ON SAFETY OBJECTIVES FOR CANDU FUEL IN DESIGN EXTENSION CONDITIONS

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ABSTRACT

To enhance protection to accidents beyond those considered in the design basis of the plant, and to reflect lessons learned from the Fukushima Daiichi accident, the Canadian Nuclear Safety Commission (CNSC) introduced the term "design extension conditions" (DECs) with the 2014 issue of regulatory document REGDOC-2.5.2, *Design of Reactor Facilities: Nuclear Power Plants,* and participated to the development of CSA Group document, CSA N290.16-16, *Requirements for beyond design basis accidents,* published in 2016. Although much work has already been done in Canada towards addressing DECs for CANDU reactors, the set of fuel safety criteria that should be used for DECs remains to be formulated. As a first step towards that goal, this paper examines fuel safety objectives that ought to be considered when formulating the fuel safety criteria to be met for CANDU-specific DECs.

The paper begins with a review of the various definitions of DECs and how DECs fit within the concept of defence-in-depth. This review is followed by a brief overview of the requirements and guidance for DECs provided by CNSC REGDOC-2.5.2 and CSA N290.16-16. A brief review of CANDU fuel behaviour in severe accidents and design-basis accidents is then provided, based on which certain fuel-related safety objectives for DECs are proposed.

The views expressed in this paper are those of the authors and do not necessarily reflect those of CNSC, or any part thereof.

1. Introduction

Ever since the March 2011 events at the Fukushima Daiichi Nuclear Power Plant (NPP) in Japan, nuclear regulators around the world launched various programs to assess and, if needed, revise their requirements and guidance regarding beyond design basis accidents (BDBAs) at existing and new water-cooled reactor facilities with the aim of further enhancing safety of nuclear facilities in their countries.

In order to promote the prevention and mitigation of BDBAs for both existing and new reactor facilities post-Fukushima, International Atomic Energy Agency (IAEA) amended the Safety Standards Series, SSR-2/1, *Safety of NPPs: Design (SSR-2/1, 2012)* of which Rev. 1 was completed in 2016 [1]. Significant efforts were made in Canada to account for lesson learned from the Fukushima accident. The Canadian Nuclear Industry updated its CANDU (Canadian Deuterium Uranium) Severe Accident Management Guidelines (SAMG) to reflect operating experience and lessons learned from Fukushima event [2]. The Canadian Stamdards Association (CSA) issued its Standard *N.290.16-16 "Requirements for BDBAs"* [3]. The Canadian Nuclear Safety Commission (CNSC) issued a number of Regulatory Documents (REGDOCs) [4, 5, 6] providing requirements and guidance regarding BDBAs. For instance, CNSC REGDOC 2.5.2 "Design of Reactor Facilities: Nuclear Power Plants" published in 2014 [4] and, to a large degree, represents the CNSC's adoption of the principles set forth by the IAEA in its Safety Standards Series SSR-2/1 Rev. 1 [1]. Although the REGDOC 2.5.2 sets out requirements and guidance for the application of design extension conditions (DECs) to new licence applications for water-cooled NPPs in Canada, the concept of DECs, as described in the document, and guidance provided regarding its application have been used [7, 8] to explore possible applications of DECs to existing facilities in Canada. In fact, following the reviews for refurbishment or extended operation at existing Canadian NPPs, many upgrades, as briefly outlined in Reference [8], to those facilities have already been made to address DECs.

This paper examines fuel safety objectives (FSOs) that ought to be considered when formulating the fuel safety criteria (criteria that must be met in order to avoid specific fuel damage/failure mechanisms and fuel element/bundle deformation behaviour) that must be met for CANDU specific DECs. Although the formulation of such objectives is based on current knowledge of high temperature fuel behaviours for existing fuel designs used in currently operating CANDU reactors, the FSOs mentioned in this paper should be still applicable to new fuel design (unless these new fuel design have significantly different high temperature behaviours) for CANDU reactors. Section 2 summarizes those fuel designs. In Section 3, the concept of DECs and its role in defence-in-depth (DiD) are reviewed. Information that proved useful for the discussion in Section 5 of FSOs for DECs is described in Section 4. Concluding remarks are provided in Section 6.

2. Current Operating CANDU Core and Fuel

The core of a CANDU reactor [9] consists of a large, thin wall, horizontal cylindrical tank (calandria) that contains low pressure/temperature heavy water moderator and pressure tubes (PTs). Each PT is located inside each calandria tube (CT). The principle function of the PT is to support and locate the fuel horizontally, and to allow the pressurized heavy water primary coolant to be pumped through the fuel and remove its heat. On-power refuelling is performed by two fuelling machines that can be attached to end fittings at each end of a fuel channel. The CANDU current fuels [10] are 28-element bundle for Pickering NPPs, regular 37-element bundle (37R) and modified 37-element bundle (37M) [11] for the Bruce/Darlington NPPs and 37R for Point Lepreau NPP. Where, as a part of the operators' plant aging management strategy, the 37M was introduced in Canada to aim at mitigating the effects of flow bypass due to pressure tube creep with a reduced central element diameter which results in an increase in bundle dryout power for a given bundle power. This 37M design improves safety margins of design basis events limited such as slow loss of regulation, loss of flow, and small-break loss of coolant, but is not enough to meet the requirements and safety goals of accident tolerant fuel (ATF) [12]. The operating conditions of those fuel bundles [10] are "about 300 ^{o}C of D_2O coolant temperatures", "9.6 ~11.6 MPa of nominal inlet pressures", "5.43 ~ 6.50 MW of nominal channel powers", "50.90 ~57.23 kW/m of maximum linear element powers", "636 ~ 900 kW of nominal bundle powers", and "170 ~ 196 MWh/kgU of average discharge bundle burnups.

3. Overall Descriptions of DECs

IAEA SSR-2/1 Rev.1 [1] sets out as Requirement 20 for DECs: "*A set of DECs shall be derived on the basis of engineering judgement, deterministic assessments and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures*."

3.1 Plant states, plant design envelope and DECs

A plant state is a configuration of NPP components, including the physical and thermodynamic states of the materials and the process fluids in them [4]. In Canada, plant states are grouped into a number of categories primarily on the basis of their frequency of occurrence at the NPP, and include operational states, DBAs and BDBAs (see Figure 1). BDBAs include events with frequencies of occurrence less than 10^{-5} per reactor year [3, 4, 5, 6]. Not included in Figure 1, but also considered part of the plant states is the "post- accident" state defined [6] as a long-term safe stable state that is achieved in the reactor facilities after an accident.

Figure 1. Plant states [5, 6]

<table>
<tr><td colspan="2">Operational states</td><td colspan="3">Accident conditions</td><td>→</td></tr>
<tr><td rowspan="3">Normal operation</td><td rowspan="3">Anticipated operational occurrence (AOO)</td><td rowspan="3">Design-basis accident (DBA)</td><td colspan="2">Beyond-design-basis accidents(BDBAs)</td><td>→</td></tr>
<tr><td>Design extension conditions(DECs)</td><td>Practically eliminated conditions</td><td>→</td></tr>
<tr><td>No severe fuel degradation (SFD)</td><td>Severe accidents</td><td>→</td></tr>
<tr><td colspan="3">Design basis</td><td>Design extension</td><td>Not considered as design extension</td><td>→</td></tr>
</table>

Reducing frequency of occurrence →

The Plant Design Envelope (PDE) concept is introduced in REGDOC-2.5.2 to represent "The range of conditions and events (including DEC) that are explicitly taken into account in the design of the nuclear power plant such that significant radioactive releases would be practically eliminated by the planned operation of process and control systems, safety systems, safety support systems and complementary design features." as described in the REGDOC. The PDE comprises the four plant states: normal operation, AOOs, DBAs and DECs.

The concept of DEC has been introduced by CNSC as part of the PDE with the purpose of defining those conditions which should be considered in plant design, in addition to the design basis conditions, with the purpose of further strengthening the plant safety. The CNSC defines DECs [3, 4, 6] as a subset of beyond-design-basis accidents that are considered in the design process of the facility in accordance with best-estimate methodology to keep releases of radioactive material within acceptable limits. As indicated in Figure 1, DECs comprises two category of plant states: one without significant fuel degradation (SFD) which are states with no core melting and no more than one channel fail, and another which involves severe accident conditions that could include core (fuel) melt and/or two or more fuel channel failures. Here we use V.G. Snell and et. al. [13] definition of a severe accident which is an accident in which the fuel heat is not removed by the coolant in the primary heat transport system.

The CNSC's definition of DECs is based on the one formulated by the IAEA [1, 14], but has been slightly modified to clarify that DEC is a subset of BDBA; it does not include BDBAs that can be considered to be "practically eliminated" where "practically eliminated" is defined [3, 4] as the possibility of certain conditions occurring being physically impossible or with a high level of confidence to be extremely unlikely to arise. CANDU specific examples of BDBAs that are considered "practically eliminated" are given in Reference [8].

3.2 Safety objectives and DECs

In support of the Nuclear Safety and Control Act **(**NSCA**)** and its associated regulations, the CNSC endorses [5] the general nuclear safety objective (also called "fundamental safety objective) established by the IAEA [15, 16] that NPPs be designed and operated in a manner that will protect individuals, society and the environment from harmful effects of ionizing radiation. This objective relies on the establishment and maintenance of effective defences against radiological hazards in NPPs. Compliance with this fundamental safety objective is required for all plant states within the PDE. This fundamental safety objective is supported by three complementary safety objectives, which deal with radiation protection, the technical aspects of the design, and environmental protection [4]. The general technical safety objectives, e.g. those associated to the technical aspects of the design, are to provide all reasonably practicable measures to prevent accidents in the NPP, and to mitigate the consequences of accidents if they do occur. This takes into account all possible accidents considered in the design, including those of very low probability such as DECs. When these objectives are achieved, any radiological consequences will be below prescribed limits, and the likelihood of accidents with serious radiological consequences will be extremely low. The primary means of achieving those general technical safety objectives is the application of the concept of DiD (IAEA Safety Fundamental Principle 8 [15]).

3.3 Roles of DECs in DiD and physical barrier integrity

DiD consists in a hierarchical deployment of different levels of equipment and procedures to maintain the effectiveness of physical barriers placed between radioactive materials and workers, the public or the environment, in normal operation, AOOs and, for some barriers, in accidents at the plant. DiD is implemented through design and operation to provide a graded protection against a wide variety of transients, incidents and accidents, including equipment failures and human errors within the plant and events initiated outside the plant [17].

Prevention and mitigation [18] are terms widely used in nuclear safety and they are mostly referred to accidents. The primary means of preventing and mitigating the consequences of accidents is DiD. With references to DiD, the essential means of each level prevent the need for activation of the essential means of the following level and, at the same time, they mitigate the consequences of the failure of the previous ones. Level 1, being the first level, has a predominant preventive function and level 5, being the last, has only a mitigatory function.

As pointed out in Reference [18], it is important to notice that currently there is not a unanimous agreement among IAEA Member States as to whether the DECs without core melt belong to level 3 or level 4 of DiD. The two positions, as summarized in Table 1, are well described in Reference [18]. Canadian approach is the approach 2. Canada [3, 4, 5. 7, 8] has adopted the approach which consists in having both categories of DECs being to level 4. The grouping of DECs without core melt, and with core melt, in level 4 facilitates the differentiation between the set of rules for design and safety assessment to be applied for DECs from those for DBA. In Canada, the general technical safety objectives for DiD levels 4a and 4b can be further refined into more specific technical safety objectives related to the containment, fuel channels and fuel (matrix and sheath). The CSA standard N290.16 [3] requires that the containment integrity be maintained for both DiD levels 4a and 4b to minimize radioactive releases.

Table 1. Levels 3 and 4 of DiD for the Design of New Nuclear Power Plants (NPPs) [18, 19]

<table>
<tr><th colspan="2">Level of DiD Approach 1</th><th>Objective</th><th>Essential design means</th><th>Essential operational means</th><th colspan="2">Level of DiD Approach 2</th></tr>
<tr><td rowspan="2">Level 3</td><td>3a</td><td>Control of DBAs</td><td>Engineered safety features (safety systems)</td><td>Emergency operating procedures</td><td colspan="2">Level 3</td></tr>
<tr><td>3b</td><td>Control of DECs to prevent core melt</td><td>Safety features for DECs without core melt</td><td>Emergency operating procedures</td><td>4a</td><td rowspan="2">Level 4</td></tr>
<tr><td colspan="2">Level 4</td><td>Control of DECs to mitigate the consequences of severe accidents</td><td>Safety features for DECs with core melts. Technical support centre</td><td>Complementary emergency operating procedures/severe accident management guidelines</td><td>4b</td></tr>
</table>

The provisions introduced at level 4a are aimed at not only ensuring that the plant's "contain" fundamental safety function will be performed to the degree of effectiveness required to ensure containment integrity, but also that the plant's "cool" and "control" fundamental safety functions will be performed to the degree of effectiveness required to ensure i) "coolable core geometry (CCG) and coolable bundle geometry (CBG)", and ii) "no contribution to core damage frequency and large release frequency", where maintenance of CCG implies no more than one channel failure, and CBG means that the channel decay heat can be removed from the bundles in a channel, in the long term, by the plant's cool safety function. In this paper, we shall refer to "the maintenance of containment integrity", "the maintenance of CCG", and "maintenance of CBG" as technical safety objective #1 (TSO1), TSO2 and TSO3, respectively.

4. Observations of CANDU Fuel Behaviours under Accident Conditions and Canadian Regulatory Requirements/Guidance

This Section will review information on i) the phenomena that can arise in nuclear fuel during high-temperature conditions [2, 20] and ii) the Canadian regulatory requirements/ guidance [4, 5] regarding fuel design and qualification for accident conditions. Of particular interest are the phenomena that could constitute a challenge to the maintenances of both a CCG and a CBG under DECs, namely those phenomena that lead to fuel bundle deformation and failure of the fuel matrix and/or sheath.

4.1 CANDU Fuel Behaviours for Accident Conditions

The understanding of CANDU fuel behaviour under high temperature conditions [20], including DECs without and with SFD, has been well advanced through many decades of experimental research and efforts in modelling and code development. And, taking into account lessons learned from the Fukushima events, the CANDU Owners Group (COG) published, in 2014, an update of its SAMG Technical Basis Document [21] which provides a description of basic characteristics of severe accident behaviour in CANDU reactors, including fuel and fuel channel behaviour. More recently, Lovell Gilbert provided an overview of the developmental aspects of CANDU SAMG [2]. Figure 2, which is based on information provided in References [2, 20], indicates the temperature at which various types of material interaction would occur during the evolution of a severe accident in a CANDU reactor.

Based on the information on a high temperature fuel behaviour with relevance to CANDU fuel [20] which relevant for at least DECs with SFD, the following thermomechanical damage and/or failure mechanisms of the fuel, sheath, element and bundle should be considered when formulating fuel safety objectives for DECs without SFD:

1) Fuel: melting and mechanical behaviours, including:
    - Relocation of fuel fragment inside of a strained fuel sheath,
    - Pellet bottoming (i.e., a pellet resting inside of a strained fuel sheath such that the pellet and the sheath are not concentric),
    - UO_2/Zircaloy interaction with either solid or liquid Zircaloy, depending on the temperatures achieved, and
    - energetic fragmentation and energetic dispersal of the fuel for accidents that include overpower transients.
2) Sheath: thermal-mechanical and chemical behaviours, including:
    - Diametral strain, oxidation (Release heat and production of hydrogen/deuterium gas; oxygen embrittlement) and hydriding, melting, etc.
3) Bundle: thermal-mechanical behaviours, including:
    - Element sag and bowing,

- Endplate deformation and bundle slumping,
- Bundle acceleration and impact for flow reverse in the fuel channel,
- Blowdown flow turbulence, and
- Axial thermal expansion and fuel string compression.

Figure 2. Material Chemical-Interaction: UO_2 Fuel Damage as a Function Temperature [2, 20]

Temperature(°C)	Note: Temperature approximate (most materials affected by O_2 content)
2840	UO_2 melting point (unsheathed); Melting of UO_2 (3120 K) [20]
2687	Melting of ZrO_2 [20]
2397	Formation of α-Zr(O)/UO_2 and U/UO_2 monotectics [20]
2100	Corium (U/Zr) Liquidus
1972	Melting of oxygen-stabilized α-Zr(O) [20]
1760	Melting of as-received Zry-4 (2030 K) [20]
1580	Significant H_2 production from Zr/H_2O (transition to cubic tetragonal)
1500	Fuel temperature when channel ruptures (full system pressure) & onset of fuel bundle gross deformation (slumping) & lowest onset of concrete ablation
1400	Stainless steel melting point & onset of H_2 production from Zr/H_2O reaction
1200	Channel sagging begins (oxidised)
1127	UO_2 in contact with Zr (liquefies U)
1120	U metal melting point; Formation of liquid U as a result of UO_2/Zry interactions [20]
1000	Channel sagging begins (unoxidized)
930	Zr/Fe eutectics; Formation of first Fe/Zr and Ni/Zr eutectics (1220 K) [20]
767	Cadmium boiling point; Melting of (Ag, In, Cd) alloy (1073 K) [20]
600	Onset of sheath failure
309	Fuel/coolant normal operation condition

- Fuel sheaths may be oxidized as a result of the exothermic chemical reaction between the high temperature steam in the fuel channel and the Zircaloy sheath
- Once the sheath temperatures exceed 1580 °C, hydrogen production accelerates until all exposed zirconium in the sheath is consumed. This may pose a challenge to containment integrity.

4.2 Canadian Regulatory Requirements and Guidance for DECs

The following Canadian regulatory requirements and guidance of fuel design and qualification for accident conditions are described in REGDOC-2.5.2 [4], and provide useful guidance regarding FSOs that ought to be considered when formulating the fuel safety criteria for DECs.

a. General design requirements for severe accidents within DECs described in REGDOC-2.5.2: The design should include the analysis performed for severe accident progression and consequence evaluation including assessments on topical issues, as applicable, such as “corium stratification”, “thermal-chemical interaction between corium, steel components and vessel”, “heat transfer from corium to vessel or end-shield”, “hydrogen burn”, “steam explosion due to molten fuel-coolant interaction”, and “corium-concrete interaction”.

b. Fuel system specific requirements for accident conditions described in REGDOC-2.5.2:
   a) Reactor core design requirement for DECs: *“The reactor core, including the fuel elements, etc. shall be designed so that the reactor can be shutdown, cooled and held subcritical with an adequate margin in DECs.*”
   b) Guidance of the fuel design and qualification which should provide assurance of the reactor core design requirements for accident conditions (DBAs and DECs). Acceptance criteria should be established for fuel rod failure and fuel coolability:
      - <u>Fuel rod failure</u> applies to operational states and accident conditions. The fuel rod failure criteria should be provided for all known fuel rod failure mechanisms. The criteria should include hydriding, overheating of fuel pellet and cladding, excessive fuel enthalpy, pellet-clad interaction, cladding bursting, mechanical fracturing, etc.

- Fuel coolability applies to DBAs and, to the extent practicable, DECs. The fuel coolability criteria should be provided for all damage mechanisms in DBAs and DECs. The cladding temperatures should not reach a temperature high enough to allow a significant metal-water reaction to occur, thereby minimizing the potential for fission product release. The criteria should include cladding embrittlement, fuel rod ballooning, structural deformation, etc.

5. Potential Safety Objectives for CANDU Fuel in DECs

The provisions introduced at level 4a are aimed at ensuring compliance with TSO1, TSO2, and TSO3 to prevent the DECs with core melt (4b; severe accident within DECs) and also to mitigate the DECs with SFD (4a). In order to be met, and depending on the specifics of the DEC being considered, theses TSOs could translate (in addition to other safety objectives not related to fuel behaviour) into a number of fuel safety objectives (FSOs) that in turn must be met. Fuel behaviour that ought to be taken into account when identifying the FSOs associated to each of the TSOs including the following (see definitions of PH# in Table 2):

1) TSO1 – Maintenance of containment integrity: PH1, etc.
2) TSO2 – Maintenance of CCG: PH2, PH3, PH4, PH5, PH6, PH7, etc.
3) TSO3 – Maintenance of CBG: PH3, PH4, PH5, PH7, PH8, PH9, PH10, etc.

As pointed out in Section 4, high temperature CANDU fuel behaviour within a fuel channel is rather complex. As a guiding principle, and to the extent practicable, FSOs should be chosen with the objective of preventing the development of complex configurations or physical phenomena that cannot be modelled with high confidence. Otherwise the demonstration, through deterministic safety analysis, of the effectiveness of safety systems for such events could be characterizing by large uncertainties.

For the fuel matrix under DEC condition without SFD, some degradation in its fission product retention capability is permitted but it must be limited and quantifiable in order to meet dose limits (or small release safety goals) and to maintain the fuel bundle in a coolable geometry. Moreover it cannot degrade to the point that the pressure-tube barrier is threatened.

Similarly, although fuel sheath damage/failure is expected to occur in DECs without SFD, and are permitted, the degree to which sheath damage/failures occur for the DEC being analyzed must be assess in order to ensure that dose limits (or small release safety goal) are met and CBG is preserved (e.g., sheath ballooning should not be so extensive as to block the channel).

Note that for ageing CANDU reactors, fuel channel sagging can have an impact on bundle geometry [21] and, depending on the specific DEC under consideration, may have to be taken into account when assessing whether a CBG is being maintained for a given DEC.

Identification of FSOs for a given DEC is only the first step towards the determination of a set of fuel safety criteria that must be met (in addition of other criteria aimed at addressing other non-fuel related material phenomena at high temperature) in order to ensure compliance with the three TSOs. The FSOs for severe accidents within DECs with fuel melt/two or more than two channel failures are expected to prevent the severe accidents (level 5) and to mitigate the DECs with the fuel melts/two or more than two channel failures (level 4b). It is also expected that FSO for a fuel design change or modification for an existing or new power reactor is to enhance fuel performances not only for operational states, but also accident conditions.

Table 2. CANDU Fuel Safety objectives (CFSOs) for DECs

Phenomena (PH) # (note 1)	***CANDU Fuel Safety objectives (CFSOs) for DECs***
1. CFSOs (of DiD Level 4a) proposed to prevent DECs with core SFD (of DiD Level 4b) and to mitigate the DECs with SFD (of DiD Level 4a)	
PH1: hydrogen generation/ Explosion (note 2)	*Hydrogen explosion must be avoided by limiting the amount of hydrogen generated by chemical reaction between coolant and sheath and between coolant and pressure tube [4].*
PH2: violent expulsion of fuel pellet (note 3)	*Melting, fragmentation and dispersal of fuel shall be avoided to maintain the core (fuel channel) integrity [4].*
PH3: fuel melting	*Fuel melting shall be avoided in order to maintain CBG and CCG.*
PH4: sheath melting (note 4)	*Generalized (i.e., nonlocal) melting of the sheath shall be avoided to maintain CBG and CCG.*
PH5: fuel element bowing/ sagging (note 5)	*Severe fuel element bowing or sagging shall be avoided to maintain CBG and CCG.*
PH6: constrained axial fuel string expansion (note 5)	*The constrained axial expansion of fuel bundle string shall be avoided to maintain CCG.*
PH7: ballooning of fuel rod	*Severe ballooning (swelling) of fuel elements shall be avoided to ensure maintenance of CBG and CCG, in other words to ensure that channel decay heat can be removed from the fuel bundles [4].*
PH8: bundle slumping (note 6)	*The fuel bundle slumping shall be avoided in order to maintain CBG [4].*
PH9: sheath Embrittlement (note 7)	*A CBG shall be ensured by preserving adequate post-quench ductility in the fuel element cladding for DECs.*
PH10: bundle deformation under fuel channel sagging	*The severe sagging of fuel channel shall be avoided to maintain CBG.*
2. CFSOs (of DiD Level 4b) to prevent severe accidents (of DiD Level 5) and to mitigate the DECs with core melt (DiD level 4b, Case 2 of severe accidents):	
Phenomena expected for severe accidents within DECs (note 8)	*"Corium stratification", "thermal-chemical interaction between corium, steel components and vessel", "heat transfer from corium to vessel or end-shield", "steam explosion due to molten fuel-coolant interaction", "hydrogen burn" and "corium-concrete interaction" shall be avoided to maintain containment integrity and to mitigate severe accidents within DEC (4b)*
Hydrogen generation /explosion (note 2)	*Hydrogen explosion must be avoided by limiting the amount of hydrogen generated by chemical reaction between coolant and sheath and between coolant and pressure tube [4].*
3. CFSOs for a fuel design change or modification for an existing or new power reactor:	
A fuel design modification or change for CANDU reactor	*The fuels shall be designed with enhanced accident tolerance features not only for operational states, but also for accident conditions (note 9).*

note 1. *PH # is referred to the phenomena number associated to fuel behaviours at high temperatures.*

note 2 *As shown in Figure 2, H_2 will be produced significantly from Zr/H_2O around 1580 °C. In order to prevent and mitigate hydrogen combustion, the amount of hydrogen production should be limited.*

note 3. *In a large break loss-of-coolant-accident (LBLOCA) of CANDU reactor, the large and rapid deposition of energy (due to the power pulse) in the fuel can result in melting, fragmentation, and dispersal of fuel. For UO_2, a limit is imposed on fuel, peak radial average fuel enthalpy to avoid such phenomena [20, 22].*

note 4. *For the current UO_2-Zicaloy fuel system, this criteria for cladding embrittlement are more stringent than sheath melting criteria. However, this may not always be the case for newer alloys or reactor types.*

note 5. *The potential fuel channel failure mechanism is the loading on the components at the channel ends due to constrained fuel string axial expansion. This constrained axial expansion exerts axial loads on the restraining components of the fuel channel (i.e., inlet-end shield plug lugs, rolled-joints, outlet-end latch) and on the fuel string itself; in a LBLOCA, this could happen during the power pulse phase.*

note 6. *End-plate deformations are assumed to occur at about 1500°C as an onset of fuel bundle gross deformation (slumping) as shown in Figure 2.*

note 7. *A fuel element will not fail due to oxygen embrittlement if the oxygen concentration remains less than 0.7 wt.% over half the sheath thickness [22]. The possibility of sheath failure due to oxygen embrittlement can be determined based on sheath temperature and time.*

note 8. *The design should include the analysis performed for severe accident progression and consequence evaluation including assessments on topical issues, as applicable, such as phenomena or interaction. For DECs with severe core damage, the containment shall maintain its role as a leak tight barrier for a period that*

note 9.	*allows sufficient time for the implementation of offsite emergency procedures following the onset of core damage. Consideration shall be given to the prevention of recriticality following severe accidents.[4]* *It is based on the definition of Accident Tolerant Fuels [23] and the safety criterion for the modification or new design of fuel for existing reactor(s) of IAEA SSR-2/1 Rev. 1 [1] and CSA N290.16-16 [3].*

6. Concluding Remarks

The focus of this paper has been on the problem of identifying FSOs for DECs without SFD (level 4a of DiD). An example of the application to the currently operating plants in Canada of such DECs is the LBLOCA with the loss of emergency core cooling (ECC), where the moderator serves as an ultimate heat sink; such an event which was formerly considered as a DBA, is now analyzed (based on frequency of occurrence) as a BDBA [7, 8, 24]. Another application of such DECs is the LBLOCA event with ECC. The Canadian nuclear industry is currently [22] developing a new analysis framework for this event; in this approach, the breaks above a certain size are treated (based on frequency of occurrence) as DECs without SFD while the remaining breaks remain within the DBA category. As part of the R&D support to this new analysis framework, the Canadian Owners Group has initiated a number of work packages aimed at the development and validation of a bundle deformation model [22, 25].

For the case of DECs within severe accidents (Level 4b of DiD), it is less clear whether it would be realistic/practicable to impose fuel safety criteria for the fuel designs used in the CANDU reactors currently operating in Canada. In such cases, complementary design features may be the only options. In terms of a fuel solution to such DECs, the use of accident-tolerant fuels (ATFs) appears to be most promising long term option. This option would not only address such DECs, but would strengthen level 4a and level 3 (DBAs) DiD. Accident-tolerant fuels (ATFs) for NPPs have become a topical item at international conference and international organizations.

Recognizing the difficulty of obtaining credible frequency values for low frequency events, the CNSC has not defined a lower frequency boundary for DECs. The concept of DEC is relatively new and the approach(s) for identifying events to be considered as DEC are currently under development, and inevitably involve a measure of judgement and are characterized by notable uncertainties. For these reasons, and at least until more experience is accumulated with consideration of DEC, in Canada it is viewed that the DECs must be selected by the designer or the applicant for a licence, and not imposed by the regulator this being true for new designs or currently operating CANDU reactors in Canada [7].

This paper did not aim to provide a final established position regarding fuel related measures that could be taken to address DECs, but rather to stimulate international discussion on the topic.

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