FUEL FOR A SUPERCRITICAL WATER PRESSURIZED HEAVY WATER REACTOR

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Abstract

Fuels for current water-cooled power reactors are primarily sheathed/clad in Zircaloy-4. While Zircaloy-4 has proven to be highly successful, it loses strength rapidly at temperatures above those of current reactor cooling systems. This makes Zircaloy-4 an unsuitable material for fuel sheath/cladding in a supercritical water-cooled reactor that operates at considerably higher coolant temperatures. Therefore, single crystal sapphire is being considered as a sheath/clad material for uranium oxide fuel in a supercritical water PHWR[1].

This paper identifies sixteen damage mechanisms as being credible for the refit sapphire fuel. They are binned into three groups: thermal integrity, structural integrity, and compatibility with interfacing components. Even though some material properties of sapphire currently have uncertainties, we expect that a sufficiently robust detailed design of the sapphire fuel can be crafted for the refit reactor.

1. Introduction

Suretech Development Limited – SDL – is developing a high-efficiency core [1] for PHWRs that can be back-fitted into current reactors. The "refit core" would almost double the electricity generated by the reactor [1]. A large component of this would come from operating the turbine at a much higher temperature – about 600 °C [1]. This compares with about 305 °C in the current CANDUs[2]. The increased thermal efficiency from the much higher temperature combined with higher average channel power would double the net electrical output.

Towards the above end, it is proposed to replace the Nuclear Steam Supply System and the turbine in the existing CANDU plants to increase the overall plant efficiency. The "refit" scheme is covered in a companion paper [1], which should be read in advance of this paper. The principal changes involved in the refit that have the largest impact on fuel design are:

- Coolant temperature increased from 305 °C to 625 °C.
- Coolant pressure increased from 10 MPa to 25 MPa.
- Natural uranium (NU) replaced by slightly enriched uranium (SEU).

To accommodate the above, several changes are proposed in the fuel design. Some of the key changes are single crystal sapphire as the clad material instead of the current Zircaloy 4; eutectic

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[1] PHWR: Pressurized Heavy Water Reactor
[2] CANDU: CANada Deuterium Uranium is a type of nuclear reactor.

bonding to assemble the fuel bundle; and tapered pellets. Section 4 describes the design in more detail.

At the operating temperatures of the refit fuel, the major advantages of single crystal sapphire -- compared to Zr-4 – are much higher Young's Modulus, higher yield strength, and higher resistance to corrosion.

But sapphire fuel's overall robustness in the refit reactor is influenced by many additional characteristics as well – for example, fatigue, impact strength, melting point, etc. Therefore, to fully confirm the viability of the refit fuel assembly, detailed assessments are required for much wider set of parameters.

To initiate this process, this paper describes an initial step towards evaluating the use of single-crystal sapphire as a sufficiently robust sheath/clad material for the above reactor. The scope of this paper is to identify the potential failure modes-- i.e., the damage mechanisms -- of the above fuel during normal operation.

We also provide our qualitative judgements for the expected performance of the sapphire fuel for a few selected damage mechanisms. Due to reasons of space, the judgements are provided for some – not all – of the damage mechanisms. At this time, we can provide only qualitative judgements -- quantitative confirmations are expected to be available in a later phase of the project.

This paper first provides technical background about the refit reactor. Then we summarize the key design and operating conditions of the refit fuel. Then we describe the methodology used to identify the pertinent damage mechanisms. This is followed by our qualitative judgements of fuel integrity for the selected damage mechanisms.

2. Background

CANDU NU fuel was developed some 60 years ago using the technology and the materials – Zr-4, etc. -- of that time. Materials limit the maximum operating temperature to 305 °C. Notwithstanding the limitations, CANDU reactors and fuels have achieved great successes.

In the fuel channel of the refit reactor, the coolant would operate at temperatures up to 625 °C and pressures up to 25 MPa. At this elevated temperature, Zircaloy-4 is expected to possess insufficient strength and inadequate resistance to corrosion.

While stainless steel can be used -- and has been tested -- at higher temperatures than Zircaloy-4, it absorbs significantly more neutrons. This makes it a poor choice for PHWRs that are designed for high neutron economy.

Therefore, the clad of the refit core would be made of single crystal sapphire [1] –Al_2O_3—which is a ceramic. At the operating conditions of the refit fuel, sapphire exhibits significant strength, as discussed in the next section.

3. Strength of single crystal sapphire

Single crystal sapphire is currently used in several applications, viz. infrared transparent lenses for heat seeking missiles, visually and thermally transparent windows for fireplace inserts, and containment tubes for plasma. Therefore, literature is available for many of its material properties, e.g., see [2, 3, 4, 5, 6] for illustrative examples. Through its use in windows of spacecrafts and in fusion reactors, some understanding is also available about the impact of irradiation on its material properties [3, 4].

It was reported in 1986 that apart from nuclear fuels, sapphire was the ceramic that had received the most irradiation testing [4]. Nevertheless, over the full range of irradiation conditions expected in the supercritical water reactor, some of sapphire's irradiation properties are currently not known sufficiently comprehensively. This introduces an important uncertainty in the current state of knowledge which will need to be bridged in a subsequent phase of this project.

3.1 Young's Modulus

Zircaloy-4 has a Young's Modulus of 74 GPa at the current operating temperature, and it would drop to 53 GPa at refit's conditions. In comparison, the Young's Modulus of sapphire is about 410 GPa at refit's conditions.

3.2 Yield strength

A similarly simple comparison of yield strengths of Zircaly-4 and single crystal sapphire is difficult because the latter's yield strength can vary significantly with the nature of the loading (i.e. compression vs. tension), direction of the loading (e.g. hoop vs. longitudinal), temperature, fluence and manufacturing route.

As but one illustrative example of above -- single crystal sapphire's yield strength generally reduces with temperature and increases with fluence, albeit by different amounts. As the fuel moves down the channel, the coolant temperature and the fluence increase. The net impact is a general reduction in the yield strength – except for the compressive longitudinal yield strength. While the latter reduces substantially with temperature, its significant increase with fluence results in a local minimum at 400 ℃. This occurs in the first bundle (inlet end) in the return channel.

Notwithstanding the above complexities, an indicative -- even if somewhat simplistic -- comparison is given in the next paragraph. More detailed information is provided in References [2 to 6] and in Sections 7 and 14 of this paper.

Zircaloy-4 has a yield strength of 371 MPa at current operating temperature, and it would drop to about 36 MPa at refit's conditions. In comparison, at the refit conditions, sapphire's yield strength in the hoop direction is 1650 MPa in compression and 320 MPa in tension.

Therefore, compared to Zr-4's Young's Modulus and yield strength at current operating conditions, equivalent properties of sapphire at refit's high coolant temperature (625 ℃) are as follows:

- Sapphire's Young's Modulus is 5.5 times higher,
- Sapphire's yield strength in compression in the hoop direction is 4.4 times higher,
- Sapphire's yield strength in compression in the longitudinal direction is 2 times higher [5][3], and
- Sapphire's yield strength in tension in both the hoop and longitudinal directions is 14% lower.

Due to the first three bullets above, we expect that detailed assessments will confirm that the sapphire fuel has adequate design margins in most of the areas that are governed primarily by the above properties. Nevertheless, if due to the fourth bullet above, detailed assessments do uncover noncompliance with any acceptance criterion, the detailed design of the fuel and/or of the interfacing system will be appropriately modified.

Further, there is considerable opportunity to increase the tensile strength of single crystal sapphire through optimization of the cladding manufacturing processes to reduce imperfections [6].

Thus, at the operating conditions of the refit reactor, prima facia, single crystal sapphire's strengths in the above two areas appear promising. Single-crystal sapphire also exhibits high resistance to oxidation/corrosion. These qualities make it an appealing material for applications in supercritical water reactors.

3.3 Other considerations regarding fuel integrity

Nevertheless, fuel's overall integrity is influenced by many additional characteristics as well – for example, fatigue, impact strength, melting point, etc. References [7, 8] provide more complete lists of damage mechanisms (i.e., failure modes) for fuels used in the current PHWRs.

The corresponding list for refit fuel may well differ from [7, 8].

Eventually, one would need to determine whether the refit sapphire fuel has sufficient strength to resist all the credibly expected loads. As an initial step towards the above end, Section 9 of this paper identifies all credible damage mechanisms of sapphire-clad fuel during the normal operating conditions that are expected in the supercritical water reactor.

4. Design of refit sapphire fuel

The 37-element bundle, or its derivative 37M, is the workhorse of the operating CANDUs. Extensive operational feedback has confirmed that CANDU fuel is by far the most reliable nuclear fuel in the world [9]. An IAEA survey [9] has identified the following rates of fuel bundle (assembly) failures worldwide, expressed as the number of fuel bundles (assemblies) with defected fuel elements per 1,000 assemblies discharged during 2006-2015 (10 years):

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[3] This strength includes neutron irradiation [5] which is present in fuel bundles in positions 2 through 12. In bundle 1, the temperature is lower and therefore the yield strength is higher.

- WWER-1000s[4]: 21.5 defected assemblies in 1,000 discharged assemblies,
- PWRs[5]: 7.1 defected assemblies in 1,000 discharged assemblies,
- BWRs[6]: 2.4 defected assemblies in 1,000 discharged assemblies,
- Indian PHWRs: 0.79 defected assemblies in 1,000 discharged assemblies,
- All CANDUs worldwide (including those in Canada): 0.11 defected assemblies in 1,000 discharged assemblies, and
- Canadian CANDUs: 0.1 defected assemblies in 1,000 discharged assemblies.

Current CANDU fuel is also inexpensive [10].

Nevertheless, in view of the considerably higher coolant temperature of the refit reactor, SDL has chosen to minimize the risk of overheating the pellets by adopting the CANFLEX geometry [11] as the configuration and the external dimensions of the refit fuel bundle. That is, the refit fuel bundle will use 43 fuel elements with the same external dimensions and geometry as the CANFLEX fuel bundle.

Compared to the current 37-element bundle, the 43-element CANFLEX bundle distributes the bundle power among (43/37=) 16% more fuel elements. Thus, other things being equal, one can expect a corresponding reduction in the average power of each fuel element of a CANFLEX bundle. Second, because of different diameters of fuel elements in different rings of the CANFLEX bundle, the bundle power is distributed more uniformly to individual fuel elements. Together, the above two effects reduce the peak power rating in the CANFLEX fuel elements by about 18%. This cascades into corresponding reductions in pellet and clad temperatures. This in turn reduces the severity of damage mechanisms that are driven by high temperatures.

Everywhere in the refit fuel bundle, Zircaloy-4 will be replaced by single-crystal sapphire.

The clad will be free-standing. That would eliminate the potential for longitudinal ridges and hence eliminate the associated plastic stresses and strains at the tips of the longitudinal ridges.

The appendages will not be brazed but joined to the clad eutectically at temperatures below sapphire's melting temperature.

To reduce stresses and strains due to differential expansions of the various rings of fuel elements, only some fuel elements will be bonded to the endplates at both ends. Others will be bonded at only one end. At the other end, the fuel elements will be allowed to slide back-and-forth in a mating hole in the endplate.

Due to the superior resistance of sapphire to stress corrosion cracking, CANLUB[7] is not expected to be required; therefore, it is not included in the current reference configuration.

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[4] WWER – Water-Water Energetic Reactor – is a type of nuclear reactor.

[5] PWR – Pressurized Water Reactor – is a type of nuclear reactor.

[6] BWR – Boiling Water Reactor – is a type of nuclear reactor.

[7] CANLUB is a thin layer of graphite that is applied to the inner surface of clads in current fuels to increase their resistance to stress corrosion cracking.

The pellets will use a mixture of natural uranium and slightly enriched uranium. This will compensate for the additional parasitic neutron absorptions in the refit reactor [1]. The enrichment will be minimal – about 0.9%.

Tapered pellets will be used to significantly reduce/eliminate circumferential ridges and the associated high stresses. The diametral gap between the pellet and the clad will be reoptimized to better balance the ridge stresses and fission gas release for conditions specific to the refit fuel.

Belleville washers will be inserted at the ends of the pellet stacks. The current plan is to make them from stainless steel that has been doped with a neutron-absorbing material such as hafnium. But this selection is currently tentative pending detailed design. The washers would: (a) reduce end flux peaking; (b) space out the axial gap; and (c) in some fuel elements, under some conditions, cushion the movement of the fuel pellets during impacts, thereby reducing the mechanical shock.

5. Operating powers in refit sapphire fuel

- Peak channel power: 7.96 MW
- Peak bundle power: 887 kW
- Peak element rating: 44.5 kW/m
- Average bundle exit burnup: 300 MWh/kgU
- Single bundle refuelling

6. Coolant conditions in refit sapphire fuel

- Temperature: 248-625 °C
- Pressure: about 25 MPa
- Coolant velocity: 1-20 m/s
- Mass flow rate: 4.2 - 7.4 kg/s

7. Key properties of sapphire at refit's operating conditions

- Young's Modulus: about 410 GPa
- Yield strength:
  - 1650 MPa in compression
  - 320MPa in tension
- Axial irradiation strain: up to 3.5%
- Plastic ductility: none
- Creep: negligible

8. Damage mechanisms--methodology

A large number of design, fabrication, and operational parameters and in-reactor processes affect the integrity of fuel. Previous studies have organized them into a more manageable number of Damage Mechanisms [7] – or Failure Modes. This section explains how the pertinent Damage Mechanisms were identified for the refit sapphire fuel.

'Damage mechanism' is a process that, if excessive, would render the fuel bundle unsuited to fulfil its design requirements. This could occur in any part of the fuel bundle or in the fuel bundle as a whole.

In this context, 'not damaged' means that the fuel elements do not fail, that the fuel bundle maintains its structural integrity, that fuel bundle dimensions remain within operational tolerances, and that functional capabilities are not reduced below those specified in design requirements and/or assumed in safety analyses. ‘Fuel element failure’ means that the fuel element leaks and that the final fission product barrier in the fuel – the clad – has therefore been breached.

In addition, it is well known that in some adverse situations, fuel has a potential to damage the pressure tube, for example through fretting, wear, crevice corrosion, etc. At AECL[8], the fuel designer has historically had the responsibility to confirm that all credible interactions of the fuel with the pressure tube are within specified limits. For this reason, damage mechanisms related to interactions between the fuel and its surroundings are also included in our checklist.

To identify damage mechanisms for the refit PHWR fuel, we started with a list of credible damage mechanisms in current CANDU fuels. They are given in References [7, 8]. They are based on first principles as well as on a comprehensive survey of fuel defect experiences in commercial as well as in experimental CANDU reactors [12].

In preparing the above list, LWR[9] literature was also surveyed. If a damage mechanism of LWR fuel was judged “generic” to water reactor fuels or otherwise relevant to CANDUs, it was added to our list.

CANDU fuel’s damage mechanisms were initially formulated [13] at AECL to design ACR[10] fuel [14]. This process included discussions with CNSC[11]. These damage mechanisms were subsequently incorporated in an IAEA[12] document [8] whose technical content was led by CNSC.

The above damage mechanisms have been used to license 37M fuel in South Korea and in China. They are similar in nature to damage mechanisms in LWR fuel that are identified by U.S. NRC[13] [15] and used to design LWR fuels in large parts of the western world.

We then adjusted the above list to accommodate the differences between the current CANDU fuel and the refit fuel. As illustrative examples:

- We have removed considerations related to brazing, beryllium, and welding.
- We have accounted for the potential for brittle fracture and for eutectic bonding in sapphire.
- We have accounted for significant temperature gradients along the length of the refit fuel bundle that are created by low mass flow of coolant in the refit fuel channel relative to existing CANDUs [1].

The resulting damage mechanisms are listed in the next section.

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[8] AECL: Atomic Energy of Canada Limited
[9] LWR: Light Water Reactor
[10] ACR: Advanced CANDU Reactor
[11] CNSC: Canadian Nuclear Safety Commission
[12] IAEA: International Atomic Energy Agency
[13] NRC: Nuclear Regulatory Commission

9. Checklist of damage mechanisms in refit sapphire fuel

The purpose of this checklist is to compile a systematic, comprehensive enumeration of all known credible damage mechanisms. This is expected to minimize the possibility of inadvertently overlooking any important damage mechanism.

Some properties of sapphire are currently not known in sufficient detail, for example the impact of neutrons on the oxidation and hydriding behaviours of sapphire. In such situations, we have chosen to be conservative and have retained those mechanisms in our checklist. Subsequent investigations may well warrant their removal.

The list below is at a level similar to the one in U.S. NRC's Standard Review Plan for Fuel System Design [15], however, the contents of our list have been tailored to the refit PHWR fuel.

U.S. NRC's checklist [15] identifies 21 damage mechanisms for all states of an LWR plant – normal operations, anticipated operational occurrences, and design basis accidents. A majority of them apply to normal operations. In comparison, this paper lists 16 damage mechanisms for refit PHWR fuel that focus exclusively on normal operations.

The checklist below categorizes the damage mechanisms into three major groups: thermal integrity, structural integrity, and compatibility between the fuel and the interfacing systems.

a) Thermal integrity of fuel
    i. Overheating of the pellet (melting),
    ii. Overheating of the clad and other structural materials (including dryout).

b) Structural integrity of fuel
    iii. Element internal gas overpressure,
    iv. Power ramps (stress corrosion cracking, pellet/clad interaction) ,
    v. Static mechanical overstress and/or overstrain,
    vi. Mechanical rupture due to impact loads,
    vii. Fatigue,
    viii. Loss of control of geometry,
    ix. Deposits, crud, oxide, primary deuteriding/hydriding, and effusion,
    x. Insufficient residual strength for post-irradiation handling.

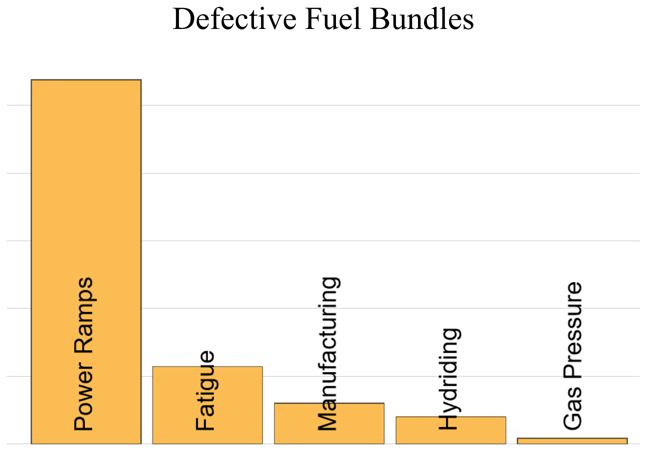
c) Compatibility with surroundings
    xi. Excessive interaction loads on the fuel string,
    xii. Excessive dimensional interference with interfacing equipment,
    xiii. Inappropriate contact among mating components that leads to overheating,
    xiv. Fretting,
    xv. Wear,
    xvi. Crevice corrosion.

In addition, given the significantly different (a) operating conditions of this fuel and (b) some of the materials, we would expect to encounter unknowns – "known unknowns" as well as "unknown unknows".

As a "reality check", Figure 1 shows the cumulative defective fuel bundles during defect excursions in Canadian power reactors during a 44-year period ending in 2013. A comparison confirms that the list above covers all the damage mechanisms encountered in Canadian defect excursions included in Figure 1.

The figure also illustrates that historically, power ramps have been a dominant cause of fuel failures in CANDU fuels.

The following sections describe the expected performance of sapphire fuel for a few damage mechanisms selected from the above list (limited by available space). The associated descriptions of the damage mechanisms are based significantly on existing published literature, e.g. [7, 8].



Above data exclude fretting failures due to debris

Figure 1: Causes of Fuel Defect Excursions in Canadian Power Reactors (1969- 2013)

10. Overheating of the pellet

If the pellet melts, the resulting volumetric expansion of the pellet may potentially push the clad past breaking. Therefore, during normal operations, the design avoids melting of the pellet.

Although many factors influence pellet temperatures, four primary drivers are as follows: (i) power produced in the fuel element; (ii) coolant temperature; (iii) gap between the pellet and the sheath; and (iv) thermal conductivity of the pellet.

Some local variations can impact the above, for example, end flux peaking creates local peaks in pellet temperatures. A CANDU fuel string consists of 12-13 short bundles in a channel. One consequence is that local peaks of flux are created at the ends of fuel bundles, which in turn lead to local peaks of pellet temperature near the ends of pellet stacks. Refs [7, 16] provide additional details.

Compared to the current 37-element fuel, the refit sapphire fuel will operate at higher coolant temperature and will have free-standing clad. These factors will increase pellet temperatures.

The above influences are compensated, in part, by the refit fuel's CANFLEX geometry, by pre-charging the fuel with high pressure helium, and by its Belleville washers. As noted in Section 4, the CANFLEX geometry reduces the peak element rating. The high-pressure helium pre-charge provides a favourable ratio of helium to fission gas in the gap space, thus improving gap thermal conductivity. The Belleville washers are located at the ends of the pellet stack; therefore, their neutron-absorbing material reduces the local peak of neutron flux.

Our judgement is that the net impact of the five competing factors above would result in higher pellet temperatures in the refit fuel. Nevertheless, our judgement is that the pellet would not melt. We intend to confirm this through more detailed quantitative evaluations.

11. Overheating of the clad and other structural materials

Overheating can degrade the strength of the clad material. It can also promote creep, oxidation, and crevice corrosion.

The operating temperatures in the refit sapphire clad will be higher than in current CANDU clads. Nevertheless, at the design conditions, the flow regime will be far from dryout, and significant degradation of heat transfer is not expected [1]. We expect the operating temperatures in clad materials to stay well below their local melting temperatures.

12. Element internal gas overpressure

During irradiation, fission gas is generated within the grains of UO_2, and some of it migrates to the ‘open’ space between the pellets and the clad. The latter is called the “released” gas. If the fission gas release is large, internal gas pressure can exceed the coolant pressure. This can potentially cause cracks at two locations of stress concentrations: (a) at the clad/end cap junction, and (b) at the junction of the clad and the bearing/spacer pad.

Internal gas overpressure can potentially also cause excessive outward creep of the clad, which in turn can thin the clad. If the thinning is excessive, the clad can crack. Excessive creep in fuel clads can potentially also affect the thermohydraulic conditions in the surrounding coolant, thus potentially also reducing heat transfer to the coolant.

For the above reasons, it is good practice to limit the maximum gas pressure that is allowed in the fuel element.

Compared to the current 37-element fuel in a C6[14] reactor, the refit sapphire fuel will operate at higher temperatures. This will release more fission gas. As a compensating factor, irradiation will elongate the sapphire clad considerably – by up to 17 mm (estimated). This is expected to provide sufficient space in the fuel to keep the gas pressure below the coolant pressure.

13. Power ramps

Irradiation can potentially reduce the strength of the clad material. During subsequent power ramps, the weakened clad can experience high stresses and strains in the presence of a corrosive internal environment. This combination can potentially crack the clad via stress corrosion cracking (SCC) or via pellet clad interaction (PCI). The most vulnerable locations are circumferential ridges, clad/end cap junctions, clad/pad junctions, and pellet chips if any.

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[14] C6 is a specific size of the CANDU reactor.

In this context, the clad stresses are caused by power ramps. Therefore, this mechanism is also called “power ramp failures”.

Compared to the current 37-element fuel’s Zircaloy clad, sapphire is expected to be significantly more resistant to SCC. Second, the single-bundle shift in the refit reactor is expected to result in much smaller power-ramps. Third, the tapered pellets in the refit sapphire fuel will minimize the size of circumferential ridges. For the above reasons, SDL feels that the SCC/PCI challenge is low in the refit sapphire fuel. Therefore. SDL has chosen to exclude CANLUB from the current configuration. This will be confirmed via more detailed assessments.

14. Static mechanical overstress and/or overstrain

During several situations such as refuelling, structural components of the fuel bundle can potentially be exposed to relatively high loads and/or to relatively sparse supports, leading to a potential for static mechanical overstress/overstrain.

In the refit fuel, axial temperature gradient along the length of the fuel bundle can be significantly higher than in current CANDU fuels. This can potentially cause differential diametral flaring in the refit fuel – larger than in current C6 fuels. This will impose additional bending stresses in the sheath, assembly joints, and endplate.

During discharge from the reactor, the refit fuel will experience quick transition from supercritical coolant to room temperature. This would rapidly quench and depressurize the fuel, and the fuel will have a potential to experience thermal and mechanical shocks.

At operating temperatures, compared to Zircaloy-4, sapphire’s Young’s Modulus is significantly higher. Further, the detailed design will ensure that the stresses stay below the yield strength. Therefore, at first glance, static mechanical stresses and strains are expected to stay within safe levels.

15. Mechanical rupture due to impact loads

Situations such as refuelling and/or start/restart can sometimes require a fuel bundle to travel at considerable speed from one location to another – until it hits a stationary fuel string. This can potentially impose significant impact loads on the fuel bundles. This usually occurs after some irradiation which may potentially affect the mechanical strength of the clad. If excessive, this combination can potentially damage the stationary and/or the travelling bundle.

Coolant mass flow rate (in kg/s) is considerably lower in the refit reactor’s fuel channel than in a C-6 fuel channel. This will result in lower impact loads in the refit fuel. Second, the high Young’s Modulus of sapphire means that it can store/absorb more elastic energy during impact. For these reasons, we expect that the sapphire fuel will have sufficient impact strength. This, however, is an area that will be confirmed with high priority in a next phase of this project.

16. Wear

Wear in the fuel bundle and in the pressure tube can be caused by a variety of sources -- e.g. sliding, erosion, fretting and vibrations. The resulting marks, scrapes and grooves -- collectively called 'flaws' -- have been observed in examinations of fuel bundles and of pressure tubes [17].

Fuel bundles slide into the fuel channel. This can cause sliding wear in the bearing pads and in the pressure tubes. In the refit fuel, sliding wear can also be caused when fuel elements slide back-and-forth in the hole in the endplate.

Excessive wear can lead to three potential consequences:

- Excessive fretting of spacer pads can potentially rub the corner of the spacer pad into the adjacent clad and damage it. Such damage has indeed been observed.
- Flaws can promote delayed deuteride/hydride cracking in pressure tubes. Fretting flaws are currently evaluated for initiation of delayed deuteride/hydride cracking in pressure tubes by using a procedure based on fitness-for-service guidelines [17].
- Wear can reduce the ability of the pressure tube to carry loads. Also, a sharp flaw can increase the local concentration of stress in the pressure tube. A flaw that is initially small can later grow; therefore, growth of flaws is monitored. Amounts of wear (including fretting) are usually controlled by limiting their driving forces to acceptable levels.

Compared to the current Zircaloy-4, sapphire is much harder. Therefore, other things being equal, sapphire can potentially cause larger wear in mating surfaces. For this reason, refit reactor's surfaces that mate with fuel will be made from, or coated with, sufficiently hard materials.

17. Summary and conclusions

Sixteen credible damage mechanisms have been identified for refit PHWR fuel during normal operations. They are organized into three groups:

- Mechanisms that can potentially threaten the thermal integrity of fuel through potential overheating. This comprises two damage mechanisms:
  - pellet melting
  - clad overheating.
- Mechanisms that can potentially threaten the structural integrity of fuel through potential cracks, breaks, or loss of structural stability. This comprises eight damage mechanisms:
  - gas pressure
  - power ramps -- stress corrosion cracking and pellet-clad interaction
  - mechanical overstress/overstrain
  - impact loads
  - fatigue
  - unstable geometry
  - deposits, crud, oxide, primary deuterides/hydrides, and effusion
  - insufficient residual strength for post-irradiation handling.

- Mechanisms that can adversely impact the geometric or the chemical compatibility of fuel with interfacing systems. Geometric compatibility is needed to ensure that critical parts mate/fit with their interfaces. Chemical compatibility is needed to ensure that crevice corrosion stays within design allowances. This group comprises six damage mechanisms:
    - string length
    - dimensional interference with interfacing equipment
    - inappropriate contact among mating components that leads to overheating
    - fretting
    - wear
    - crevice corrosion.

The above checklist of sixteen damage mechanisms is intended as an initial guide towards facilitating, in a later step, a comprehensive verification of the integrity of refit fuel during normal operations.

Our judgements suggest that the refit sapphire fuel will be more severely challenged in some areas such as pellet and clad temperatures, and less severely challenged in some other areas such as power ramps. We do expect that a sufficiently robust detailed design of the sapphire fuel can be crafted to successfully resist all credible damage mechanisms expected in the refit reactor.

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19. References

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[1] R. Lounsbury, “System design of a refittable supercritical water primary heat transport system for pressurized heavy water reactors”, to be presented at this conference.

[2] E.R. Dobrovinskaya, L.A. Lytvynov, V. Pishchik, “Sapphire: material, manufacturing, applications”, Springer, 2009.

[3] G.P. Pells, “Radiation damage effects in alumina”, Science of Alumina, Journal of American Ceramic Society, 77 [2] 368-377 (1994).

[4] F.W. Clinard, Jr., “The effect of irradiation-induced defects on fusion reactor ceramics”, Los Alamos National Laboratory, Report LA-UR-86-3123, DE87 000144, 1986.

[5] T. M. Regan, D. C Harris et al., “Neutron irradiation of sapphire for compressive strengthening. II Physical property changes”, Journal of Nuclear Materials, (300) 47 – 53, 2002.

[6] D. Black, “Strength-limiting surface damage in single-crystal sapphire imaged by X-ray topography”, Journal of American Ceramic Society, 84 [10] 2351 – 55 (2001).

[7] M. Tayal, M. Gacesa, “Fuel”, Chapter 17 in “The essential CANDU: A textbook on the CANDU power plant technology”, (ed.) W.J. Garland, University Network of Excellence in Nuclear Engineering (UNENE): McMaster University, Hamilton, Ontario, Canada (2014); www.unene.ca/education/candu-textbook

[8] International Atomic Energy Agency, “Fuel acceptance criteria during operational states – A designer’s perspective”. Annex 1 in “Technical review of acceptance criteria for pressurized heavy reactor fuel”, IAEA-TECDOC-1926, IAEA, Vienna (2020).

[9] International Atomic Energy Agency, “Review of fuel failures in water cooled reactors (2006-2015)”, IAEA Report NF-T-2.5, Vienna, 2019.

[10] R.D. Page, “Canadian power reactor fuel”, Atomic Energy of Canada Limited, Report AECL-5609, 1976.

[11] A.D. Lane, D.F. Sears, et al., “Bringing the CANFLEX fuel bundle to market”, Proceedings of the 4th international conference on CANDU fuel, V.1,2 (p 830), Pembroke, Canada, 1995 October 1 to 4.

[12] A. Sun, M. Tayal, “Technical basis for ACR-1000 fuel acceptance criteria”, Proceedings of the 11th International Conference on CANDU Fuel, Canadian Nuclear Society, Niagara Falls, Ontario, Canada, 17-20 October 2010.

[13] M. Tayal, P. Reid, M. Gacesa, et al., “ACR-1000 fuel acceptance criteria for normal operation and for anticipated operational occurrences”, Proceedings of the 10th International Conference on CANDU Fuel, Canadian Nuclear Society, Ottawa, Canada, 5-8 October 2008.

[14] P. Reid, M. Gacesa. M. Tayal, “The ACR fuel bundle design”, Proceedings of the 10th International Conference on CANDU Fuel, Canadian Nuclear Society, Ottawa, 2008.

[15] United States Nuclear Regulatory Commission, “Fuel system design”, Standard Review Plan, Section 4.2, NUREG-0800, Revision 3 (2007).

[16] M.H.M. Roshd, H.C. Chow, “The analysis of end flux peaking at nuclear fuel bundle ends using PEAKAN”, Report AECL-6174, Atomic Energy of Canada Limited, Canada (1978).

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[17] D.A. Scarth, T. Smith, "Developments in flaw evaluation for CANDU reactor Zr-Nb pressure tubes", J. Pressure Vessel Technol., 123 (2001) 41- 48.