Graduate Project Proposal: MECH 5908 [1.5 credit] (MCG 5398)

Independent Engineering Study:

Students pursuing a master's degree by course work carry out an independent study, analysis, and solution of an engineering problem or design project. The results are given in the form of a written report and presented at a departmental seminar.

Project title:

Design of a low hydrogen rolled joint for CANDU fuel channels

Project manager: Glenn McRae

Problem statement

In July 2021 Bruce Power reported high concentrations of hydrogen isotopes, Heq, in the Zr-2.5Nb pressure tubes of some rolled joints in Units 3 and 6 that were beyond licencing limits. In the same month the Canadian Nuclear Safety Commission (CNSC) issued an order requiring that, prior to restart, reactor operators needed to demonstrate that a.) hydrogen isotope concentrations were within allowed limits, and/or, b.) that no flaws are present in the regions where the industry models failed to conservatively predict elevated hydrogen isotope concentrations [1]. It was the opinion of CNSC staff that the industry "does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding" of elevated Heq in the Zr-2.5Nb alloy at the rolled joints of some pressure tubes [2]. The industry response has been to undertake a detailed evaluation of whether pressure tube leak-before-break can be relied upon to foretell potential accidents that could arise from these elevated concentrations, and to update and enhance its probabilistic safety assessments for flaws that could lead to delayed hydride cracking.

Anticipating high Heq concentrations at the rolled joints, researchers at Carleton University have developed a working hypothesis for the ingress mechanism and ideas to retrofit and re-design fuel channels to reduce concentrations [3,4]. A mechanistic model has been proposed that predicts ingress spatial profiles to within observed measurement uncertainties for tubes that are assumed to getter hydrogen from the rolled joint stainless-steel end-fittings early in-service [5]. Based on laboratory testing, it was proposed that strategic placement of a strong hydrogen getter on the outside surface of the end-fitting could pull hydrogen isotopes away from the pressure tubes at the rolled joints perhaps reducing concentrations to levels below cracking thresholds. Concentrations might also be reduced by using low-Hydrogen 403 stainless steel to make the end-fittings.

Technical objectives

The goal of this project is to design a low-hydrogen rolled joint for CANDU fuel channels.

- A method to retrofit current end-fittings in CANDU reactors will be developed based on ways and means of fixing suitable getters to end-fittings. Yttrium has been shown to getter hydrogen from zirconium through stainless steel in laboratory experiments. Results of simple lab-scale diffusivity experiments have been shown to scale to reactor-size [5], so it is expected that yttrium suitably placed outside of the reactor core and on the stainless-steel end-fittings should also getter hydrogen from the zirconium at the rolled joint. The challenge will be to find a way to retrofit the end-fitting by attaching yttrium to the stainless steel. Techniques to be investigated will include, for example, threading a ‘bolt’ of getter material into the end-fitting, and cold spraying a thin layer of getter on the surface of the end-fitting. Any technique will have to be simple, clean, and quick to apply because the radiation at the reactor face limits time for any work, and because of the time-imperative to have the reactors running to keep the lights on – shutting the reactors down for lengthy retrofits will not do. The technique must also meet the regulations associated with work done at reactor sites. The constraints on how this retrofit will be accomplished are severe. The designs of the team will need to satisfy the physics of gettering, will need to make an effective mechanical attachment work, should that be the way to go, and do so in a timely manner, and satisfy the regulator. The cost and effectiveness of additional methods and ideas to reduce Heq at the rolled joints will be discussed and developed.

- The second anticipated design path will be to investigate whether low-Hydrogen stainless steels can be manufactured and whether they maintain low hydrogen concentrations in-service. This path would be used to make low-hydrogen end-fittings for new builds. Currently, surprisingly, there is no standard provided by the Canadian Standard Association for hydrogen concentration in the stainless steel used to manufacture end-fittings – gettering hydrogen from the end-fittings into the Zr-2.5Nb pressure tube at the rolled joint has not been considered until recently [3-5]. This second design path will provide opportunities for students to talk with steel manufacturers about their processing methods, and to work with them to find methods to reduce hydrogen in as-received end-fittings for new builds.
- There will also be an opportunity for students to develop a solid model CAD rendering of the rolled joint that shows the movement of hydrogen isotopes during the gettering process. The model will be based on the Einstein flux equation for hydrogen diffusion in the presence of concentration gradients and stress gradients (G.A. McRae, C.E. Coleman, H.M. Nordin, B.W. Leitch, S.M. Hanlon, “Diffusivity of hydrogen isotopes in the alpha phase of zirconium alloys interpreted with the Einstein flux equation”, J. Nuclear Materials, 510 (2018) 337-347.).

Learning objectives

Students will

- work with professionals from industry and government (CNSC) in a professional setting like they would experience in real life. The students will learn to organize meetings, take minutes, suggest and take actions, and report on actions.
- learn how to give effective presentations and write informative and logical reports.
- experience the iterative design process personally with their own contribution to the project, but also through discussions with other students about their contributions.
- work independently and in teams.
- learn about materials science and engineering, thermodynamics, material properties, metallurgy, diffusion in stress gradients, hydrogen embrittlement and delayed hydride cracking, methods of measuring hydrogen concentrations, and models of solubility limits.
- learn about working in a regulated radiation environment.
- learn about how to design a retrofit.
- work on a current world-class problem that is economically vital to the province.

A desired outcome of this project is for students to present the results of these investigations at the CANDU Maintenance and Nuclear Component Conference of the Canadian Nuclear Society (CNS),

usually held at the end of April, and at the annual CNS conference that is usually held in June. Of course, presenting at a conference is not a requirement of the project, it is just an opportunity that will be offered, especially to students who might wish to work in the nuclear industry. Students can attend CNS conferences for free and travel expenses will covered by NSERC and our industry collaborators. Information about these conferences can be found by following these links:
CANDU Conference - CNS CANDU Conference (cns-candu.com)
Canadian Nuclear Society (cns-annual-conference.org)

Scope

The scope will be to assess the practical feasibility of the proposed solution to lower hydrogen concentrations in the Zr-2.5Nb pressure tubes of CANDU rolled joints. There are two goals. First, to provide a few promising methods of applying getters that could be used to retrofit existing end-fittings. Second, to evaluate methods to lower hydrogen concentrations in as-received end-fittings by modifying manufacturing. The direction of the project will depend on the skills and interests of the students but will include the following milestones:

- Review relevant references [1-5] and references therein.
- Review CNSC rulings and licencing procedures.
- Collate methods that might be used to apply getters to stainless steels (i.e., bolts, cold-spray films, gasses, etc.) and design methods of fixture and application.
- Review manufacturing methods for making stainless steels with a focus on hydrogen concentrations.
- Talk with steel manufactures to learn about the flexibility of production processing, and their experience with hydrogen.
- Collaborate with metallurgists to design a low-hydrogen manufacturing process.
- Construct a solid model CAD rendering of the rolled joint that shows hydrogen isotope movement to be used to optimize getter geometry on the end-fitting.
- Make and test lab-scale prototypes

Application Procedure

Please send a CV and a brief description of why you are interested in this project to the project manager at glenn.mcrae@carleton.ca . The project will officially start May 1, 2025.

References

1. 20210726-designated-officer-order-to-Bruce-Power.pdf (nuclearsafety.gc.ca), Canadian Nuclear Safety Commission, July 2021
2. Canadian Nuclear Safety Commission, March 24, 2022, Event Initial Report CMD 22-M16
3. G.A. McRae, C.E. Coleman, S.T. Langille, A method for prevention of ingress of hydrogen isotopes and their removal from components made from hydride forming metals and alloys, Canadian Patent Application No. 3,007,703 Filed June 8, 2018.
4. S.T. Langille, C.E. Coleman, G.A. McRae, (April 1, 2021). “Deuterium Ingress at the Rolled Joints in CANDU Reactors: Where Does It Come From and How Can It Be Reduced?”, ASME J. of Nuclear Eng. and Rad. Sci. July 2021; 7(3): 031801. https://doi.org/10.1115/1.4048313
5. G.A. McRae, C.E. Coleman, Deuterium concentration profiles at the rolled joints of CANDU fuel channels, Journal of Nuclear Materials 573 (2023) 154128