# Annex: Fuel Acceptance Criteria during Operating States: A Designer's Perspective

## Executive Summary

A fuel designer sometimes encounters needs beyond those experienced at current operating stations, such as to design fuel for a new, significantly different reactor, or to materially alter operating conditions. To accommodate such needs, AECL's fuel designers have, in the early 21$^{st}$ century, further evolved the traditional approach for design and verification of CANDU fuel during normal operations and during anticipated operational occurrences.

The new approach is called "Criteria-Based Verification" (CBV). In it, as in the traditional approach, verification experiments, analyses, and assessments are performed to demonstrate that the fuel bundle can meet each of the design requirements imposed by plant design and operation without unacceptable damage to the fuel bundle or to its surroundings. This is done for the full range of credible combinations of design specifications for manufacturing and for operation. Each verification experiment, analysis, and assessment considers a set of related design requirements and determines the numeric values of the fuel design performance parameters associated with pertinent damage mechanisms under the relevant operational conditions.

In the traditional approach, numeric values of these performance parameters constitute "limits" within which the fuel bundle design has been verified to satisfy its design requirements, and within which it must be used; in other words, limits beyond which the fuel may still not be damaged but for which the necessary analyses and validation tests have not yet been performed.

In the new approach, numeric values of the performance parameters are compared to pre-determined numerical limits ("acceptance criteria") associated with the damage mechanisms in order to demonstrate that the design requirements are met and that neither the fuel nor its surroundings are damaged. To the extent practical, the acceptance criteria are developed from "first principles", i.e., from known material damage mechanisms in operational states and from fundamental applications of engineering principles. Their numeric values are obtained by subtracting prudent margins from material damage limits.

To a large extent, the new approach establishes acceptance criteria that are independent of specific design features; however, numeric values of some material properties may well differ from one design to another. The new approach also allows a designer to quantify the margin(s) by which the fuel avoids damage from each damage mechanism.

Compared to the traditional approach, fuel verification using mature CBV would (a) be quicker; (b) facilitate enhanced comprehensiveness; and (c) enable easier licensing in some international jurisdictions.

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## Contents

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## 1. INTRODUCTION

The main text of this TECDOC provides the perspectives of reactor operators about fuel safety criteria for current CANDU fuels, at current nuclear power plants, during current operating conditions or ones that are reasonably similar.

A fuel designer sometimes has additional needs beyond that – for example to design new fuel for a new reactor and/or for new operating condition that differ significantly from current ones, as explained in more detail in the next section. To satisfy such additional needs, fuel designers at Atomic Energy of Canada Limited (AECL) have, in the early 21$^{st}$ century, further evolved the traditional CANDU approach for fuel design and called it "Criteria-Based Verification" (CBV). This Annex describes that approach.

The detailed descriptions in this Annex are focussed towards normal operating conditions (NOC); nevertheless, the approach described here and the resulting criteria also apply to anticipated operational occurrences (AOOs).

The current definition of AOO revolves around frequency of occurrence of identified events. But for damage mechanisms, local temperature is an important driver. The specific damage mechanisms covered in this document are those that are active at temperatures near those experienced during normal operations. If an AOO were to drive the fuel to significantly higher temperatures, then additional damage mechanism(s) may also need to be considered where appropriate, for example beryllium braze penetration.

Although the new approach was developed for a significantly advanced fuel design, it can also be applied to any evolution(s) of current designs and/or operating conditions – small, medium or large.

Some aspects of the new approach, and illustrative examples of its implementation, have already been described in several publications [1, 2, 3, 4, 5, 6, 7]. Later in this Annex, we summarize the main features of this approach.

Different jurisdictions and organizations use a variety of words for the activity that confirms whether or not a proposed design is adequate for its intended use, such as "verification", "validation", "qualification", etc. For simplicity, this Annex uses the same word that is used in existing literature on CBV [1 to 7]: "Verification". For the same reason, this Annex labels the related criteria as "Acceptance Criteria". Thus in this Annex, "Acceptance Criteria" have the same meaning as "Safety Criteria" do in the main text of this TECDOC. Various other labels are also used in the literature to describe essentially the same thing, such as “Design Criteria”, etc. This Annex considers them interchangeable.

This Annex starts with an illustration of a relatively broader need of a fuel designer and some of the attendant challenges. It then provides a check-list of credible damage mechanisms and an illustrative list of related acceptance criteria at a “high level”. Explanations and key features of above are also included.

## 2. ILLUSTRATIVE NEED

CANDU fuel has a glorious tradition of robust research, design, manufacturing and operation -- as evidenced by exemplary performance in operating reactors. This tradition is documented in the various current Fuel Design Manuals. So why did AECL’s fuel designers consider further evolutions of the traditional approach?

One role of a fuel designer is to modify the fuel design or its operating conditions, sometimes significantly, to address new challenges. This can include designing fuel for a new reactor.

The CBV approach was initially developed during the design of the Advanced CANDU Reactor – ACR. The reactor’s designers called for fuel to achieve average discharge burnup of about 20 GW·d/tU. This is about 2-3 times the current average discharge burnup of CANDU fuels. Also, ACR’s coolant was hotter than the current CANDU reactors.

The current fuel designs were judged incapable of meeting this challenge satisfactorily; therefore, a new fuel design was crafted for this application. But in many performance areas, insufficient operational experience was available to reliably confirm whether or not this new design would be consistently satisfactory in *all* the intended operating conditions.

One such aspect was the strength of the endplate and of the assembly weld during discharge from the reactor. One way to confirm the strength of the ACR bundle would have been via an out-reactor “type test” using a string of prototype unirradiated fuel bundles. Unirradiated Zircaloy has considerable ductility; therefore it can survive large plastic strains that were expected during discharge of ACR fuel. In the reactor, however, the fuel is discharged after irradiation, and ductility of Zircaloy decreases considerably with fast fluence [8]. Therefore, in principle, the strength test for the ACR fuel string would ideally be performed on a string of irradiated high-burnup ACR prototype bundles. That would have required considerable time and expense – see Section 3.3 for a more detailed discussion.

Several other similar situations were also encountered during the design of ACR fuel – mostly due to combinations of longer in-reactor residence and hotter coolant. These included: additional oxidation, additional deuteriding, more demanding power ramps, additional creep droop, etc. Traditional methodologies for verifications of these aspects were judged to be too time-consuming, and/or sometimes quite expensive, and/or sometimes simply not capable of providing the degree of comprehensiveness that ACR's high-burnup fuel designers preferred (e.g. for creep droop) – see Section 3.3 for additional details. Therefore, the traditional approach was evolved where needed.

## 3. CRITERIA-BASED VERIFICATION

In this section, we first provide an overview of the process that is employed in criteria-based verification for NOC, and then examine its similarity with approaches that are used in verifications of some other aspects of fuel designs.

### 3.1.OVERVIEW

CBV starts with a systematic, comprehensive check-list of *all* credible damage mechanisms (DMs). The purpose of the check-list is to minimize the possibility of inadvertently overlooking a damage mechanism that may well be important in the new circumstances but is off the designer's radar because, for example, the current fuel has not failed recently from that mechanism in a power reactor. Section 4.2 provides an illustrative check-list. To this "standard" list of DMs, one would also add additional damage mechanisms, if appropriate, to reflect new circumstances pertinent to the new design and/or operating conditions.

During an initial stage of the design process, *all* damage mechanisms in the above check-list need to be at least considered, and a conscious decision needs to be made for each. For example, one possible decision may well be to quickly dismiss that DM outright, e.g. because its severity in that specific application is judged to be nowhere near damaging. But that still needs to be a conscious decision, not an inadvertent one. Another possible decision may well be to flag that DM for more detailed evaluation.

For all relevant damage scenarios, each pertinent damage mechanism is evaluated against a corresponding "Acceptance Criterion". The evaluations can be done using engineering judgements, and/or tests, and/or analyses, and/or a combination.

To the extent permitted by available technology, an acceptance criterion is built from material damage limit minus a minimum acceptable margin, i.e. from "first principles". A later section of this Annex provides more complete descriptions of these and other key features of the acceptance criteria.

Sometimes, total damage from a damage mechanism comprises a combination of a series of damages that are accumulated during multiple events in the life of a fuel bundle. For example, fatigue damage can accumulate during lateral flow-induced vibrations in the reactor, and during repeated changes in power, and also during passage of the fuel bundle through the cross-flow region. Such cumulative damages need to be summed from individual components as appropriate.

Thus, evaluations are made for the entire life of the fuel during which fuel integrity is required. This means that one would also consider “upstream damages” – from fuel’s transportation to the reactor -- as well as “hand-off” requirements for downstream operations after discharge from the reactor. However, the scope of this Annex is limited to fuel’s life in the reactor during operating states.

CBV quantifies the margins to failure in terms of damage parameters. This is useful if one wants to explore the possibility of extending the fuel design and operating envelope, or to estimate the remaining margin to accommodate significant deviations from the fuel’s traditional operating envelope.

### 3.2.SIMILARITIES WITH OTHER APPROACHES

For some damage mechanisms, CBV is very similar to CANDU fuel’s traditional approach. For example, in the traditional design verifications, avoidance of pellet melting is confirmed by checking pellet temperature against the melting point of the pellet. The latter is a material damage limit. CBV is built on the same principle; thus CBV is largely similar to CANDU fuel’s traditional approach in this and other similar areas. In addition, CBV (a) extends this approach to *all* damage mechanisms, and (b) provides a systematic framework for doing so, e.g. by making an explicit provision of minimum acceptable margins. A later section described these aspects in greater detail.

CBV also shares many features with the approach that is currently used in accident analyses of CANDU fuel.

CBV is also very similar to the approach that has already been used for operating states in LWR and AGR fuel designs for a number of years. In a broad sense, the stronger elements of the LWR approach have now been adapted to CANDU fuel, albeit with appropriate adjustments to reflect CANDU conditions. As well, in some aspects, the CBV approach also reflects increased knowledge that is now available.

### 3.3.ADVANTAGES OF MATURE CRITERIA-BASED VERIFICATION

Full application of the CBV approach would need numeric values of material damage limits in a number of areas. The CANDU fuel industry already has a few, for example melting point of $UO_2$. In a few other subject areas, the LWR community has already accumulated significant generic research data on $UO_2$ and on Zircaloy that can also be applied to CANDU fuel. Nevertheless, in some other areas, additional CANDU-specific research would be helpful, for example to refine some material damage limits to CANDU’s conditions. Also, one would consider adding, enhancing, and validating a few additional features in computer codes. After initial one-off investments of this nature, mature CBV can be expected to yield the advantages listed below.

Speed and Cost: Some verification experiments require very long elapsed times. As an illustrative example: To perform a strength test on a string of fully-irradiated high-burnup bundles, one would need to first irradiate at least a dozen such bundles. Even more bundles would need to be irradiated if we were to also investigate the full spectrum of credible combinations of fabrication and operational variabilities.

First, when the new fuel design and/or coolant conditions differ significantly from current, it sometimes becomes very hard to build the required consensus to test the new fuel at appropriate conditions in an operating power reactor. The alternative would be to consider irradiating the test bundles in a research reactor that can accommodate CANDU fuel bundles. But even when domestic research reactors are functional, they usually offer very few locations where the flux is high enough to mimic power reactor fuel at high power. Therefore, the dozen (or more) fuel bundles that would be required for the test would need to be irradiated in series; that would require a long time. Further, even if appropriate capability and capacity can be found in overseas research reactors, overseas research reactors are used, irradiations to ACR burnups would be very expensive.

Second, after irradiating the prototype fuel bundles, the type test would need to be done in a shielded facility such as a hot cell. It may be a challenge to find an existing shielded facility that can accommodate a full string of CANDU fuel bundles in a horizontal orientation. Building appropriate new facilities would be time consuming as well as expensive.

In contrast, numerical analyses can usually be done relatively quickly and at significantly lower cost. Overall, selection of experiments vs. analyses would need to be done on a case-by-case basis after considering their relative merits in each specific situation.

Comprehensiveness: For some aspects of fuel verification, the traditional approach poses considerable challenges. As an illustrative example, fuel is irradiated horizontally in CANDU power reactors; therefore gravity activates some unique processes such as droop. Operational feedback to-date tells us that this aspect is satisfactory in current fuel designs and reactors. But the droop can be expected to be higher in ACR fuel because (a) its outer elements have smaller diameter, and (b) its high burnup and hooter coolant would cause larger creep. The creep droop would be absent in a vertical irradiation in a research reactor, but it can be covered through numeric analyses during CBV. Similar other illustrative examples can also be constructed. Thus, comprehensiveness of fuel verification can be enhanced through CBV.

Licensing: CBV is better aligned with current practices in the LWR and AGR fuel industries; therefore it facilitates easier licensing of CANDU fuel in some international jurisdictions.

## 4. DAMAGE MECHANISMS

In this section, we first describe the salient features of damage mechanisms, then list credible damage mechanisms in CANDU fuel, and then explain the listed mechanisms.

## 4.1.FEATURES

A "damage mechanism" is a process that, if excessive, would render the fuel unsuited to fulfill its design requirements. Acceptance criteria are pertinent numeric limits that are used to determine whether or not the fuel or its surroundings are damaged.

In this context, to repeat an observation from the main text of this document: "not damaged" means that the fuel elements do not fail, that fuel bundle dimensions remain within operational tolerances, that functional capabilities are not reduced below those assumed in safety analyses and/or specified in design requirements, and that the fuel bundle maintains its structural integrity. "Fuel element failure" means that the fuel element leaks and that the final fission product barrier in the fuel – the sheath – has therefore been breached.

In addition, it is well known that in some adverse situations, fuel has a potential to damage the pressure tube, e.g. through fretting and wear. AECL's designers of pressure tubes have historically assigned an allowance for such purposes, traditionally called the "wear and corrosion allowance". At AECL, it has historically been the responsibility of the fuel designer to confirm that all credible interactions of the fuel with the pressure tube are within such allowances. For this reason, damage mechanisms related to interactions between the fuel and its surroundings are also included in the check-list in the next section.

A variety of techniques are available to a designer to avoid damage. They can be implemented during any of the three stages of a fuel's life – (a) during design, e.g. through choices for materials, geometries, dimensions, etc.; (b) during fabrication, e.g. by building fuel within the range of specifications set by the designer; and (c) during operation, e.g. by operating the fuel within parameters set by the designer. To avoid significant damage, a designer will often choose whichever combination of above is the most effective, practical, safe, and/or economic. Consider the following three illustrative examples:

- Power ramp damage is currently avoided through three key steps: (i) by specifying a Canlub layer of a certain thickness and composition; (ii) by specifying the allowable combinations of power ramps, powers, and burnups; and (iii) by devising practical fuelling schemes that achieve (ii) above. In addition, control of pellet density has also been suggested. Specifications for all above are crafted during design. Step (i) above then implemented during manufacturing and the next two are implemented during operation.
- Deuteride/hydride damage is currently avoided mainly by limiting the amount of initial hydrogen within a fuel element, and by controlling the pH of the coolant. Both steps are identified and specified during the design phase. The first is implemented during manufacturing, the second during operation.
- Contact between a deformed fuel sheath and the pressure tube is avoided by strategically locating and sizing the bearing pads, and by controlling several other dimensions and

clearances. These aspects are implemented during the design phase by controlling the geometry and dimensions of the fuel, and during manufacturing by building within those specifications.

In the above examples, the designer has controlled the above damage mechanisms through a combination of steps during all three phases, viz. design (e.g. geometry), manufacturing (e.g. hydrogen content), and operations (e.g. fuelling scheme).

For the above reason, ACR's fuel designers considered it their responsibility to systematically identify and limit *all* credible damage mechanisms – regardless of whether they are avoided during design, or during manufacturing, or during operation, or during their combinations.

Although the damage mechanisms listed in the next subsection were identified during design studies of ACR fuel, they are considered generic to fuel designs that are germane to the current CANDU fuel designs.

Sometimes a designer is tempted to consider features that may introduce new potential damage mechanisms. As one illustrative example, in the past AECL's researchers have investigated inserting thin discs between neighbouring pellets [ 9]. This provides an additional path to conduct the heat away to the coolant and reduces pellet temperature. In such situations, appropriate new damage mechanisms need to be added to the check-list.

In several cases, a number of individual processes and/or operational parameters contribute to a given damage mechanism. For example, melting of the pellet – a damage mechanism – is affected by element power, thermal conductivity of the pellet, heat conduction, etc.

Conversely, sometimes a given operational parameter and/or a process affect a number of damage mechanisms. For example, element power (and its change) – an operational parameter -- can contribute to a variety of damage mechanisms including central melting, gas overpressure, and stress corrosion cracking. Likewise, bundle geometry change – a process -- can potentially contribute to the following damage mechanisms: degradation of heat transfer between the fuel element and the coolant; excessive interaction loads along the fuel string; excessive interference with interfacing equipment; fuel bundle jamming; etc. Nevertheless, neither element power, nor bundle deformation, are damage mechanisms per se—power is an operational parameter, deformation is a process. The check-list in the next subsection is based on damage mechanisms.

To recap: The primary purpose of the check-list in the next subsection is to help probe that no known damage mechanism is inadvertently ignored during the design process. Inclusion of a damage mechanism in this check-list does not mean that that specific damage mechanism will necessarily be at a dangerous level in a given fuel design for given operating conditions. Rather, its inclusion here merely means that the potential impact of that damage mechanism needs to at least be consciously considered – however briefly – at some stage of fuel design.

In the following two subsections, we first list the damage mechanisms and then describe them.

## 4.2.CHECK-LIST

Based on first principles -- and confirmed later through a comprehensive search of CANDU fuel defect experiences [3] -- ACR's fuel designers have identified the damage mechanisms listed below [1].

The check-list below is at a level similar to the one in US NRC's Standard Review Plan for Fuel System Design (SRP 4.2) [10], however, the contents of this Annex have been tailored towards CANDU fuels. The check-list in SRP 4.2 lists 21 damage mechanisms for all states of LWR fuel – normal operations, anticipated operational occurrences (AOOs), and design basis accidents; a majority of them apply to operating states. In comparison, this Annex lists 14 damage mechanisms for CANDU fuel that focus only on operating states.

The check-list organizes the damage mechanisms into three major groups: thermal integrity, structural integrity, and considerations of compatibility between the fuel and the interfacing systems.

(a) Thermal Integrity

- i. Overheating of the pellet
- ii. Overheating of the sheath and other structural materials

(b) Structural Integrity

- iii. Element internal gas pressure
- iv. Stress corrosion cracking
- v. Static mechanical overstress and/or overstrain
- vi. Mechanical rupture due to impact loads
- vii. Fatigue
- viii. Loss of control of geometry
- ix. Primary deuteriding/hydriding
- x. Oxides, crud and deposits

(c) Compatibility with surroundings

- xi. Excessive interaction loads along the fuel string
- xii. Excessive interference with interfacing equipment
- xiii. Wear
- xiv. Crevice corrosion

The next three subsections describe the above damage mechanisms.

## 4.3. THERMAL INTEGRITY

### (i) Overheating of the Pellet

If the pellet melts, the resulting volumetric expansion of the pellet may potentially push the sheath past breaking.

CANDU experience so far is that molten $UO_2$ stays confined to its original location. Nevertheless, if it does flow away, it can potentially reach the sheath or the endcap and melt them too.

Although many factors determine pellet temperatures, a primary driver is the power produced in the fuel element.

Some local variations can impact the above, for example, end flux peaking can potentially create a temporary but significant local peak in pellet temperature in some CANDU reactors: A CANDU fuel string consists of a number of 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. A variety of factors determine the magnitudes of the temperature peaks. Their detailed discussion is beyond the scope of this Annex, however, References [11,12] provide additional information. Under some situations during operating states in some reactors, the end flux peak could be considerable [11], and for a short duration in some reactors, it can potentially even occur in a high-power location.

### (ii) Overheating of the Sheath and Other Structural Materials

Overheating can quickly degrade the strength of the sheath material. It can also lead to rapid oxidation, crevice corrosion, and creep. Excessive bowing can occur if the overheating is localized, large and circumferentially non-uniform. Excessive local bowing can potentially damage a neighbouring fuel element and even the pressure tube. In the extreme, the sheath could melt.

At joineries, specifications frequently permit some degree of incomplete bonding. The unbonded areas can impede heat transfer and increase local temperatures. Local eutectics may form in the brazed region; this may alter some local material properties. In the extreme, the appendage may no longer stay attached to the sheath.

The current practice is to avoid dryout at power during normal operation. This is sufficient to prevent overheating of the sheath.

Although this is a sufficient condition to avoid overheating the sheath, it is not necessarily necessary. A more nuanced mechanistic approach is also possible.

During AOOs, limited dryout for a short duration is currently permitted.

Dryout is affected primarily by thermal and hydraulic conditions in and surrounding a fuel element. They, in turn, are affected by a number of other performance parameters as well -- including fuel deformations. Therefore the latter also needs to be considered where appropriate.

## 4.4.STRUCTURAL INTEGRITY

### (iii) Element Internal Gas Pressure

Fission gas is produced within the grains of $UO_2$, and some of it travels to the "open" space between the pellets and the sheath. If the fission gas release is large, internal gas pressure can exceed the coolant pressure. In conjunction with corrosive internal environment, local hydrides, and local oxides, excessive internal overpressure in a fuel element can potentially cause cracks at two locations of stress concentrations: (a) at the sheath/endcap junction, and (b) at the junction of the sheath and the bearing/spacer pad.

Internal gas overpressure can potentially also cause excessive outward creep of the sheath, which in turn can thin the sheath. If the thinning is excessive, the sheath can crack. Excessive creep in fuel elements can potentially also affect the thermal-hydraulic conditions in the surrounding coolant, thus potentially also affecting critical heat flux.

For the above reasons, it is good engineering practice to limit the maximum gas pressure that is allowed in the fuel element. In the current practice, this is achieved by providing sufficient "empty" space within the fuel element, and by controlling the power and the burnup of the fuel element.

### (iv) Stress Corrosion Cracking

During irradiation, Zircaloy is embrittled by fast neutrons, hydrides, and oxides. During subsequent power ramps, the embrittled Zircaloy can experience high stresses and strains in the presence of a corrosive internal environment. This combination can potentially crack the fuel element via stress corrosion cracking (SCC). The most vulnerable locations are circumferential ridges, sheath/endcap junctions, sheath/pad junctions, and pellet chips if any.

This can be avoided by keeping the local combinations of stresses, strains, corrodants, neutron embrittlement, hydrides, and oxides below the level that causes SCC in the sheath material.

(v) Static Mechanical Overstress/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.

A variety of loads and processes affect the magnitudes of resulting stresses and strains including: coolant drag load, coolant pressure, internal gas pressure, thermal expansion and contraction, pellet densification, fission product swelling, elastic stresses and strains, plasticity, creep, pellet cracking, local stress concentrations, etc.

Different combinations of loads and supports result in different magnitudes of peak local stresses and strains at various locations. Some illustrative locations of high local stress/strain concentrations are: circumferential ridges, sheath/endcap junctions, sheath/pad junctions, endcap/endplate junctions; rib/ring junctions; axial gaps between the pellet stack and the sheath; and longitudinal ridges.

At the various joineries in CANDU fuel, the unbonded areas (allowed by specifications) also affect the local levels and concentrations of stresses.

The resulting stresses and strains are often quite complex and frequently well into the plastic range. For the latter reason, some fuel designers favour using strains rather than stresses to ascertain damage from static loads.

To avoid potential failures due to overstress/overstrain, a balance is maintained between the bundle's strength and applied loads.

(vi) Mechanical Rupture due to Impact Loads

Situations such as refuelling and/or start/restart can sometimes require a fuel bundle to travel from one location to another where it hits a stationary fuel string. This can potentially impose significant impact loads on the fuel bundles. This usually occurs after some amount of embrittlement has already occurred in the Zircaloy, e.g. due to fast neutrons, hydrides, and oxides. If excessive, this combination can potentially damage the stationary bundle and/or the travelling bundle.

This is currently controlled by limiting the impact velocity to an acceptable level.

(vii) Fatigue

Fuel can experience cycles of stresses and strains due to a variety of repetitive loads such as flow-induced vibrations, axial resonance due to acoustics, cross-flow, pressure and temperature cycles in the coolant, and repeated maneuvers in power. These can expose the fuel to potential failure via fatigue.

In parallel, depending on which part of the fuel is so affected, the corresponding strength could have been degraded from effects such as corrosive environment, neutron-embrittlement, hydrides, and oxides.

Prior to the irradiation, fuel may have also accumulated some fatigue cycles during transportation from the fabricator to the reactor. If so, there would be a corresponding reduction in the number of cycles that are available to resist alternating loads during fuel's residence in the reactor.

This damage mechanism is avoided by ensuring that the cumulative life-time fatigue loads are below the pertinent fatigue strength.

(viii) Loss of Control of Geometry

Fuel designers are sometimes tempted to reduce the diameter of a fuel element or to increase its length. Some illustrative examples are: CANFLEX fuel bundle [13] in which some fuel elements have relatively smaller diameter, HAC fuel bundle [14] in which some fuel elements have even smaller diameter, and CARA fuel bundle [15,16] which is twice the usual length of a CANDU bundle. Excessive changes of such nature can eventually risk introducing mechanical buckling into the fuel design, which can potentially deform the bundle into an uncontrolled, unknown shape. Therefore the designer needs to check for this possibility and if necessary, mitigate it.

(ix) Primary Deuteriding/Hydriding

Fuel sheath can pick up hydrogen from the CANLUB layer and the fuel matrix. In addition, it can pick up deuterium from the coolant. Over time, the hydrogen and the deuterium can migrate within the fuel bundle to locations that are relatively cooler or at higher tensile stresses.

The migration can concentrate the overall deuterium and the hydrogen into a few locations. If excessive, this in turn can result in precipitation of deuterides and hydrides. Excessive local deuterides and hydrides can reduce the local ductility of Zircaloy, rendering it less capable of carrying its loads.

In the above context, relatively cooler locations are: outer surface of the sheath; endcap region; assembly weld; and endplate. If a fuel string is supported by a latch, the endplate and the assembly weld can become locations of relatively higher long-term tensile stress.

Primary failures due to deuterides/hydrides can be prevented by limiting the local concentrations of deuterides/hydrides to acceptable levels.

(x) Oxides, Crud and Deposits

Burnup is usually low in natural uranium fuel. Also, CANDU reactors generally maintain excellent control of coolant chemistry. These features mean that sheath oxidation and crud are both usually very low.

An atypical incident did occur in the Pickering reactor during 2008-2012: Coolant chemistry was affected for a brief period which led to significant deposits of crud on the fuel [17]. Corrective actions restored the required balance.

During the design of ACR fuel, (a) fuel burnup was significantly higher and (b) coolant temperature was also higher. Sufficiently significant operational experience was not available for this combination. Therefore, oxidation and crud were included in this check-list.

References [18, 19, 20 ] discuss consequences of oxides, cruds, and deposits. While some consequences differ between oxides, crud, and deposits, others are largely similar. Due to the significant overall similarities in their impacts, they are listed together in this subsection.

*(a) Heat Transfer*

Excessive levels of oxides, crud and deposits can impair heat transfer between the sheath and the coolant. This can aggravate other damage mechanisms that are driven by temperature -- as listed in other parts of this section. Some illustrative examples are: accelerated fission gas release and higher internal pressure; and circumferentially non-uniform temperature resulting in bowing.

*(b) Flaking/Spalling*

If the oxide is too thick, it can flake/spall and create radioactive debris in the primary heat transport.

Crud and deposits are created not in the fuel but elsewhere in the reactor; therefore fuel is not the original source for that particular debris.

*(c) Deuteride/Hydride Lens*

If the oxide, crud and deposits flake in a non-uniform manner, local gradients of temperature are created in the underlying sheath. That in turn causes migration of deuterium hydrogen to cooler areas. This concentrates deuterium/hydrogen at local cold spots and can form local deuterides/hydrides. They have been observed in LWR fuels; LWR industry calls them "hydride lenses". The sheath can fail at a hydride lens due to reduced ductility.

*(d)* *Through-Wall Hole*

In the limit, through-wall oxidation will create a hole in the sheath through which fission products can escape.

*(e)* *Loss of Load-Carrying Materialand Ductility*

Zircaloy is lost during oxidation. Also, material adjacent to oxide has high oxygen content which reduces its ductility. These aspects reduce the capacity of the component to carry load.

*(f)* *Flux Distortion*

Light water reactors have reported that heavy local deposits of crud can change the local absorption of neutrons, hence distort the flux shape and power distribution. These can have power-related consequences.

In summary, in current PHWRs with natural uranium fuel, except for an atypical incidence in Pickering during 2008-2012, oxidation and crud are usually insignificant. Nevertheless, they are included in this check-list mainly to cover more demanding duty cycles such as higher burnups.

## 4.5. COMPATIBILITY WITH SURROUNDINGS

### (xi) Excessive Interaction Loads along the Fuel String

In the reactor, the fuel string can potentially expand thermally at the operating temperature. If the corresponding cavity in the fuel channel does not provide sufficient length to accommodate this expansion, failure can result.

This is usually addressed by providing sufficient space in the channel's cavity.

### (xii) Excessive Interference with Interfacing Equipment

The as-built bundle usually undergoes a variety of deformations during irradiation, such as diametral expansion/contraction, bowing, droop, sag, doming, creep, parallelogramming, etc. This can affect the clearances with equipment that interface with the fuel bundle, such as pressure tube, fuelling machine, etc. The altered clearances must not be below those that have been assumed in safety analyses such as in calculations of heat transfer coefficients, critical heat flux, etc.

Second, during loading and unloading in and from the reactor, the fuel bundle needs to navigate narrow spaces and sometimes even bends. Thus there is a need to ensure that the as-built as well as the deformed fuel bundle would pass through the fuel channel and through the fuel handling equipment without jamming.

Third, to avoid local overheating, the hot sheath of a deformed bundle must not contact the pressure tube or even a neighbouring sheath.

These aspects are usually addressed by tight control of bundle's dimensions, flexibility and deformations.

(xiii) 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 in the pressure tube are collectively called "flaws". Flaws due to wear have been found in examinations of fuel bundles and of pressure tubes [21].

Fuel bundles slide into the fuel channel. This can cause sliding wear in the bearing pads and in the pressure tubes.

Erosion can occur due to the high velocity of the coolant, sometimes exacerbated by debris in the coolant.

An earlier sub section on fatigue has already listed drivers that can vibrate the fuel element and the bundle. Fretting due to vibrations can potentially cause wear in spacer pads, bearing pads, and pressure tube.

Vibrations can also "rock" the fuel bundle, which results in sliding marks.

Excessive wear can lead to three potential consequences, as described below.

- Excessive fretting of spacer pads can potentially rub the corner of a spacer pad into the adjacent sheath and damage it. Such damage has indeed been observed.
- Flaws can promote delayed deuteride/hydride cracking (DDC/DHC) in pressure tubes. Fretting flaws are indeed currently evaluated for initiation of DDC/DHC in pressure tubes by using a procedure based on fitness-for-service guidelines [21].
- 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.

(xiv) Crevice Corrosion

Crevice corrosion can potentially occur in crevices such as between bearing pads and the pressure tube or between bearing pads and the sheath.

Crevices restrict the flow of coolant. The reduced amount coolant can partially boil off locally, which in turn can increase the local concentration of corrodants such as Li. This, in turn, can potentially accelerate the local corrosion of Zircaloy.

To-date, crevice corrosion has occurred at two locations:

- *Crevice between the bearing pad and the pressure tube:* In this region, the local temperature can reach of the order of 350°C. This can elevate local concentrations of lithium hydroxide, causing accelerated local oxidation of the zirconium alloys. In operating reactors, local corrosion has been observed in the crevice between bearing pads and pressure tubes [22]. Subsequent test programs have confirmed this mechanism [22]. In some CANDU reactors, pressure tubes are periodically monitored for crevice corrosion marks. Unusual growth, if any, is investigated further.

- *Crevice between the bearing pad and the sheath*: This region can experience temperatures of the order of 400°C. In fuel simulation tests, through-wall penetration of the sheath was observed in only a few days. Through-wall hole in the sheath has also been observed in the reactor.

Crevice corrosion is limited by controlling local temperature, geometry, and lithium concentration.

## 5. FORMULATIONS OF ACCEPTANCE CRITERIA

Acceptance criteria are used to confirm whether or not damage parameters are within acceptable levels.

The fuel acceptance criteria described in this Annex are not an outcome of the fuel design verification process, but are upfront inputs into this process. Defining fuel acceptance criteria is now one of element of the process by which requirements of CSA N286 are met.

The objective is to establish, to the extent practical, fuel acceptance criteria which are independent of specific fuel design features. They need to be established for all credible fuel element and fuel bundle damage mechanisms that may be activated during operational states.

This section first provides an overview of the process that is used to establish acceptance criteria; then an illustrative numeric example is given for one specific acceptance criterion; and then the key features of acceptance criteria are described.

## 5.1.HIERARCHY

A variety of parameters and processes are usually involved in a given damage mechanism, and they have a hierarchy which plays an important role in establishing the "ideal" acceptance criterion for any damage mechanism.

Figure 1 illustrates this concept for pellet melting.

At "Level 1" are parameters that are controlled directly by humans, namely:

- Design aspects. These include choices of materials, shapes, dimensions, etc.;
- Fabrication aspects. These include manufacturing techniques used to implement the designer's specifications, for example for pellet density, for filling gas, for diametral clearance, for integrity and completeness of bonding between components, etc.; and
- Operational aspects. These include control of pertinent operating conditions to within the designer's specifications, for example, element power, coolant conditions, etc.

The above parameters then interact with each other in the reactor through processes such as radial distributions of neutron flux, end flux peaking, heat generation, heat conduction, heat transfer coefficients, etc. These are labelled as "Level 2" in Figure 1.

The processes of Level 2 result in the two key penultimate mechanistic parameters that determine melting: temperature and melting point. Figure 1 labels them as "Level 3".

Their interaction determines whether or not the damage will occur, i.e., in this specific example, whether or not the local material will melt. This is labelled as "Level 4" in Figure 1 – the damage mechanism.

In principle, an acceptance criterion can be specified through several parameters, individually or in combination. To the extent practical, a fuel designer would ideally prefer to formulate it at Level 3, so that (a) the criterion is independent of specific design features to the extent practical, and (b) the fuel designer can retain flexibility to adjust *all* Level 1 parameters for an optimal balance among various design objectives.

For the above reason, to the extent practical, this Annex has reported acceptance criteria at Level 3 of Figure 1, i.e. in terms of key mechanistic parameters that measure the degree of damage in the "penultimate" stage.

After the key mechanistic parameters are so identified, the acceptance criteria are formulated by first establishing a numeric value for the material damage limit associated with those parameters,

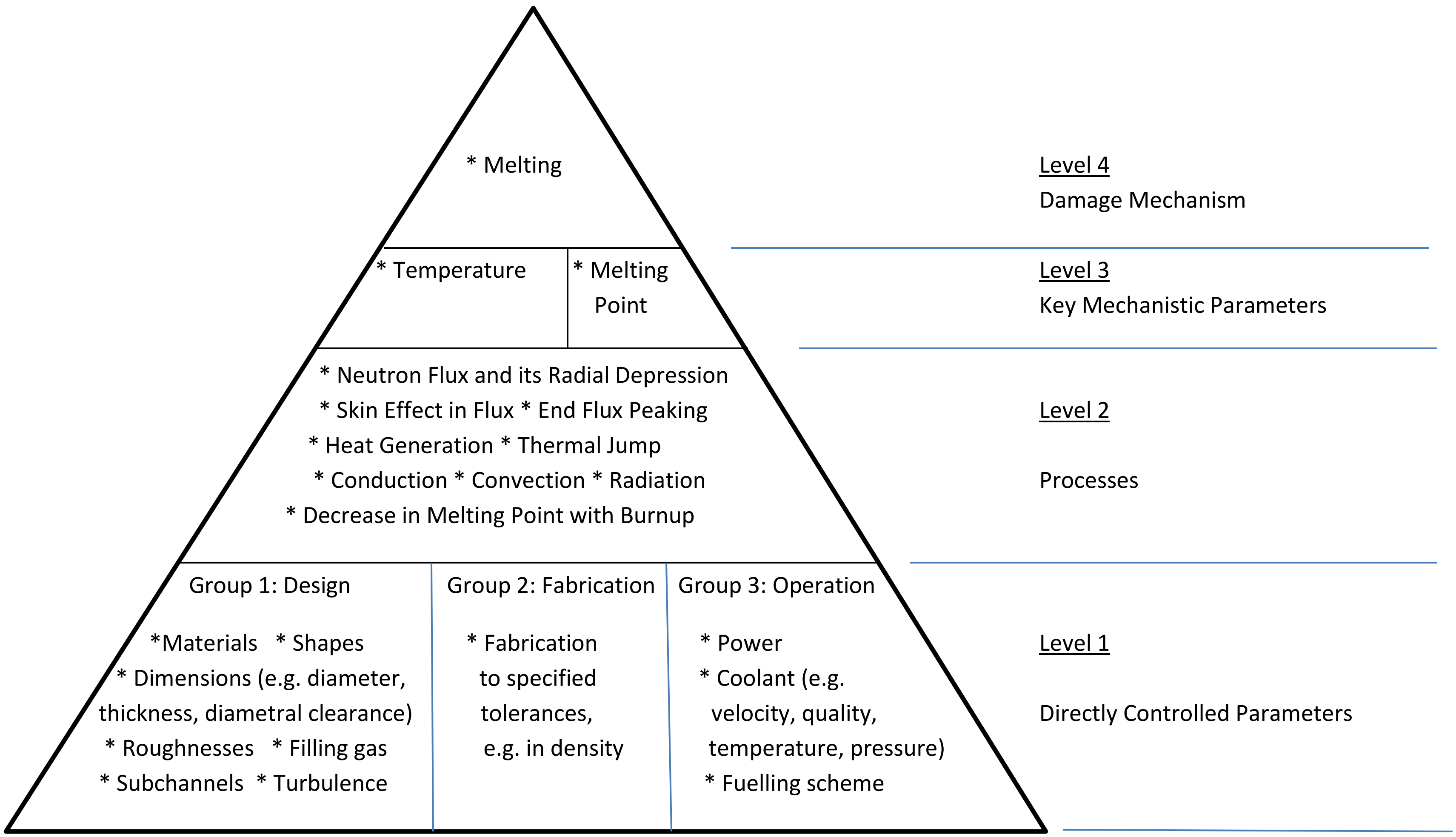



**Figure 1 Simplified Hierarchy of Illustrative Parameters in Pellet Melting**

and then subtracting a minimum acceptable margin from it. Thus, four steps are required in total, as explained in the next two subsections.

## 5.2.MATERIAL DAMAGE LIMITS

In the first step, we draw a hierarchical diagram for each damage mechanism similar to Figure 1, and based on that, we identify the most appropriate damage parameter, ideally at “Level 3” – to the extent practical.

In the second step, we establish the numeric value of the “Material Damage Limit” (MDL) for the identified damage parameter. At this numeric value, the material “fails” – e.g. it cracks, or it melts, etc. Thus MDLs are the limits beyond which the fuel would be damaged to the extent that it would no longer meet some of its design requirements.

The above numeric values are established through experiments and related analyses of the condition of the material when damage occurs. Where these MDLs are not known in sufficient detail, close precursors can be used as surrogates.

There is almost always scatter in the data for material damage. For constructing an acceptance criterion, one would use an appropriately conservative end of the range.

## 5.3.PRUDENT MARGINS

Then, in the third step, a “Minimum Acceptable Margin” (MAM) is established for that damage mechanism. A MAM largely reflects the state of knowledge in that damage mechanism. Reference [1] provides some guidelines for establishing numeric values of MAMs.

Lastly, in the fourth and final step, acceptance criterion is obtained by subtracting the minimum acceptable margin from the material damage limit.

This process establishes an acceptance criterion in the sense that if it is met, no further justification is needed to assert that the associated damage mechanism is avoided. Even when the fuel is operating at the limit of the acceptance criterion, it is still operating with the minimum acceptable margin. Thus the acceptance criterion represents a sufficient but not necessarily necessary condition to avoid damage.

Therefore, when the design verification process subsequently confirms that all acceptance criteria are met, it also means that damage from each mechanism is avoided by at least its minimum acceptable margin.

Figure 2 illustrates the above concepts. Note from Figure 2 that the actual range of operation may well be below the acceptance criterion. Therefore the actual margin may well be higher than the minimum acceptable margin.

An illustrative numeric example is given in the next subsection.

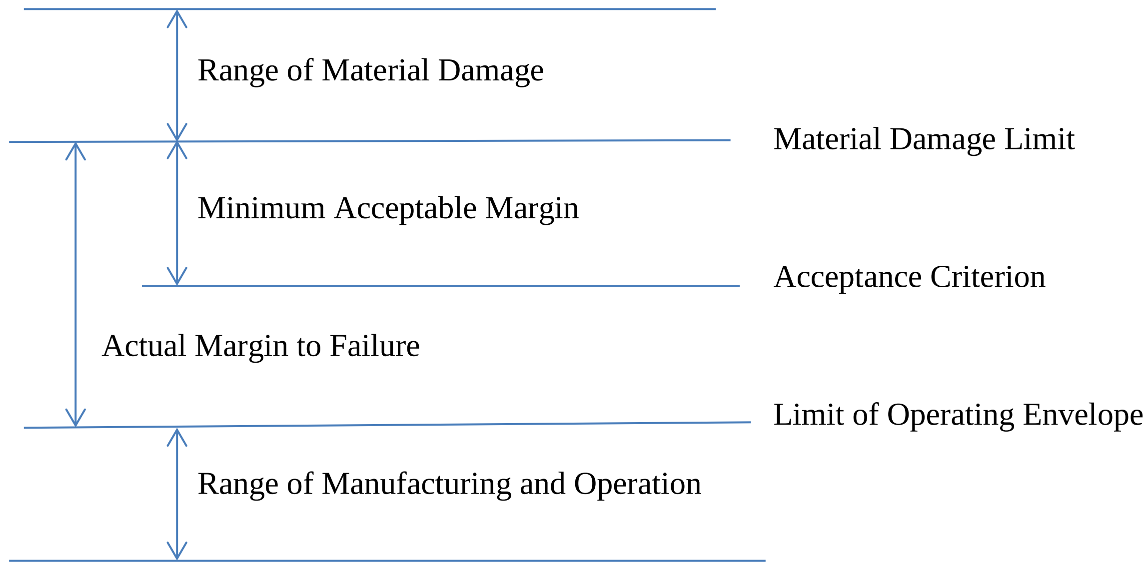



**Figure 2: Damage Limits and Margins**

## 5.4. ILLUSTRATIVE NUMERIC EXAMPLE

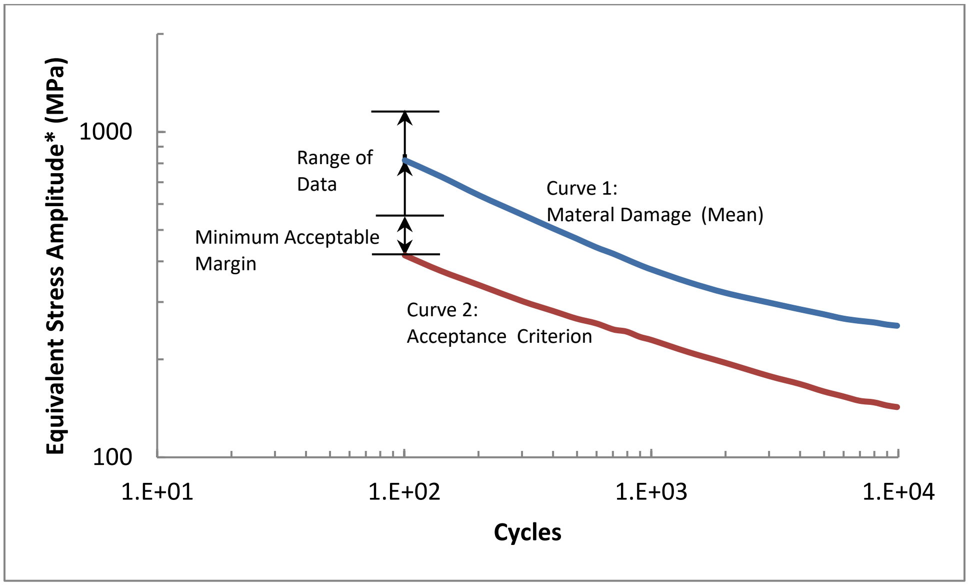
Figure 3 is a numeric example that illustrates the acceptance criterion proposed by O'Donnell and Langer for fatigue of Zircaloy [23]. Curve 1 was determined experimentally and represents the magnitude of alternating stress – peak-to-mean -- that results in failure for a given number of cycles. O'Donnell and Langer chose to draw Curve 1 through the middle of the scatter of data rather than through the lower end of the scatter.

To Curve 1, O'Donnell and Langer applied a factor of 2 to stress or a factor of 20 to number of cycles [23], whichever was more conservative at any point. These factors account for the scatter in data as well as an additional margin to cover (a) minor "known unknowns" such as surface finish, and (b) "unknown unknowns". This results in Curve 2 which is the acceptance criterion.

In Figure 3 we have also illustrated the Minimum Acceptable Margin at 100 cycles that is reflected in this criterion.

## 5.5.KEY FEATURES

In a new fuel design, a fuel designer may sometimes consider using slightly different materials than current ones. As an illustrative example, a neutronic poison was added into the pellets of the central fuel element of the ACR fuel bundle. Features such as these can alter numeric values of some material properties. For this reason, a fuel designer usually prefers to use "generic" language to formulate acceptance criteria. For example, a fuel designer would normally say “pellet material” rather than “$UO_2$”.




* Equivalent Stress Amplitude = Stain Amplitude (mean-to-peak) * Young’s modulus

[Adapted from O’Donnell and Langer, 1964]

**Figure 3: Fatigue Design Limit**

Also, he/she would normally not include the specific number for a material property in the formulation of the criterion. For example, he/she would prefer to say “pellet’s melting point” rather than “2840 °C”.

Regardless of whether or not numeric values of material properties are embedded in a criterion, the analysis would need to establish and use numeric values pertinent to the specific material, for that particular fuel design and its operating conditions. Thus the numeric values of material properties may well differ from one design and operating conditions to another.

Sometimes a given damage mechanism may have several major aspects which are better controlled through more than one acceptance criterion. For example, in the traditional approach, excessive local stress/strain are avoided through separate criteria for, among others, longitudinal ridging of the sheath and structural integrity of endplates.

In using the criteria listed in the next section, the norm would be to deal with peak local values – unless a good reason is explicitly established to do otherwise. This means accounting for local influences such as the highest degree of local end flux peaking, local concentrations of stresses and strains, migration and precipitation of deuterium and hydrogen, etc.

One would consider the impacts of all pertinent conditions, processes and mechanisms that significantly affect any given material property or performance parameter. For example, when calculating critical heat flux, one would consider not only thermal and hydraulic conditions, but also the impacts of fuel deformations if significant. Similarly, when calculating ductility, one would account for influences of fluence, temperature, deuterides, hydrides, oxides, crud, and deposits. Many other illustrative examples can also be similarly constructed.

Interactions among the mechanisms would also be considered. As an illustrative example, impacts of oxides, crud and deposits would be considered in calculating temperatures.

Fuel acceptance criteria differ from operating values. As an illustrative example, consider pellet centerline temperature. One might, for example, formulate a fuel acceptance criterion that centreline temperature of the pellet shall stay below the melting point of the pellet -- the melting point being a material damage limit. However, fuel design and its operating conditions may be such that the actual operating temperature during normal operation is significantly below the melting point—i.e., the fuel may operate with considerable margin, and the margin may well be different in different designs and reactors.

# 6. SPECIFIC ACCEPTANCE CRITERIA FOR CANDU FUEL

To respect commercial proprietary interests, numeric contents of specific criteria below are limited to open-literature information.

## 6.1. THERMAL INTEGRITY

### i. Overheating of the pellet

Local temperature in all parts of the pellet shall stay below the minimum acceptable margin to the local melting point of pellet material.

### ii. Overheating of the sheath and other structural materials

Local temperature in all parts of the sheath shall stay below the minimum acceptable margin to the local melting point of the sheath material.

In practice, a precursor is used to implement this objective – e.g. by avoiding dryout during normal operations, and by limiting the severity and duration of dryout during AOOs.

Dryout is not in itself a damage mechanism, and it is a sufficient – though not necessarily necessary -- condition to avoid overheating the sheath.

## 6.2. STRUCTURAL INTEGRITY

### iii. Element Internal Gas Pressure

Excess of internal pressure over coolant pressure shall be less than the minimum acceptable margin to the differential pressure that causes cracking in the fuel sheath or endcap.

### iv. Stress Corrosion Cracking

Stresses/strains (or related powers and ramps) during power increases in fuel elements at circumferential ridges and at sheath/endcap junctions shall be below the minimum acceptable margin to the appropriate defect threshold. This should include the effects of pellet chips, if any, from refuelling impacts.

### v. Static Mechanical Overstress and/or Overstrain

Local principal strain/stress (elastic plus plastic) shall be less than the minimum acceptable margin to the available ductility/ultimate tensile strength; and local creep strain shall be less than the minimum acceptable margin to the creep rupture strain.

### vi. Mechanical Rupture due to Impact Loads

Strain energy density during impact shall be less than the minimum acceptable margin to that required to crack or break any metallic component of the fuel bundles.

### vii. Fatigue

Cumulative fatigue damage from repeated cycles of alternating stresses/strains shall be below the allowable design fatigue life, with a minimum acceptable margin on magnitude of cyclic stress/strain or on number of cycles. When the fatigue cycles have variable amplitudes of strains/stresses, the sum of fatigue life fractions shall be less than 1.0.

An illustrative numeric example of this criterion has already been discussed in an earlier subsection (Section 5.4**Error! Reference source not found.**).

### viii. Loss of Control of Geometry

Axial and related loads on the fuel bundle shall be less than the minimum acceptable margin to the bundle's buckling strength.

ix. Primary Deuteriding/Hydriding

Equivalent concentration of internal hydrogen gas of an as-fabricated fuel element, excluding the sheath, shall not exceed the minimum acceptable limit.

In addition, volume-average concentration of hydrogen/deuterium (in the form of soluble atomic hydrogen/deuterium and equivalent hydrides and deuterides including their orientations) over the cross-section of load-bearing components shall be below the minimum acceptable margin to the amount required to retain sufficient ductility.

x. Oxides, Crud and Deposits

The combined thickness of oxide, crud and deposits on fuel sheath outer surface shall be below the minimum acceptable margins to the amount required for spalling from the surface and also for a through-wall hole.

## 6.3. COMPATIBILITY WITH SURROUNDINGS

xi. Excessive Interaction Loads Along the Fuel String

After considering all pertinent in-reactor deformations, the maximum length of the fuel string (e.g., in the fuel channel) shall be less than the minimum available space (e.g., between shield plugs or latches), with an acceptable minimum margin.

xii. Excessive Interference with Interfacing Equipment

Fuel bundle dimensional changes (e.g., due to irradiation, loads, creep, bowing, droop, etc.) shall not result in clearances that are less than the minimum acceptable margin to contact between neighbouring sheaths or endcaps, nor between pressure tube and sheath/endcap. Nor shall the on-power clearances – with or without the fuel's deformations -- be below those assumed in verification and safety assessments, for example in calculations of heat transfer coefficients.

Net dimensions including dimensional changes throughout fuel bundle's residence in the reactor shall be within specified limits for interfacing equipment.

To allow passage of fuel through the reactor in all fuel handling operations, axial force required to move the bundle shall be within design allowance including all pertinent considerations such as on-power deformations, in-service contacts with neighbouring components if any are permitted, and changes in material properties.

xiii. Wear

At spacer pads, total wear from all sources such as lateral vibrations, axial vibrations, fretting, sliding and erosion shall be less than that which brings any part of a spacer in contact with a neighbouring sheath, with a minimum acceptable margin.

At bearing pads, total wear and corrosion from all sources shall be less than the thickness of the pad, with a minimum acceptable margin.

Depth of all wear and corrosion in the pressure tube from fuel bearing pads shall be within specified allowances.

xiv. Crevice Corrosion

Below bearing pad or spacer pad, temperature at sheath outer surface shall be below the minimum acceptable margin to that required to cause crevice corrosion of the sheath.

Depth of crevice corrosion in the pressure tube from fuel bearing pads shall be within specified allowances.

## 7. CLOSURE AND SUMMARY

In a recently developed process – called "Criteria-Based Verification" – fourteen credible damage mechanisms have been identified for CANDU fuel during operating states during which fuel experiences temperatures near those experienced during normal operations. Their associated "Acceptance Criteria" help verify that the fuel is not damaged while delivering its functional requirements during normal operations, nor does it damage its surroundings. The criteria reflect basic limits of materials (such as melting point, ductility, etc.) minus prudent margins.

The damage mechanisms are organized into three groups:

- Mechanisms that can potentially threaten the thermal integrity of fuel through potential overheating. This comprises of 2 damage mechanisms: pellet melting and sheath overheating.
- Mechanisms that can potentially threaten the structural integrity of fuel through potential cracks, breaks, or loss of structural stability in appropriate parts. This comprises 8 damage mechanisms: gas pressure; power ramps; mechanical overstress/overstrain; impact loads; fatigue; unstable geometry; primary hydrides/deuterides; and oxide, crud, deposits.
- Mechanisms that can adversely impact the geometric or other compatibility of fuel with interfacing systems. Geometric compatibility would ensure that critical parts mate/fit

with their interfaces. Other compatibility would include chemical compatibility, such as limiting crevice corrosion to within design allowances. This comprises 4 damage mechanisms: string length; interference with interfacing equipment; wear; and crevice corrosion.

The fuel acceptance criteria -- introduced relatively recently in the context of design and qualification of the ACR fuel -- are design basis inputs which have the following characteristics:

- They are required inputs to the fuel design and fuel design qualification process. Defining fuel acceptance criteria is now one element of the process by which CSA N286 requirements are met.
- They are established for each known fuel damage mechanism in operational states.
- To the extent practical, they are independent of specific design features. Therefore, numeric values of material properties would usually not be built into the criterion. Nevertheless, when the criteria are applied, different numeric values may well be used in different designs if they use different materials or operate at different conditions. Likewise, if a new design feature is added, additional criteria may well be also required.
- The resulting limits are sufficient, but not necessarily necessary. Even at the acceptance criterion, the design would still contain residual margin to failure.
- If these criteria are met, no further justification is required to assert that the fuel is not damaged while delivering its functional requirements, nor does it damage its surroundings.

Compared to the traditional approach, fuel verification using mature CBV would (a) be quicker; (b) facilitate enhanced comprehensiveness; and (c) enable easier licensing in some international jurisdictions.

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