TECHNICAL SPECIFICATIONS AND PERFORMANCE OF CANDU FUEL

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Abstract

The relations between Technical Specifications and fuel performance are discussed in terms of design limits and margins. The excellent performance record of CANDU® reactor fuel demonstrates that the fuel design defined in the Technical Specifications (and with it other components of the procurement cycle, such as fuel manufacturing), satisfy the requirements.

New requirements, changing conditions of fuel application, and accumulating experience make periodic updates of the Technical Specifications necessary. Under the CANDU Owners Group (COG) Working Party 9, a Work Package has been conducted to support the review of the Specifications and the documentation of the rationales for their requirements. So far, the review has been completed for 4 Specifications: 1 for Zircaloy tubing, and 3 for uranium dioxide powder. It is planned to complete the review of all 11 currently used specifications by 1999. The paper summarizes the results achieved to mid 1997.

Introduction

AECL-issued Technical Specifications for fuel bundles, subassemblies, parts and materials, have been used in the procurement of CANDU fuel for about 40 years. The documents evolved to their current shape gradually, together with the development of the CANDU system. References [1-5] describe their history.

The performance of CANDU fuel has been excellent, and in recent years there have been no incidents of systematic fuel defects attributable to fuel design. Also, during recent years, there seemed to be little change in the specifications of fuel materials and in the design of the fuel element, with the effort being concentrated more in the area of bundle configuration.

This may lead to an impression that for the CANDU system, the development of fuel materials or of the fuel element design is no longer required. Such an impression, however, is not correct. New requirements are being formulated that will have their effect on fuel design, new fuel applications and conditions of use are under consideration, and accumulated experience with fuel manufacturing and performance has resulted in a number of fuel parameter changes. Fuel Technical Specifications have to keep pace with this, and therefore require periodic reviews and updates.

To update a specification requirement in a technically justified manner, we first have to understand the background of the parameter and the rationale of the requirement. There are links between fuel design parameters and fuel performance, and changes that are done without adequate knowledge of the technical implications, may lead to undesirable consequences, such as in-reactor defects.

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Because there was little change in Technical Specifications during recent years, it is sometimes difficult today to find the relevant information on the technical background and the rationales of existing parameters and limits. This is why the COG Working Party 9 initiated Work Package 0908, "Fuel Specification Review", with the objective to review and document the rationales for the requirements in fuel design documents, and to analyze selected topics. At present, there are 11 important specifications that are currently used for power reactor fuel. It is planned to complete the review of all of them by 1999. To date, 4 Technical Specifications have been reviewed: 1 for Zircaloy tubing, and 3 for uranium dioxide powder. This paper summarizes the results.

Limits and Margins

A fuel Technical Specification should reflect the needs of all steps in the fuel supply chain. This includes factors such as availability of materials, manufacturability, fuel handling, disposal of spent fuel, and, of course, defect-free performance in-reactor.

Figure 1 shows the relations between the main parts of the CANDU fuel supply chain. The parameters that govern performance in-reactor, are related to the "fuel design requirements", i.e. to the design of the reactor and systems that interact with fuel. The operation of the fuel and the interacting systems impose loads on fuel. Fuel is able to withstand the loads up to critical levels, "defect thresholds" or "performance limits". Under normal conditions, the loads should be at a safe distance ("margin") below the limits - there should be no fuel defects.

Figure 2 schematically illustrates the concept of limits and margins developed by the International Atomic Energy Agency (IAEA) [6], with the terminology adjusted for the application to fuel.

Design defines the minimum values of defect thresholds - either directly or indirectly, e.g. by specifying the minimum thickness of CANLUB. Manufacturing conforms to the design-related limits and yields products with defect threshold distributions of the type shown in Figure 2, satisfying the design requirement at a predetermined Acceptable Quality Level (AQL). Similarly, there is a distribution of loads from operational conditions, also shown schematically in Figure 2.

A deviation ("excursion") of manufacturing conditions may cause changes in product properties, leading to lower values of a defect threshold. Similarly, a deviation of operational conditions may result in higher loads on fuel. Figure 2 shows schematically the effect of a manufacturing deviation on the distribution of defect thresholds, and of an operational deviation on the distribution of loads.

If the margins are sufficient, a small deviation causes non-conformance only, i.e. violates the limits without producing defects. Eventually, it may reach an extent that does result in defects ("manufacturing defects" and "operational defects", respectively). Each of the two excursions, schematically shown in Figure 2, would lead to some defects, as the corresponding distribution curves for defect thresholds and loads overlap.

If the margins are too small or absent, the fuel will suffer "design defects" - the distributions of loads and defect thresholds will overlap even for normal manufacturing and operating conditions. On the other hand, the design-defined margins may be very large. In this case, there will be no "design defects", but the product will likely be expensive, difficult to manufacture, or inefficient in use.

Large margins imposed by design and not matched by proper programs in manufacturing or reactor operation, do not necessarily provide a 100% guarantee of defect-free performance. A joint approach that balances the role of design, manufacturing and operation, is needed. CANDU fuel procurement uses such a joint approach, with the result of a very low defect rate. In addition, the CANDU system is prepared in case fuel defects occur. If a fuel defect develops in a CANDU reactor, it can be promptly detected and removed.

Insufficient margins are usually corrected promptly, because they tend to be accompanied by defects, and therefore are highly "visible". When the margins are excessive, relaxing the limits is often more difficult. Some of the margins, in particular their components attributable to single parameters, have not been positively determined, and so the "excess margin" should first be identified and a justified new limit should be confirmed. It is a design change, and as such should be properly verified and validated.

Review of Technical Specifications for Zircaloy Tubing and Uranium Dioxide Powder

All sectors of the CANDU fuel community in Canada were involved in the review, starting with the manufacturer of UO_2 powder and 2 manufacturers of Zircaloy tubing, continuing with fuel development and design, fuel manufacturing (2 manufacturers), fuel use (3 utilities), and ending with specialists in the disposal of spent fuel. Overseas manufacturers and users of CANDU fuel are welcome to join the review. Among other reasons, their input is valuable also because they use different sources of materials, in particular of UO_2 powder.

a. Zircaloy Tubing for Fuel Sheaths

The CANDU fuel sheaths are different from those of other reactor types (for example, fuel cladding for pressurized water reactors). There are two major differences:

- Appendages are brazed to the sheaths during their manufacture, and this significantly affects their microstructure, texture and properties. To control the changes, there are some CANDU-specific requirements for the chemical composition of the tubing.

- CANDU fuel sheaths are designed to operate beyond their yield strength ("collapsible sheaths").

Initially, there was uncertainty as to which tubing parameters are important for such conditions of use, and the requirements underwent several dramatic changes [3].

In our review, the rationales were formulated for all existing requirements. In several cases, we recommend analysis and further work on the requirements, mainly with respect to possible application of CANDU fuel to extended burnups, and in connection with disposal of spent fuel. Table 1 provides a summary of the review.

b. Uranium Dioxide Powder

Three Technical Specifications for UO_2 powder (natural, depleted and enriched) have been reviewed. The requirements on the natural powder, the basic material for pellets in CANDU power reactor fuel, are again different from those for LWR fuel. The important factor is the need to achieve criticality and economically viable discharge burnup with natural uranium. This imposes strict limitations on the level of the "equivalent boron content" (EBC), i.e. on the limits of impurities. Chalder et al. [4] and Hastings et al. [5] describe the development of the uranium dioxide powder and pellets for CANDU fuel.

The summary of our review can be found in Table 2. Again, the rationales have been formulated for all requirements. Need for further work is seen in connection with several impurities in the powder, important for pellet/sheath interaction or for disposal of spent fuel.

Conclusions

Technical Specifications for CANDU fuel need periodic reviews and updates to reflect lessons learned and new requirements under the changing conditions. Understanding of the rationales of the Specification requirements is a necessary condition for a successful update of the documents.

Although spearheaded by AECL under the auspices of COG, the review has benefited from the involvement of all sectors of the CANDU fuel community in Canada. Participation of CANDU fuel manufacturers and users from overseas is encouraged.

Four Specifications (Zircaloy tubing and UO_2 powder) have been reviewed. The rationales of all requirements have been formulated, and several recommendations have been made for modification and analysis. Other specification reviews are in progress or planned, with the intent to review all important specifications within the next 2 years.

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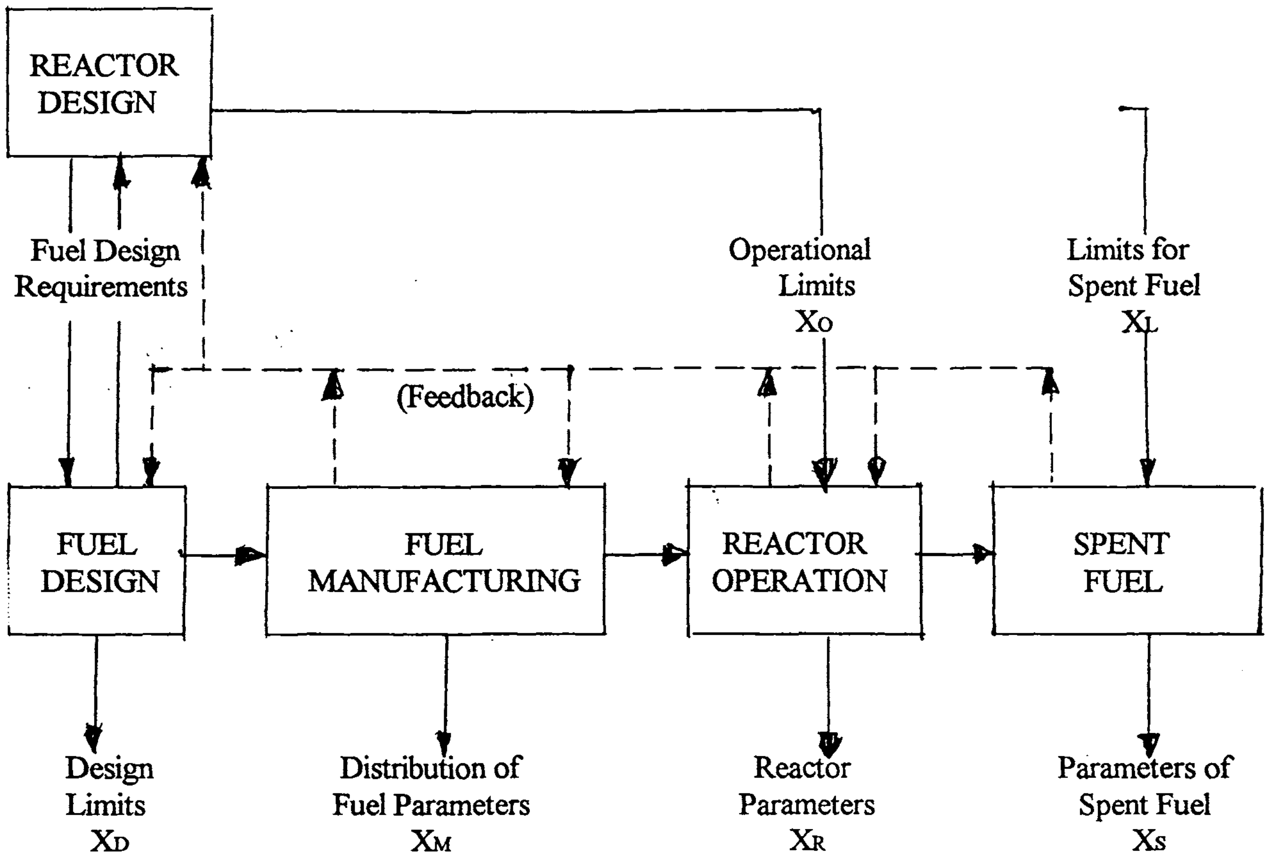
6. "Design Limits and Margins". IAEA Circular Letter, 1992 July.

Table 1 - Review of TS for Zircaloy Tubing

Parameters Reviewed (Concerns and Rationales)	Comments
Chemical Composition Neutronic properties Basic physical properties Mechanical strength Heat transfer Corrosion resistance Hydriding characteristics Equivalent boron content, burnup Isotopes in sheaths of discharged fuel	Alloying elements may need modifications (lower Sn, addition of Nb, increased Fe+Cr), if CANDU fuel is used at high burnups (enriched uranium). The existing low limit for H in the tubing is justified, as this hydrogen may aggravate the effect of hydrogen gas from fuel element interior. For several of the "unlisted impurities" (e.g., Cl) limits lower than 50 ppm should be considered. A minimum concentration of some impurities helps to prevent excessive grain growth in the braze HAZ - they should be considered as "alloying elements".
Mechanical Properties Sheath strength Failure-free straining of the collapsible sheath Containment of fission products	Yield strength of the tubing is affected by brazing of appendages; statistical formulation of the requirement may be revised. Total circumferential elongation characterizes both the ductility and wall thickness uniformity; statistical formulation of the requirement is justified.
Corrosion Resistance Sheath residual thickness and strength Sheath integrity in-reactor and after discharge	---
Microstructure and Texture Mechanical properties and their uniformity Anisotropy of mechanical properties Resistance to crack growth across the wall	The requirement for maximum grain size comes from the time when annealed condition was also specified for the tubing. For the currently specified cold-worked and stress-relieved condition, the grain is much finer, and the requirement should be revised. Improved texture would increase the resistance to crack growth across the wall. However, present limit is adequate, as the texture is affected by brazing during sheath manufacture.

Table 2 - Review of Technical Specifications for Uranium Dioxide Powder

Parameters Reviewed (Concerns and Rationales)	Comments
Chemical Composition Criticality Achievable burnup Powder reactivity Powder processing Corrosion of the sheath Stress-corrosion cracking of the sheath Density and microstructure of sintered pellets	Formulate limits for the "unlisted impurities". Identify impurities from the "unlisted" category that should have the requirements specified separately. Determine the distribution of chlorine and nitrogen in powder and pellet lots, and specify limits for them.
Particle Size Microstructure after sintering Powder processing	Unify the requirements in the Specifications for natural, depleted and enriched powder.
Bulk Density Powder processing	Unify the requirements in the Specifications for natural, depleted and enriched powder.
Sintering Performance Powder processing	Add a reference to the "Advance Processing Test".



Examples:

Strengths and Loads: $X_R < X_O < X_D < X_M$

Impurities: $X_M < X_D \leftrightarrow X_S < X_L$

Figure 1 - Supply Chain for CANDU Fuel and Assurance of Acceptable Fuel Performance

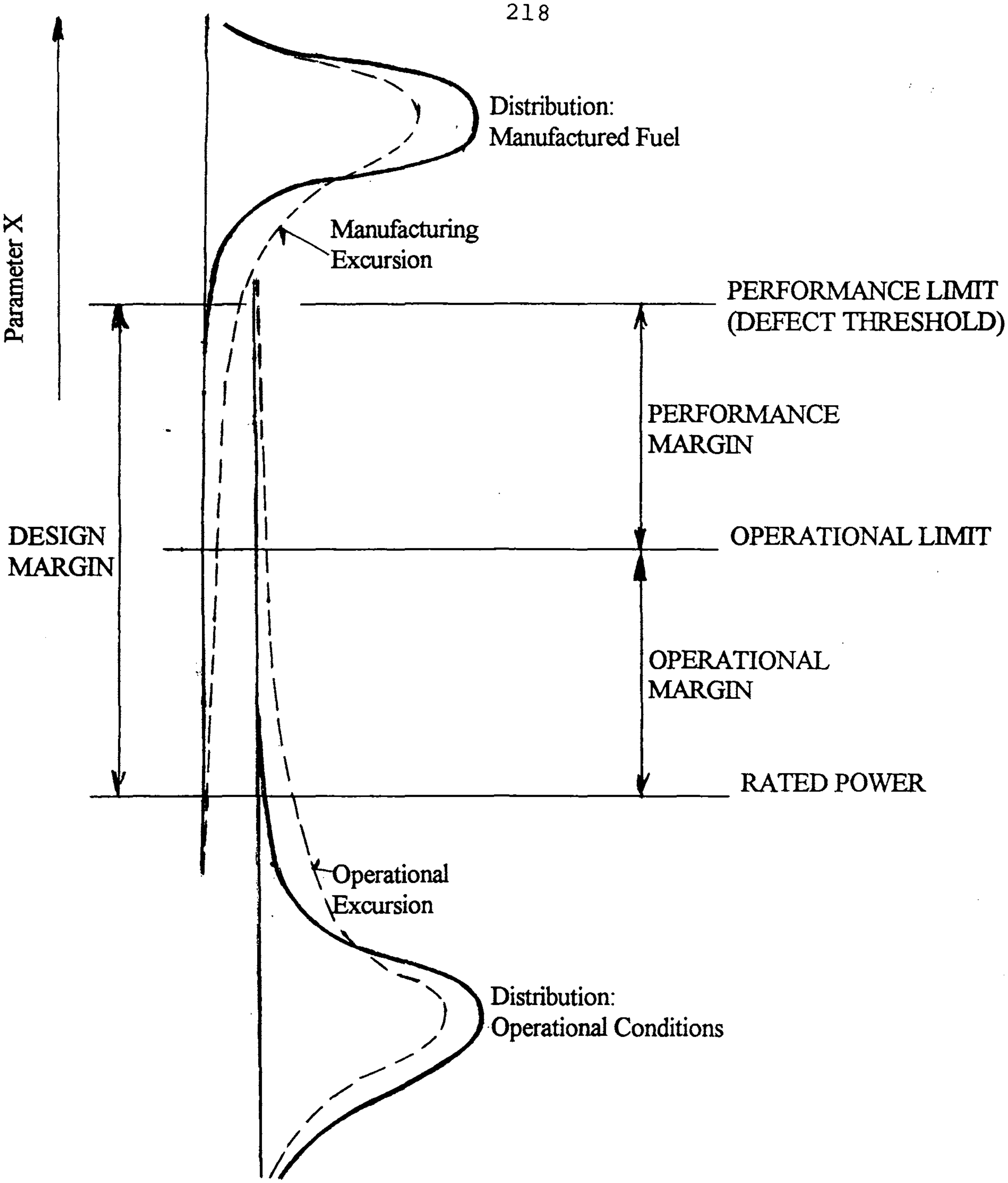


Figure 2 - Fuel Limits and Margins: Probability of Non-conformance and of Defects