THE ACR-1000 FUEL DESIGN VERIFICATION PROCESS

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Abstract

The ACR-1000®[1] CANFLEX®[2]-ACR fuel bundle design is being developed according to AECL design quality assurance procedures, which are CSA N286.2-00[1] compliant. An important part of the design process for any system is design verification. For the ACR-1000 fuel bundle design verification, an approach has been adopted which builds on AECL's successful experience in design and qualification of fuel, while enhancing the planning and execution of the process, providing a more objective and explicit demonstration of design compliance with requirements, and improving the alignment of the process with internationally recognized approaches.

The cornerstone of the ACR-1000 fuel design verification process is the adoption of a set of fuel acceptance criteria for normal operating conditions. These criteria, if met, mean that the fuel is not damaged as a result of normal operation. It is recognized that other approaches are also available to evaluate whether fuel is damaged or not damaged, as is evidenced by successful past AECL fuel designs. 'Not damaged', as used within the context of the criteria, means that fuel elements do not fail, that fuel bundle dimensions remain within specified tolerances, and that functional capabilities are not reduced below those assumed in safety analyses. With a set of fuel acceptance criteria established, the design verification process consists of considering the design requirements in light of the acceptance criteria and demonstrating that the design can fulfil the design requirements without violating the acceptance criteria. This is done through a combination of testing and analysis.

1. Introduction/Background

The process of CANDU®[3] fuel design and development has always focussed on demonstrating that the fuel can successfully fulfil the design requirements without failure. CANDU power reactor fuel has achieved an enviable performance record with fewer than 0.1 % of fuel bundles irradiated showing a defect of some type[2]. This performance record is a clear demonstration that the fuel design, development, and verification processes used in the past have been extremely successful.

CANDU fuel design is now a discipline that has been in existence for over a half century. This span of time gives rise to an experience base that allows for a high level of confidence in the understanding of fuel behaviour, particularly in the understanding of potential fuel failure mechanisms. Therefore, in ACR-1000 fuel design verification, advantage is taken of this understanding to refine the process of design verification.

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[1] ACR-1000® (Advanced CANDU Reactor®) is a registered trademark of Atomic Energy of Canada Limited (AECL).
[2] CANFLEX® is a registered trademark of AECL and the Korea Atomic Energy Research Institute (KAERI)
[3] CANDU® (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

The ACR-1000 fuel design verification process has also been better aligned with internationally recognized practices, to support the overall ACR-1000 design goal of having a reactor design that would be easily adaptable to licensing requirements in a broad range of jurisdictions, while maintaining compliance with Canadian standards and practices.

In this paper, the overall design verification process will be discussed by outlining the key components of the process: namely the design requirements, the Fuel Acceptance Criteria and the design verification strategy.

2. Design Requirements

The design of the ACR-1000 follows an established process for defining design requirements. This process ensures that overall requirements on the reactor design, including regulatory requirements, are cascaded to each appropriate SSC (structure, system or component). The process also ensures that interfacing systems' requirements are propagated between all of the relevant SSC's that comprise the NSSS. The design requirements for ACR-1000 fuel have been established in accordance with this process.

The highest-level requirements for the ACR-1000 fuel bundle have been established as follows:

Functional Safety Requirements

- Fuel bundle elements in the reactor contain the uranium fuel and its fission products in Normal Operation, AOOs and DBAs[4].

Functional Production Requirements

- Fuel bundle elements containing uranium produce thermal fission power when placed in the fuel channel of operating reactor core in Normal Operation and AOOs.
- Fuel bundle transfers heat produced in the fuel elements to the coolant flowing over the elements and in the bundle sub-channels in Normal Operation and AOOs.
- Fuel bundle enables on-power refuelling in Normal Operation and AOOs.

Safety Design Requirements

- Fuel bundle is an SSC of Safety Function Category A-I and Safety Class I.
- Fuel bundle is considered a Category A component for seismic qualification.
- The fuel bundle in a fuel channel maintains proper position and does not get damaged, or release radioactivity into the coolant larger than the allowable limits, during or after exposure to the FRS resulting from a DBE.
- Seismic qualification of the fuel bundle is in accordance with the CSA Standards CAN3-N289.1[3], CAN3-N289.3[4] and CAN3-N289.4[5].

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4 This requirement does not apply to certain DBAs, namely; large break LOCA prior to ECC system establishment, the affected channel in single channel events, and inadvertent entrainment of small size debris in HTS coolant.

Materials and Chemistry Requirements

- Materials used in the fuel bundle do not lead to adverse impacts on other reactor components that cannot be mitigated by reactor operating procedures.
- Fuel bundle materials have specified limits on Cobalt content to minimize hazardous radiations for radiation protection.

There are other, supplementary, performance, environmental, inspection and testing, operations and maintenance (O&M) and other requirements, but they are considered to be an additional level of detail to the main requirements outlined above.

2. Fuel Acceptance Criteria

Design verification can be defined based on CSA N286.2-00 [1] as the process of determining and documenting that the design conforms to the design requirements. There are many means of performing design verification and there is a broad range of potential tools that can be used in determining whether a design conforms to the design requirements. Use of acceptance criteria is mandated within CSA-N286.2-00 in conjunction with design verification through qualification testing. Within the design verification process for the ACR-1000 fuel bundle, the concept of acceptance criteria is used more broadly by establishing a comprehensive set of “Fuel Acceptance Criteria” for application in NOC (Normal Operating Conditions) and AOO (Anticipated Operating Occurrences).

The IAEA defines “Acceptance Criteria” as:[6]

> “Specified bounds on the value of a functional indicator or condition indicator used to assess the ability of a structure, system or component to perform its design function”

Application of the concept of acceptance criteria in ACR-1000 fuel bundle design is guided by internationally recognized approaches to design and regulatory approval of fuel designs. For example, the US NRC, in its Standard Review Plan for Section 4.2, Fuel System Design[7] establishes a requirement that the design bases for fuel system design include “acceptance criteria for fuel system damage, fuel rod failure, and fuel coolability.”

For ACR-1000 fuel bundle design, we have established “Fuel Acceptance Criteria” that are used to evaluate if the fuel is ‘damaged’ or ‘not damaged’ as part of demonstrating that a particular design requirement is met. ‘Not damaged’, as used in this definition, means that fuel elements do not fail, that fuel bundle dimensions remain within specified tolerances, and that functional capabilities are not reduced below those assumed in safety analyses. ‘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

The objective of CANDU fuel design, development, and qualification has always been to demonstrate that fuel is not damaged in fulfilling design requirements in which maintenance of fuel integrity is required, and hence appropriate Fuel Acceptance Criteria have been met, *de facto*, by previous CANDU fuel designs. The new approach in ACR-1000 fuel bundle design provides more objective and explicit acceptance limits for all of these criteria.

Not all design requirements entail the potential for fuel to be ‘damaged’ in an environment or scenario related to NOC or AOO. Design requirements may be in respect to fuel behaviour in design basis accidents, or may be in respect to functionality, economy, jurisdiction, , regulatory restrictions, contractual obligations, codes, standards, guides, etc. Addressing such requirements does not involve the use of Fuel Acceptance Criteria. The criteria have been developed from basic engineering principles and from known damage mechanisms. In establishing acceptance criteria two separate aspects have to be considered, first one must ensure that all potential damage mechanisms are addressed, and second a quantifiable bound for parameter(s) associated with each mechanism has to be defined to ensure that the damage is avoided. To ensure that each potential or observed damage mechanism is identified a team of CANDU fuel experts dubbed the "old elephants" performed an extensive review of the available fuel defect data. The review included defect data from research reactors (including, for instance, the WR1 reactor) as well as power reactors. The review included personal recollections as well as documented incidents. The maturity of the industry and the range of defect mechanisms observed, give us confidence that no new defect mechanisms are likely to be identified for CANDU fuel bundles. In addition, existing fuel acceptance criteria established for other (non-CANDU) reactor designs were also considered in determining the ACR-1000 Fuel Acceptance Criteria.

To establish the quantifiable bound, the first step is to identify the actual condition of the material when damage occurs, e.g., melting of the pellet, or crack in the sheath, etc. Where the actual material limits are not known in sufficient detail, close precursors are used as surrogates. These conditions where damage occurs (or their precursors) form Material Failure Limits. To these, reasonable margins are applied for prudence as described below. The net values are the Fuel Acceptance Criteria.

3.1 Categorization of the Selected Fuel Acceptance Criteria

Fuel Acceptance Criteria for ACR fuel are based on known credible damage mechanisms and organized into three major groups as follows:

1. Criteria to ensure thermal integrity of fuel. These criteria protect relevant parts from potential overheating, and are assigned unique identifiers in the "T" series.
2. Criteria to ensure structural integrity of fuel. These criteria protect against potential cracks, breaks, or loss of structural stability in appropriate critical parts. They are assigned unique identifiers in the "S" series.
3. Criteria to ensure compatibility of fuel with interfacing systems. These criteria ensure that critical parts mate/fit with their interfaces. They also limit other interactions (such as chemical interactions) between fuel bundle/element and other interfaces to within design allowances. They are assigned unique identifiers in the "C" series.

3.2 Minimum Acceptable Margins within Fuel Acceptance Criteria

The Fuel Acceptance Criteria are established with minimum acceptable margins from the identified material failure limit within them. These margins are established such that, if they are met the associated damage mechanism will be avoided". That is to say, although it is desirable to have a prudent margin, the minimum acceptable margins within the criteria are sufficient but not necessary. Any encroachment on these margins must be justified (e.g., by crediting existing applicable operating experience that shows a smaller margin does not result in fuel damage, by sensitivity analysis indicating that the actual margin provides assurance that fuel damage will be avoided with sufficient confidence, etc.). The essential element provided by the margins is additional confidence that fuel damage is avoided relative to that provided by simple avoidance of the material failure limit. The margins proposed for AOO will be equal to or smaller than those that were proposed for NOC. Smaller margins can be used for AOO because of the low probability of occurrence of an AOO, which means that the amount of confidence that is deemed to be sufficient to avoid fuel damage is less. In this paper, the magnitudes of the minimum acceptable margins for the Fuel Acceptance Criteria are not discussed.

3.2 The Fuel Acceptance Criteria

The Fuel Acceptance Criteria used in ACR-1000 fuel bundle design are as follows:

Table 1
ACR-1000 Fuel Acceptance Criteria

Damage Condition	Acceptance Criterion
"T" Series	
Fuel element failure due to fuel melting	Local temperature in all parts of the pellet shall stay below the minimum acceptable margin to the melting point of pellet material
Fuel element failure due to sheath melting	Local temperature in all parts of the sheath shall stay below the minimum acceptable margin to the melting point of the sheath material[5]
Fuel element failure due to 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
Fuel or pressure tube failure due to overheating by contact	Fuel bundle dimensional changes (e.g., due to irradiation, loads, creep, bowing, etc.) shall not result in clearance that is less than the minimum acceptable margin to contact between neighbouring sheaths or endcaps, nor between pressure tube and sheath/endcap
"S" Series	
Fuel sheath failure due to overpressure	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
Fuel sheath failure due to environmentally-assisted cracking due to power ramps	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, including the effects of pellet chips, if any, from refuelling impacts
Fuel failure due to static mechanical overstrain	Local principal strain (elastic plus plastic) shall be less than the minimum acceptable margin to the available ductility; and local creep strain shall be less than the minimum acceptable margin to the creep rupture strain
Fuel failure due to uncontrolled loss of geometry	Axial and related loads on the fuel bundle shall be less than the minimum acceptable margin to the bundle buckling strength

[5] It is noted that the ACR-1000 has a design requirement to preclude fuel dryout before reactor trip, which is generally more restrictive than this criterion

Damage Condition	Acceptance Criterion
Fuel failure due to fatigue	Cumulative fatigue damage from repeated cycles of alternating stresses/strains shall be below the allowable design fatigue life, with a minimum acceptable factor of safety on magnitude of cyclic strain or and on number of cycles
Fuel mechanical rupture due to impact loads such as refuelling and/or start/restart	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
Primary hydride failures	Equivalent concentration of internal hydrogen gas of an as-fabricated fuel element, excluding the sheath, shall not exceed the minimum acceptable limit
Formation of a local hydride lens due to oxide and crud	The combined thickness of oxide and crud on fuel sheath outer surface shall be below the minimum acceptable margin to the amount required for spalling from the surface
Failure due to insufficient ductility during post-irradiation handling	Volume-average concentration of hydrogen (in the form of soluble atomic hydrogen and equivalent hydrides and deuterides) over the cross-section of load-bearing components shall be below the minimum acceptable margin to the amount required to retain sufficient ductility
"C" Series	
Failure due to excessive interaction loads along the fuel string	Maximum length of the fuel string (e.g., in the fuel channel) shall be less than the minimum available distance (e.g., between shield plugs or latches), with an acceptable minimum margin
Failure from damage by interfacing equipment	Net dimensions including dimensional changes throughout fuel bundle residence in the reactor shall be within specified limits for interfacing equipment
Fuel sheath failure due to spacer pad fretting	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
Fuel bundle jamming	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, and changes in material properties
Protection of pressure tube from bearing pads	Depth of crevice corrosion, sliding wear and fretting wear in the pressure tube from fuel bearing pads shall be within specified allowances

3.2 Use of the Fuel Acceptance Criteria

In determining the numeric value of any given parameter associated with a Fuel Acceptance Criterion, all its significant on-power contributors shall be considered. For example, in determining the ductility to failure, the "base" value of ductility; effect of fabrication parameters (e.g., microstructure, cold work, heat treatment, texture, etc.); effect of fluence; effect of temperature; effect of corrosive environment; effect of hydrides; etc. must all be considered.

In the same vein, the criteria refer to the allowable range of operating values for the fuel's entire lifetime in the reactor. Further, in evaluating whether fuel meets the criteria, the residual and cumulative effects, if any, of situations that may be experienced by the fuel prior to loading are also to be included as appropriate. Note that Design Acceptance Criteria limits differ from values during operation values. Let us consider pellet centreline temperature as an illustrative example. We might, for example, formulate a Fuel Acceptance Criterion that centreline temperature of the pellet stay below the melting point of the pellet. 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.

Accident analyses frequently require operating values of some key parameters during normal operating conditions (NOC) as starting point for the accident analysis. Some typical examples are: pre-transient pellet temperature, pre-transient fission gas volume, etc. In AECL's accident analyses, the current practice is to use appropriate limiting operating values - not design limits - to cover the worst credible conditions for such parameters. This practice will be maintained. There is no intention that accident analyses start with the assumption that the fuel is at Fuel Acceptance Criteria limits for NOC rather than appropriate limiting NOC operating values. This also applies to the design verifications, in which design requirements are shown to be met.

4. The Design Verification Strategy

The Design Verification Strategy identifies combinations of tests and/or analyses that will be employed to demonstrate that ACR-1000 fuel meets the design requirements, and, at the same time, is not damaged. The design verification strategy is established in consideration of the Fuel Acceptance Criteria. Whether the Fuel Acceptance Criteria are met in respect to the relevant design requirements will be controlled by the materials selected for the design; dimensions and shapes prescribed in design drawings; design specifications; trip setpoints; and/or operational limits.

Consideration of all of the design requirements, including the supplementary performance, environmental, and other requirements, has led to the establishment of 35 design verification assessments to be performed in order to complete the design verification for NOC. In addition, 4 groups of design verification assessment "scenarios" have been identified for verifying compliance of the fuel design with the requirements arising from AOO. It is beyond the scope of this paper to identify all 39 of the design verification assessments in detail. However, some attention will be paid to discussion of how the verification assessments to be performed are established.

Sometimes a number of different strategies can be envisioned to verify any given requirement. When there have been different possible strategies, the following guidelines have been applied to select an optimal strategy (in decreasing order of relative priority):

- completeness (priority: essential)
- confidence in successful outcome (priority: essential)
- sufficient and appropriate technical depth, accuracy and precision (priority: high)
- ability to consider worst credible scenario/combination (priority: high)
- existing validated computer codes (priority: high)
- timeliness (priority: high)
- cost (priority: high)
- consistency with past practices (priority: medium)

Existing verifications of current CANFLEX fuels - natural uranium (NU) and Low Void Reactivity Fuel (LVRF) - represent close antecedents to ACR-1000 fuel. The development of specific strategies for ACR-1000 fuel verification considers the approaches adopted in comparable aspects of those design verifications, when applicable.

In addition to the tests and analyses that are used as part of the verification strategy, the overall design verification strategy also includes some tests that are confirmatory in nature. There are additional tests being conducted beyond the requirements of the design verification to further demonstrate the design performance and to provide additional information. Thus they are not required elements of the design verification. Nevertheless, since these tests do provide additional information, they are planned as part of the overall ACR-1000 fuel design verification.

The verification assessments will consider the following:

- All credible damage scenarios, design tolerances, and operational envelopes;
- On-power and time/burnup-dependent changes, such as in material properties, in geometry, in oxides and hydrides; in wear; etc.;
- Appropriate uncertainties in measurements, data, tools, codes, and analyses;
- All appropriate significant feedbacks of related processes and cumulative effects.

A particular design requirement may require a number of thermal, structural and compatibility assessments for its verification.

To strike an optimal balance amongst all key considerations noted above, the verification strategies employ a judicious mix of the following components:

- in-reactor tests, such as high-power irradiations;
- out-reactor qualification tests, such as endurance tests;
- out-reactor tests to obtain data to calibrate models and to validate computer codes, such as strength tests;
- out-reactor tests to obtain data for inputs for analytical assessments, such as material property tests;
- analytical assessments that employ validated computer codes and correlations, such as fission gas pressure assessments.

5. Conclusion

To verify that ACR-1000 fuel meets its design requirements, AECL plans to conduct a comprehensive, integrated set of appropriate in-reactor tests, out-reactor tests, analyses and engineering evaluations. This design verification program will ensure that ACR fuel will maintain the excellent performance exhibited by current CANDU fuel, for configurations permitted by design and operational tolerances.

The ACR-1000 fuel design verification process is part of a larger structured fuel design process defined by

- An overall design QA program that is compliant with the CSA Standard N 286.2 [1],
- The overall ACR-1000 Design Verification Plan,
- The ACR-1000 Fuel Design Requirements,
- The ACR-1000 Fuel Design Description,
- The ACR-1000 Fuel Acceptance Criteria, and
- The ACR-1000 Fuel Design Verification Strategy.

In this paper, the fuel design requirements, acceptance criteria and verification strategy have been discussed in the context of the overall ACR-1000 fuel design verification process. This process has been established in a way that builds on AECL's successful experience in fuel design development, while providing a more objective and explicit process, easing the planning of design verification and improving its alignment with internationally recognized approaches.

6. References

[1] CSA Standard N286.2-00, "Design Quality Assurance for Nuclear Power Plants"

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[3] CSA Standard CAN3 N289.1-80 (R2003), "General Requirements for Seismic Qualification of CANDU Nuclear Power Plants"

[4] CSA Standard CAN3 N289.3-M81 (R2003), "Design Procedures for Seismic Qualification of CANDU Nuclear Power Plants"

[5] CSA Standard CAN3 N289.4-M86 (R2003), "Testing Procedures for Seismic Qualification of CANDU Nuclear Power Plants"

[6] IAEA Safety Glossary : Terminology Used in Nuclear Safety and Radiation Protection : 2007 Edition. - Vienna : International Atomic Energy Agency, 2007.

[7] "Fuel System Design", U.S. Nuclear Regulatory Commission, Standard Review Plan, Section 4.2 of Report NUREG-0800, Rev 3, March 2007.