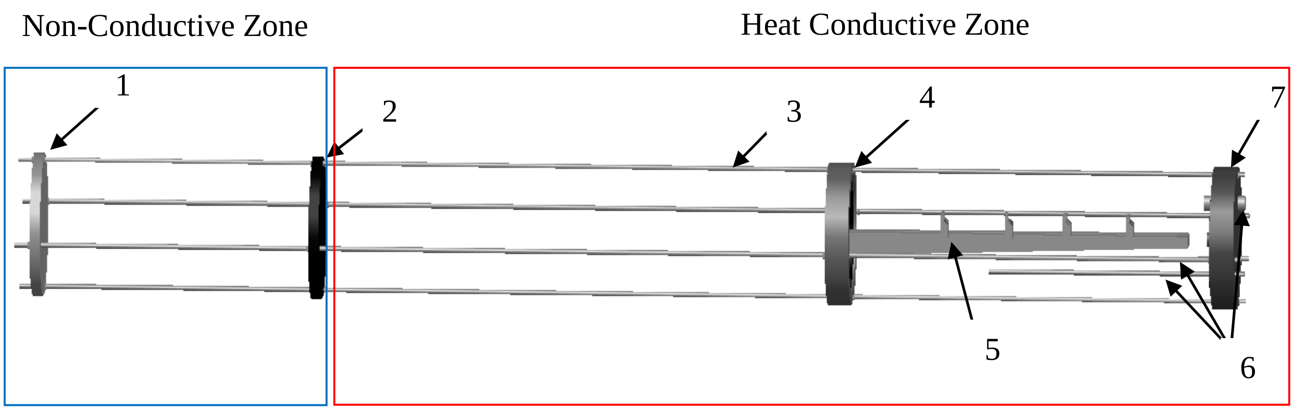


Figure 1: Structural components of the DLA - 1) Stainless steel support disk; 2) Ceramic disk; 3) Support rods; 4) Inner stainless steel end cap; 5) Stationary sample holder assembly; 6) Access holes; and 7) Outer stainless steel end cap.

The samples will be held in a sample holder and exposed to corrosive gas mixtures (e.g., I and Cs in He) within a containment vessel (Figure 2) that is end-capped by two 316 stainless steel disks. The end caps will be machined to accommodate Teflon gaskets and access holes. The gaskets seal the corrosive gas mixture in the containment vessel, while the access holes permit gas connections and instrumentation wiring (e.g., thermocouples, strain gauges, and a pressure transducer). Finally, the containment vessel wall, which is not depicted in Figure 1, will be a 2 mm thick 316 stainless steel sheet rolled into a cylinder.

The sample holder for the split-ring Zircaloy-4 cladding samples will revolve around three parallel bars. Two bars will be stationary while a mobile third bar, attached to a controlled linear actuator, applies load to the samples. The cladding samples are held to the bars using a series of teeth-like structures as illustrated in Figures 2 and 3. The spacing between the stationary and mobile teeth at the unstressed position is the initial displacement of the C-ring. As the mobile centre bar is pushed into the containment vessel, a hoop stress is applied to the cladding samples.

A programmable hybrid non-captive stepper linear actuator (Anaheim Automation, 11AV102AX06-SB) controls the applied stress to the split-ring cladding samples, with a displacement and cycling frequency that are controlled and recorded by an in-house designed LABVIEW™ program. The linear actuator will be located outside of the heated zone and will be connected to the centre-stressing bar through a heat shield and a 316 stainless steel Huntington bellows (Figure 3).

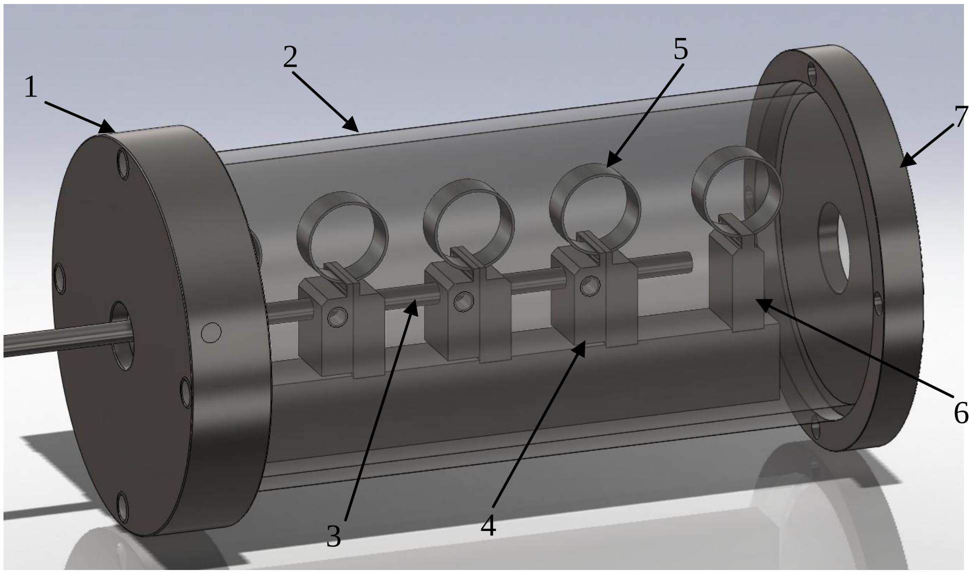


Figure 2: Components of the containment vessel - 1) Inner stainless steel end cap; 2) Outer boundary of the containment vessel; 3) Mobile rod; 4) Mobile teeth; 5) C-ring sample; 6) Stationary sample assembly; and 7) Outer stainless steel end cap

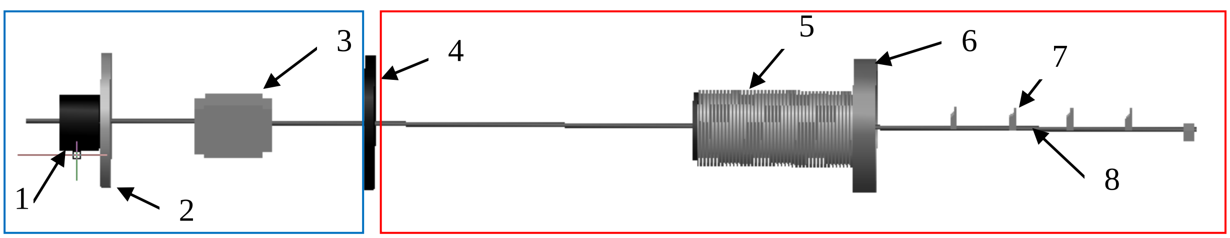


Figure 3: Stressing mechanism in the DLA, which contains the following - 1) Stepper linear actuator; 2) Stainless steel support disk; 3) Load cell; 4) Ceramic disk; 5) Huntington bellows; 6) Stainless steel end cap; 7) Mobile sample holder; and 8) Mobile bar.

3.0 DLA Instrumentation and Measurement

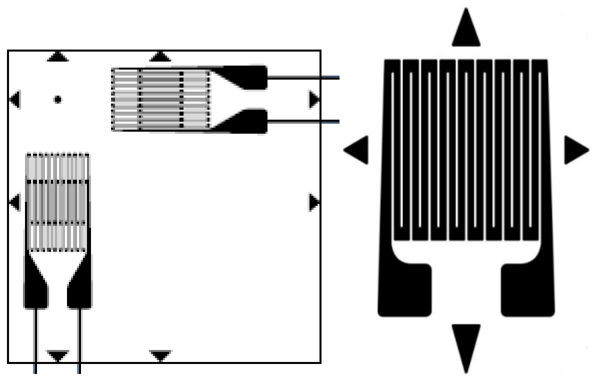
During operation, the DLA will measure the stress field applied by the linear actuator, as well as the temperature and pressure in the containment vessel. Accurate measurements of hoop stress will be achieved using two strain gauge configurations: 1) a strain gauge rosette (Tokyo Sokki Kenkyujo (TML), ZFCA-1-350) (Figure 4a); and 2) a unidirectional strain gauge (HITEC Products, Inc., HFK Series Free Filament) (Figure 4b).

There are two reasons for implementing the strain gauge rosette. First, the perpendicular circuit combined with the quarter bridge allows for temperature compensation, so that stresses induced from thermal expansion can be differentiated from the stress induced by the linear actuator. Second, using a rosette with a regular bridge allows measurement of both the parallel and perpendicular strains on the rings.

Each configuration will have two resistance values, 120 Ω and 350 Ω. Higher resistance strain gauges have higher strain sensitivity at the expense of reduced fatigue lifetime. Therefore, having both resistances allows measurements to be minimally compromised by sensitivity and lifetime.

A load cell (Omega, LCFD-10) will be used to determine when a C-ring has failed. Since the experiments will be conducted in a tube furnace, no visual cues are available to indicate C-ring failure. Consequently, we will rely on a real-time graph of force vs. time, in which a sharp decrease in force below a constant operational value indicates each C-ring failure.

Temperature measurements will be collected using K-type thermocouples (Omega, CA316SS-18U-12-NHX) in a well that is fabricated in the outer end-cap of the containment vessel. The potential lag in temperature measurement is well outweighed by the benefit of having the thermocouple protected from the corrosive environment within the containment vessel. Finally, the total pressure will be measured using a pressure transducer (Omega, PX1009L0-025AV) located in the centre of the outer end cap of the containment vessel (Figure 2).



(a) (b)

Figure 4: Circuit Schematic for Strain Gauges a) Strain Gauge Rosette b) Single Gauge

4.0 Summary

This paper has outlined the design of a DLA for performing SCC experiments in the laboratory. Construction of this apparatus is underway at RMCC. It is expected that the DLA will be a valuable tool in the development of novel SCC mitigation strategies for nuclear fuel.

5.0 Acknowledgements

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6.0 References

1) Gacesa, M., Boczar, P.G., Lau, J.H.K., Truant, P.T., Young, E.G., and Macici, N., *Canadian Fuel Development Program*. Atomic Energy of Canada Ltd. (AECL) CANDU, AECL-1064, November 1992.

2) Wood, J.C., Surette, B.A., Aitchison, I., and Clendening, W.R., *Pellet Cladding Interaction – Evaluations of Lubrication by Graphite.* Journal of Nuclear Materials, Volume 88, Number 1, Pages 81-94, 1980.

3) Chan, P.K., Irving, K.G., and Mitchell, J.R., *The Role of Zr_xI_yC Compounds in Minimizing Stress Corrosion Cracking in Fuel Cladding.* Proceedings of the 3rd International Conference on CANDU Fuel Performance, 7-24/7-40, 1992.

4) Cox, B. and Wood, J.C., *Iodine Induced Cracking of Zircaloy Fuel Cladding - A Review*. Atomic Energy of Canada Limited, Report AECL-4936, 1974.

5) Wood, J.C., *Factors Affecting Stress Corrosion Cracking in Iodine Vapour*. Journal of Nuclear Materials, Number 45, Pages 105-122, 1972/73.

6) Private Communication with Surette, B.A., Atomic Energy of Canada, June 2012.