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Preface

This regulatory document is part of the CNSC's safety analysis series of regulatory documents, which also covers deterministic safety analysis, probabilistic safety assessment and nuclear criticality safety. The full list of regulatory document series is included at the end of this document and can also be found on the CNSC's website.

Regulatory document REGDOC-2.4.5, *Nuclear Fuel Safety*, clarifies requirements and provides guidance for the design, operation, monitoring and safety assessments of fuel for operating reactor facilities.

This document is the first version of REGDOC-2.4.5, *Nuclear Fuel Safety*.

For information on the implementation of regulatory documents and on the graded approach, see REGDOC-3.5.3, *Regulatory Fundamentals*.

The words "shall" and "must" are used to express requirements to be satisfied by the licensee or licence applicant. "Should" is used to express guidance or that which is advised. "May" is used to express an option or that which is advised or permissible within the limits of this regulatory document. "Can" is used to express possibility or capability.

Nothing contained in this document is to be construed as relieving any licensee from any other pertinent requirements. It is the licensee's responsibility to identify and comply with all applicable regulations and licence conditions.

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Nuclear Fuel Safety

1. Introduction

1.1 Purpose

This regulatory document clarifies the requirements and provides guidance for the design, operation, monitoring and safety assessments of fuel for operating reactor facilities.

It articulates a set of comprehensive fuel-related requirements and provides guidance that is risk-informed and aligns with accepted national and international codes and practices.

1.2 Scope

This document focuses on fuel design, operation, monitoring and safety assessments for operating facilities, with implicit concentration on operating CANDU reactors, but remains as technology neutral as practicable. It applies, primarily, to fuel programs and designs that are already licenced, and to modified or new fuel designs envisioned for operating plants at the time of publication of this document.

The high-level concepts and technology-neutral information also apply to proposed new reactor facilities, including technologies other than water-cooled reactors. While this document focuses on CANDU fuel, high-level concepts within it may apply to other technologies. If a design other than a CANDU reactor is being considered for licensing in Canada, the associated fuel design, qualification and oversight will be subject to the safety objectives, high-level safety concepts and safety-management requirements associated with this regulatory document, where applicable.

This document will be revised as appropriate to incorporate operating experience (OPEX) with new reactor technologies.

1.3 Relevant legislation

The following provisions of the *Nuclear Safety and Control Act* (NSCA) and the regulations made under it are relevant to this document:

- *Nuclear Safety and Control Act*, paragraphs 3(a), 9(a)(i), and subsections 24(4) and (5)
- *General Nuclear Safety and Control Regulations* (GNSCR), paragraph 12(1)(c)
- *Class I Nuclear Facilities Regulations*, paragraphs 6(b) and (g)

1.4 National and international standards

The key principles and elements used in developing this document are consistent with national and international standards.

The following standards are relevant to this regulatory document:

- N286-12 *Management system requirements for nuclear facilities* [1]
- N299.1 series, *Quality assurance program requirements for the supply of items and services for nuclear power plants* [2]
- IAEA SSR-2/1: *Safety of Nuclear Power Plants: Design* [3]

- IAEA SSG-52 *Design of the Reactor Core* [4]

2. Fuel Safety

Defence in Depth (DiD) is a cornerstone of the Canadian regulatory philosophy. Each level of defence has its specific objectives, including the protection of relevant barriers and the essential means for this protection. Defence in Depth is used when determining nuclear fuel safety in water-cooled reactors such as CANDUs. For such reactors, the first two of five physical barriers to the release of radioactive material are the fuel matrix and the fuel cladding. The primary heat transport system, the containment, and the exclusion zone constitute the other three physical barriers. Other reactor designs achieve the same requirements and level of safety for these latter three physical barriers by other means.

Appendix A contains information on the application of DiD for fuel safety. For more information on the concept and application of DiD, see REGDOC-3.5.3, *Regulatory Fundamentals* [5] and REGDOC-2.5.2, *Design of Reactor Facilities: Nuclear Power Plants* [6].

3. Fuel Design

The fuel design program ensures that fuel design is controlled and accurately reflected in the safety analysis of the reactor facility, and that the fuel design is properly qualified for the subset of all facility states considered in the fuel design process. It also confirms that the fuel will remain within its safety limits at all levels of DiD, where each safety limit is explicitly taken into account in the fuel design basis.

Requirements

Licensees shall have a fuel design program that ensures the fuel design is:

1. controlled;
2. accurately reflected in the safety analysis of the reactor facility;
3. properly qualified for the subset of all facility states considered in the fuel design process; and
4. within its safety limits at all levels of DiD, where each safety limit is explicitly taken into account in the fuel design basis.

3.1 Fuel design and fuel design limits

The fuel design program ensures that the fuel design and fuel design limits are established.

Requirements

In its fuel design program, the licensee shall ensure that:

1. all phases of the facility’s lifecycle, and all levels of DiD, are taken into account;
2. the fuel remains within its safety limits for the facility’s design envelope;
3. the design inputs are defined;
4. the design requirements are defined;
5. design and safety analysis computer codes are validated; and
6. the fuel design is qualified for use.

3.2 Control of fuel design and design process

Requirements

The licensee shall ensure that, as part of the fuel design program, the fuel design and design process are established, documented and controlled.

The licensee shall ensure that the fuel documentation is updated when new information or understanding is gained.

3.3 Management system and quality assurance

Requirements

The licensee shall ensure that the fuel design program complies with the management system requirements found in CSA N286-12, *Management system requirements for nuclear facilities* [1]. Licensees not using CSA N286-12 shall identify the codes, standards and specifications on which their supply chain quality assurance (QA) is based.

The licensee shall ensure that the fuel design program includes a manufacturing QA program that ensures the supply chain for fuel employs an appropriate national standard supply chain QA, such as CSA N299.1, *Quality assurance program requirements for the supply of items and services for nuclear power plants* [2]. Licensees not using CSA N299.1 shall identify the codes, standards and specifications on which their supply chain QA is based.

Guidance

Licensees that are not using CSA N286-12 and/or CSA N299.1 should map their management system and QA control measures to the requisite standards to demonstrate that they satisfy the requirements for the fuel design program. Where gaps are identified, the licensee shall describe the measures that address them.

3.4 Fuel operation and monitoring

Requirements

The licensee shall ensure that, as part of the fuel design program, the fuel successfully performs its safety functions for the facility's design envelope.

3.5 Fuel design authority

Requirements

The licensee shall ensure that the fuel design program identifies a fuel design authority who is responsible for:

1. establishing a knowledge base;
2. the fuel design process;
3. the documentation of the design and its technical basis;
4. change control; and
5. the qualification of the fuel design.

4. Fuel Design Process

In the fuel design process, the licensee identifies the requirements and limits the fuel must meet, produces a fuel design, and documents how the design meets the requirements. The fuel design process includes assessments that show how the fuel design requirements have been met. The complexity of the fuel design process, including the qualification stage, is a function of the novelty of the design. The design process must take into account all applicable facility states.

4.1 Notification

Requirements

When considering possible changes to the fuel design, the licensee shall engage CNSC staff to confirm that the changes are within the licensing basis, before implementing the change.

Guidance

The CNSC encourages early engagement by the licensee to confirm that the changes are within the licensing basis.

4.2 Design change

Requirements

The licensee shall assess proposed changes to design specifications and manufacturing methods to determine if the change may affect the licensing basis, design basis or safety case. If these might be affected, then the licensee shall treat the change as a design change.

4.3 Defence in depth

Requirements

For the fuel design process, the licensee shall take into account the core principles of level 1 DiD (see appendix A), through:

1. careful selection of materials;
2. use of qualified fabrication processes;
3. use of proven technology;
4. extensive testing;
5. conservatism in the design;
6. high quality in construction and manufacturing;
7. use of appropriate standards;
8. suitable safety margins; and
9. due consideration of site characteristics.

Guidance

For more information on DiD, see REGDOC-3.5.3, *Regulatory Fundamentals* [5].

4.4 Safety analysis

Requirements

The licensee shall commence safety analysis at an early point in the fuel design process, with iterations between design activities and confirmatory analytical activities. The objective is the demonstration of an increase in scope and level of detail as the design process progresses in accordance with IAEA SSR-2/1: *Safety of Nuclear Power Plants: Design* [3].

4.5 Design consideration scope

Requirements

The licensee shall take into account the reactor conditions, from commissioning to core end-of-life conditions, in the design process.

In the design considerations, the licensee shall take into account all facility states within the facility's design envelope.

4.6 Input to design process considerations

Requirements

In the design process, the licensee shall demonstrate that input has been considered from:

1. reactor physics and the nuclear design;
2. reactor thermalhydraulics;
3. nuclear criticality safety;
4. interfacing systems such as:
    a. interfacing physical barriers (for example, the primary heat transport system components)
    b. fuel handling
    c. fuel storage
    d. transport
5. waste storage and minimization; and
6. OPEX.

4.7 Design requirements

Requirements

As part of the fuel design process, the licensee shall identify:

1. functional requirements;
2. performance requirements;
3. safety requirements;
4. environmental impact;
5. inspection and testing requirements;
6. requirements that are imposed on the interfacing systems by the fuel design;
7. requirements that are imposed on the fuel by the interfacing systems; and
8. applicable codes and standards.

Guidance

Applicable codes and standards should include welding, transport packaging, workplace safety and handling of hazardous materials.

Licensees should refer to CSA N286-12, *Management system requirements for nuclear facilities* [1], for more information.

4.8 Design safety objectives

Requirements

The licensee shall define the fuel design safety objectives.

Guidance

For current operating CANDU reactors, these objectives may be formulated as follows:

1. For normal operating conditions, including the effects of anticipated operational occurrences (AOOs):
   a. the fuel elements will not fail;
   b. fuel pellet, element and bundle dimensions will remain within operational tolerances as described in TECDOC No. 1926, *Technical Review Of Acceptance Criteria For Pressurized Heavy Water Reactor Fuel* [6];
   c. the fuel bundle will maintain its structural integrity;
   d. the functional capabilities of the fuel will not be reduced below those assumed in the deterministic safety analysis; and
   e. the damage that the fuel may cause to the fuel channel components is acceptable in the sense that these components remain fit for service.
2. For accident conditions considered in the safety report:
   a. the fuel design achieves the safety functions commensurate to the event class;
   b. fuel sheath failures will be kept to a minimum; and
   c. the fuel assembly and its component parts will remain in position with no distortion that would prevent effective core cooling during or post-accident.

If the fuel design is for a reactor other than a CANDU, the fuel design safety objectives shall be defined following international best practices, but might differ significantly from the guidance provided for currently operating CANDU reactors.

4.9 Degradation mechanisms

Requirements

In the design process, the licensee shall identify fuel degradation mechanisms and associated limits that may challenge the fuel design. To do this:

1. damage mechanisms shall be identified and defined;
2. failure mechanisms shall be identified and defined;
3. conservatism shall be employed in setting limits associated with degradation mechanisms;
4. limits associated with damage mechanisms shall be set such that, if complied with, they preclude, with margin, the fuel (element or bundle) and fuel channel components being damaged (that is, the fuel and fuel channel components remain fit for service) during operational states; and

5. fuel damage and failure mechanisms and associated limits shall reflect a verified and auditable knowledge base.

Guidance

The design process should identify fuel failure limits. If a fuel failure limit is not well defined or known, a measurable surrogate limit should be defined. These surrogate limits should incorporate conservative engineering safety factors.

4.10 Documentation

Requirements

As part of the fuel design process, the licensee shall document the fuel design and describe how it meets the identified requirements.

5. Fuel Qualification Process

Fuel qualification is a key activity of the fuel design process. The aim is to ensure that the final design meets all of the fuel design requirements. Fuel design qualification is achieved through analysis using qualified methods and through qualification testing.

Requirements

The licensee shall ensure that qualification of the manufacturing process complies with the manufacturing QA program described in section 3.3, Management system and quality assurance.

5.1 Qualification objective

Requirements

As part of the qualification program, the licensee shall demonstrate that the design meets all of the requirements and the associated limits.

Guidance

Typically, this requirement has been demonstrated by OPEX, testing, analytical prediction and the surveillance program (lead test assembly).

5.2 Technical basis

Requirements

The licensee shall ensure that the technical basis for the qualification program:

1. is based upon OPEX or is demonstrated through a program of experimental testing and analysis, or a combination of both, where:
    a. the referenced OPEX must be documented and auditable; and
    b. operating experience may be with the same or similar fuel design in the same or a similar reactor design. For any technical basis that is based upon OPEX with similar designs, the licensee shall document and assess the differences between the two designs.
2. demonstrates the adequacy of:
    a. qualification analysis and modeling;

b. qualification testing regime; and
c. the documented design and operating envelope of the fuel.

5.3 Management system and quality assurance

Requirements

The licensee shall ensure that the qualification process meets the licensee's management system and QA requirements.

5.4 Qualification certification

Requirements

The licensee shall ensure that the qualification of the fuel is certified for use by the licensee's fuel design authority.

6. Fuel Design Submissions

Requirements

Before loading a new or modified fuel design into a reactor core, the licensee shall submit, to the CNSC, the following information and obtain CNSC staff's confirmation that the design is within the licensing basis and is qualified for use:

1. for a modified fuel design, an assessment on whether or not the change is a licensing basis change
2. the fuel design requirements
3. a detailed description of the fuel design
4. the current/updated safety case
5. a statement of qualification of the design
6. the technical basis for qualification
7. the documented qualification envelope
8. a summary of the qualification results

The licensee shall provide additional information as requested by CNSC staff.

Guidance

The CNSC encourages early engagement by the licensee for assessments of new or modified fuel designs.

7. Fuel Fitness for Service

Safe operation of fuel requires that the fuel condition meets the criteria for fuel fitness for service (FFS). In this context, FFS is the physical condition necessary for the fuel barriers to remain intact, the fuel system dimensions to remain within operational tolerances, the structural integrity to be maintained, fuel parameters to remain within the initial conditions assumed by the Safety Analysis Report, and the fuel to remain compatible with interfacing systems such as the fuel channel components.

Typically FFS assessments are performed on new or modified fuel designs through the design and qualification process prior to first load, through continual monitoring and inspection during normal operations, and by post anticipated operational occurrence (AOO)/design basis accidents (DBA) event reviews.

7.1 Fuel fitness for service criteria

Requirements

The licensee shall identify and document, to the extent practicable, the fuel FFS criteria.

Guidance

The licensee should consider and the criteria should be consistent with:

1. the requirements placed on the fuel through the design and qualification process;
2. licensing limits;
3. OPEX;
4. the challenges to which the fuel is subjected by AOO events; and
5. requirements for return to service after an accident.

7.2 Technical basis

Requirements

The licensee shall have a documented technical basis for the set of FFS criteria and a methodology to demonstrate compliance.

7.3 Fuel fitness for service assessments

Requirements

The licensee shall implement a process that:

1. identifies when fuel FFS assessments are required; and
2. assesses fuel FFS.

Guidance

Computer codes used to perform FFS assessments should be validated for the application, and should comply with CSA N286.7, *Quality assurance of analytical, scientific and design computer programs for nuclear power plants* [7].

7.4 Record keeping

Requirements

The licensee shall keep records on the assessed fuel condition.

8. Fuel Monitoring and Inspection Program

The fuel monitoring and inspection program identifies the condition of the fuel and the extent of qualitative or quantitative degradations to determine whether the fuel remains fit for service.

Monitoring and fuel inspection activities play an important role in ensuring the licensee's acceptable safety performance in a number of safety and control areas (SCAs), including operating performance, physical design, safety analysis and waste management. Information gathered during those activities ensures events that are significant to safety, and that occur at various levels of DiD, are promptly detected, therefore allowing adequate time for corrective measures to be effectively implemented to avoid repetitions.

8.1 Program

Requirements

The licensee shall establish a monitoring and inspection program that ensures that the fuel is fit for service.

8.2 Capabilities

Requirements

The licensee shall ensure that the monitoring and inspection program includes onsite and in-bay inspections of fresh and irradiated fuel and, if necessary, hot-cell examinations.

The fuel monitoring and inspection program shall:

1. require that only qualified personnel perform inspections;
2. include procedures and guidance on how to perform inspections;
3. require properly functioning and calibrated testing, measurement and inspection equipment be available;
4. ensure the capability to perform the number of inspections required;
5. require that equipment and qualified personnel needed to perform online fuel condition monitoring are sufficiently available; and
6. create and maintain a repository for recording fuel inspection findings.

Guidance

The objective of the fresh fuel inspections is to ensure that the incoming fuel was manufactured in accordance with the appropriate quality standard and that the fuel has not been damaged or contaminated by transportation or storage. Once fresh fuel inspections are completed, the licensee should minimize interactions with the fuel prior to loading.

The objective of irradiated fuel inspections is to infer the existing in-core condition of the fuel and to trigger mitigating measures when required.

Data obtained from irradiated fuel inspections can also be useful to assess whether fuel, under accident conditions, will perform in accordance with its design safety objectives and whether the operators can take the necessary measures.

8.3 Assessment of findings

Requirements

As part of the fuel monitoring and inspection program, the licensee shall regularly assess findings and their potential impacts and confirm that fuel remains fit for service and within the analysed condition.

Guidance

The licensee should ensure that expertise from a diverse range of disciplines is involved in the program and in the assessment of findings. Some examples of disciplines that should be involved are fuel channels, safety analysis, fuel handling and reactor physics.

The impact on interfacing systems should be considered as part of the program.

8.4 Reporting

Requirements

The licensee shall report findings of the program in accordance with REGDOC-3.1.1, *Reporting Requirements for Nuclear Power Plants* [8].

8.5 Corrective actions

Requirements

The licensee shall ensure that the fuel monitoring and inspection program has mechanisms in place to take corrective or mitigating actions on findings that have potential impacts on fuel FFS or on the analysed condition.

Guidance

The licensee should take actions that are proportional to the level of risk presented by the findings.

8.6 Trending

Requirements

The licensee shall define levels related to expected fuel conditions and degraded states in order to identify negative trends.

Guidance

Training on fuel conditions and degraded states levels should be a component of a fuel inspector's qualification, to ensure the data collected for trending is coherent.

8.7 Inspection process

Requirements

Where sampling is used, the licensee shall ensure that there is a documented inspection sample selection process.

The sample selection process shall include both random surveillance and targeted surveillance components.

Guidance

The majority of the inspections should be by random surveillance.

Targeted surveillance should result in selection of bundles that represent different conditions in the reactor.

The fuel inspection process should produce a robust plan for inspections, including the number of inspections that should be performed each quarter in order to meet annual inspection requirements (section 8.8).

8.8 Inspection

Requirements

For CANDU reactors, the minimum number of in-bay inspections for a normally operating reactor with no identified active degradation mechanisms is 20 bundles per year per reactor. For reactors of other designs, the licensee shall seek acceptance from CNSC staff on an acceptable minimum level of inspections.

Additional inspections shall be performed when active degradation mechanisms or other challenges are present.

Guidance

Fuel removed from the core due to it not being, or being suspected of not being, fit for service should be inspected for relevant information.

Inspections done on fuel defects, in excess of the number typical for an operating year, should not be credited towards the minimum level of inspections. In cases where the fuel was removed but the exact location (bundle or element) of the defect cannot be determined, all known information should be recorded.

8.9 Maintenance of equipment

Requirements

The licensee shall ensure that equipment used to monitor for, locate and remove fuel that is not fit for service is properly maintained and is functional when required.

Guidance

Monitoring equipment should be operating whenever the reactor is operating. Location and removal equipment is only required when fuel defects are detected.

8.10 Failed fuel and fuel not fit for service

Requirements

The licensee shall remove fuel that has been identified as failed or not meeting the FFS criteria. If the fuel cannot be removed immediately, the licensee shall take appropriate mitigating actions in the interim.

The licensee shall minimize failed fuel residency times, as fission product release into the coolant and its deposition on the primary heat transport system piping may result in higher worker doses.

The licensee shall apply the principle of ALARA (as low as reasonably achievable) when determining the resources and efforts being put towards failed fuel detection and removal.

8.11 Record keeping

Requirements

The licensee shall keep records of the fuel monitoring and inspection findings in a manner that is usable for analysis and trending.

9. Fuel Operating Limits and Conditions

When used in conjunction with the operations program, the fuel program shall ensure that fuel is operated within its design and operating envelope.

In conjunction, these programs set operational limits and conditions (OLCs) to ensure that fuel is not damaged during normal operations or AOO conditions. The OLCs also provide a documented limit to degradation on the fuel to ensure that fuel remains within the design and qualification envelope.

9.1 Establishment principles

Requirements

The licensee shall establish fuel OLCs to ensure that fuel is operated in accordance with the licensing basis, the design of the reactor, and the qualification and operating envelope. The fuel OLCs shall include the limits within which the operation of the fuel has been shown to be safe.

Fuel OLCs shall have the largest safety margins practicable.

9.2 Fitness for service

Requirements

The licensee shall use the fuel OLCs to ensure FFS during normal operating conditions and AOO conditions.

9.3 Modes of operation

Requirements

The licensee shall use the fuel OLCs to establish the operational requirements applicable to each mode of operation before entering that mode. The operational modes for normal operating conditions should include:

- shutdown;
- power production;
- refuelling;
- shutting down;
- starting up;
- commissioning;
- transitional states;
- maintenance or outage;
- life extension;
- refurbishment; and

- testing.

Guidance

For commissioning, refurbishment and post-refurbishment operations, the licensee should consider primary heat transport system (PHTS) pressure tests, hot conditioning, a chemistry control program and a foreign material exclusion program to minimize fuel defects.

9.4 Entering new operating conditions

Requirements

The licensee shall assess the fuel OLCs before entering operating conditions that are infrequent in nature. This assessment shall ensure the existing fuel OLCs are adequate to ensure safety and FFS.

9.5 Aging

Requirements

In the fuel OLCs, the licensee shall take into account the impact of aging of the PHTS on fuel performance.

9.6 Corrosion

Requirements

In the fuel OLCs, the licensee shall define the operating parameters to minimize, within acceptable limits, corrosion of the sheath and the creation of deposits.

9.7 Changes in operation

Requirements

The licensee shall review significant changes to operation of fuel and fuel handling against the fuel OLCs and update the fuel OLCs as required.

Guidance

Significant changes are those that potentially could affect neutronics, thermalhydraulics or safety analysis assumptions, inputs or limits.

Examples of significant changes include:

- an increase in plant power rating;
- an increase in burn-up;
- major changes to the facility's PHTS; and
- changes in fuel placement/shift or fuelling direction.

9.8 Periodic review

Guidance

The licensee should undertake periodic reviews of fuel OLCs to ensure that they remain applicable and are updated as needed.

9.9 Actions limits and response timelines

Requirements

The licensee shall define and address actions and the timelines to take actions when fuel is not or is suspected of not being FFS.

9.10 Documentation of basis

Requirements

The licensee shall ensure that the basis on which the OLCs are derived is readily available in order to facilitate the ability of plant personnel to interpret, observe and apply the OLCs.

Appendix A: Application of Defence in Depth for Fuel Safety

Defence in Depth (DiD) is a cornerstone of the Canadian regulatory philosophy. Each level of defence has its specific objectives, including the protection of relevant barriers and the essential means for this protection. Defence in Depth is used when determining nuclear fuel safety in water-cooled reactors such as CANDUs. For such reactors, the first two of five physical barriers to the release of radioactive material are the fuel matrix and the fuel cladding. The primary heat transport system, the containment, and the exclusion zone constitute the other three physical barriers. Other reactor designs achieve the same requirements by other means.

REGDOC-3.5.3, *Regulatory Fundamentals* [5] provides information on the principles of DiD. Refer to the information below for implementing DiD for nuclear fuel safety.

The CNSC has formulated requirements and provided guidance regarding fuel design, degradation mechanisms and associated limits, qualification, monitoring, inspection and operations, to ensure the application of DiD principles to all fuel-related activities so that the fuel will perform in accordance with its design safety objectives during both operational states and accident conditions. These formulated requirements and guidance can be categorized into their respective levels of defence:

Level 1 DiD is achieved by robust engineering and construction. To ensure this, it is imperative that the fuel design and qualification processes are comprehensive and that the manufacturing is controlled. Fitness for service limits in conjunction with operating limits and conditions are defined to inform and prevent operations from deviating outside the licensing basis.

Level 2 DiD is achieved by having appropriate fitness for service limits to support level-2 deterministic safety analysis. Level 2 is further enhanced by having a functioning monitoring and inspection program to identify deviations and abnormalities and take corrective actions to return the fuel condition to normal.

Level 3 & 4 DiD is achieved by having documented and understood failure mechanisms and safety criteria in conjunction with a robust fuel design, such that if a design basis accident did occur, the fuel behaviour would be understood and the barrier protected as per the fuel design basis. For beyond design basis accidents (level 4), the understanding and protection should be to the extent practicable.

Level 5 DiD does not apply to nuclear fuel safety.

To further ensure success of all four levels of DiD, the assignment and subdivision of responsibility for safety must be kept well defined throughout the design phase of a new fuel design, and during any subsequent modifications. This is usually done by assigning a qualified fuel design authority.

Appendix B: Key Degradation Mechanisms for Normal Operation

This appendix lists the key degradation mechanisms in normal operating conditions.

Table B-A: Key degradation mechanisms affecting CANDU fuel in normal operation conditions

Degradation category	Observable effect	Key influencing parameters	Impacts relevant to safety
Deformation without material loss	• Sheath collapse and ridging	• Coolant pressure • Temperature	• Mechanical strength • Heat transfer
	• Sheath ballooning (uniform) or bulging (non-uniform)	• Internal gas pressure • Temperature	• Mechanical strength • Heat transfer • Loss of sheath integrity
	• Pellet/clad mechanical interaction	• Power ramps	• Loss of sheath integrity
	• Element bowing	• Loads • Temperature	• Mechanical strength • Heat transfer
	• End-plate deformation	• Loads	• Mechanical strength • Heat transfer
	• Bundle drooping, sagging	• Loads	• Mechanical strength • Heat transfer
	• Athermal sheath strain	• Loads	• Loss of sheath integrity
Deformation with material loss	• Fretting	• Interaction with debris	• Loss of sheath integrity
	• Bearing pad wear	• Interaction with pressure tubes	• Heat transfer • Impact on pressure tube condition
	• Spacer wear	• Interaction with pressure tubes	• Heat transfer
	• Scratching, nicks	• Interaction with in-reactor components	• Loss of sheath integrity
Change in material properties	• Sheath oxidation	• Temperature • Coolant chemistry	• Mechanical strength • Heat transfer
	• Hydriding	• Coolant chemistry	• Mechanical strength • Sheath temperature
	• Stress corrosion	• Power ramps • Internal gas composition	• Loss of sheath integrity
	• Crevice corrosion	• Coolant chemistry	• Impact on pressure tube condition

Degradation category	Observable effect	Key influencing parameters	Impacts relevant to safety
	• Material phase transitions	• Temperature • Irradiation	• Mechanical strength
	• Fuel grain growth	• Temperature • Irradiation	• Heat transfer
	• Internal gas pressure and composition change	• Burn-up • Temperature	• Heat transfer • Stress corrosion
Integrity failures	• End-cap to sheath weld failures	• Manufacturing defects • Loads	• Loss of sheath integrity
	• End-cap to end-plate weld breaks	• Manufacturing defects • Loads • Fatigue	• Mechanical strength
	• End-plate cracks	• Vibration • Loads • Fatigue	• Mechanical strength

Appendix C: Fuel Degradation Mechanisms

Some examples of fuel degradation mechanisms in anticipated operational occurrences (AOOs) (Defence in Depth [DiD] level 2 without fail) and slow events of design basis accidents (DBAs) (DiD Level 2 with fail and DiD level 3) include:

- sheath collapse and ridging (axial or longitudinal);
- sheath ballooning (uniform) or bulging (non-uniform);
- pellet/clad mechanical interaction;
- element bowing;
- end-plate deformation;
- bundle drooping, sagging;
- sheath oxidation;
- hydriding;
- stress corrosion;
- material phase transitions;
- element internal gas pressure and composition change;
- end-cap to sheath weld failures;
- end-cap to end-plate weld breaks; and
- end-plate cracks.

Appendix D: Acceptance Criteria for Design-Basis Accidents

This appendix shows examples of acceptance criteria for design-basis accidents.

Table D-A: Examples of acceptance criteria of CANDU fuel systems for design-basis accidents

Barrier to fission product releases or fundamental safety function	Qualitative acceptance criteria as derived acceptance criteria
Fuel matrix	• No fuel centre line melting • No fuel breakup • No excessive energy deposition
Fuel sheath (fuel cladding)	• Fuel elements (fuel rods) that exceed the critical heat flux (CHF) or depart from nuclear boiling (DNB) criteria are assumed to rupture and contribute to offsite dose. • No excessive strain of fuel sheath • Fuel elements are to meet applicable limits for: o sheath temperature; o local sheath oxidation; and o oxygen embrittlement of fuel sheath.
Fuel assembly	• Maintain fuel coolability. • Retain rod-bundle geometry or fuel assembly with adequate coolant channels to permit removal of residual heat. • No impediment to reactor shutdown means due to geometry change (light water reactor [LWR])

Glossary

For definitions of terms used in this document, see REGDOC-3.6, *Glossary of CNSC Terminology*, which includes terms and definitions used in the *Nuclear Safety and Control Act* and the regulations made under it, and in CNSC regulatory documents and other publications. REGDOC-3.6 is provided for reference and information.

The following terms are either new terms being defined, or include revisions to the current definition for that term. Following public consultation, the final terms and definitions will be submitted for inclusion in the next version of REGDOC-3.6, *Glossary of CNSC Terminology*.

fuel design
The design of the system that provides, supports, contains and cools the fuel matrix. Holistically, this includes groupings of fuel components into bundles, assemblies, piles and fuel strings.

References

The CNSC may include references to information on best practices and standards such as those published by CSA Group. With permission of the publisher, CSA Group, all nuclear-related CSA standards may be viewed at no cost through the CNSC Web page "How to gain free access to all nuclear-related CSA standards".

1. CSA Group, CSA N286-12, *Management system requirements for nuclear facilities*, Toronto, Canada, 2012.

2. CSA Group, CSA N299.1, *Quality assurance program requirements for the supply of items and services for nuclear power plants*, Toronto, Canada, 2019.

3. International Atomic Energy Agency (IAEA), SSR-2/1: *Safety of Nuclear Power Plants: Design* (Rev. 1), Vienna, Austria, 2019.

4. IAEA, SSG-52, *Design of the Reactor Core for Nuclear Power Plants*, Vienna, Austria, 2019

5. Canadian Nuclear Safety Commission (CNSC), REGDOC-3.5.3, *Regulatory Fundamentals*, Ottawa, Canada.

6. IAEA, TECDOC No. 1926 *Technical Review Of Acceptance Criteria For Pressurized Heavy Water Reactor Fuel*, Vienna, Austria, 2020.

7. CSA Group. CSA N286.7, *Quality assurance of analytical, scientific and design computer programs for nuclear power plants*, Toronto, Canada, 2016

8. CNSC, REGDOC-3.1.1, *Reporting Requirements for Nuclear Power Plants*, Ottawa, Canada.

Additional Information

The CNSC may recommend additional information on best practices and standards such as those published by CSA Group. With permission of the publisher, CSA Group, all nuclear-related CSA standards may be viewed at no cost through the CNSC webpage "How to gain free access to all nuclear-related CSA standards".

The following documents provide additional information that may be relevant and useful for understanding the requirements and guidance provided in this regulatory document:

- Canadian Nuclear Safety Commission (CNSC), REGDOC-2.4.1, *Deterministic Safety Analysis*, Ottawa, Canada.
- CNSC, REGDOC-2.5.2, *Design of Reactor Facilities: Nuclear Power Plants*, Ottawa, Canada.
- US Department of Defense, Systems Engineering Fundamentals, Washington, United States of America, 2001.

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Facilities and activities within the nuclear sector in Canada are regulated by the CNSC. In addition to the *Nuclear Safety and Control Act* and associated regulations, these facilities and activities may also be required to comply with other regulatory instruments such as regulatory documents or standards.

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