CANDU Fuel Design Process

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ABSTRACT

The fuel design process notionally consists of three stages: pre-conceptual, conceptual and detailed design. This paper describes the CANDU® fuel design process followed by AECL in Canada, with salient features illustrated from the design and verification of CANFLEX® and Low Void Reactivity Fuel (LVRF).

INTRODUCTION

Early CANDU fuel design evolution was largely driven by the need to obtain more power out of the fuel bundle and the fuel channel, in order to improve the economics of nuclear-generated electricity. This increased the subdivision of the bundle -- smaller diameter and increased number of fuel elements -- which resulted in more power from the bundle while maintaining the peak linear element ratings for fuel performance and safety margins [1]. An increase in pressure tube diameter in the Pickering and subsequent reactors also allowed more power from the bundle, channel and reactor core.

The first Nuclear Power Demonstration (NPD) reactor used both 7-element and 19-element fuel bundles in an 82.6 mm inside diameter (ID) pressure tube, with a nominal maximum bundle power of 220 kW. The 7-element bundles had an element outer diameter (OD) of 25.4 mm, while the 19-element bundles had an element OD of 15.2 mm. NPD went into commercial operation in 1962. The Douglas Point reactor went into commercial operation in 1967, and continued with the 19-element fuel bundle and a nominal maximum bundle power of 420 kW, again in an 82.6 mm ID pressure tube. To further increase channel and reactor power, the pressure tube ID was increased to 103.4 mm in the Pickering reactor, which went into commercial operation in 1971. Bundle subdivision was increased with a 28-element bundle having 15.2 mm element OD and nominal maximum bundle power of 636 kW. The trend towards increased subdivision continued with the Bruce/Darlington/CANDU 6 reactors, which featured a 37-element bundle with 13 mm OD fuel elements, and a nominal maximum bundle power of 800-900 kW. The Bruce reactor entered commercial operation in 1977. All of these fuel bundles used natural uranium UO_2.

As well as changes to bundle geometry, changes were made to bundle appendages early in the evolution of CANDU fuel. The use of wire-wrapping to maintain inter-element spacing and to protect the pressure tube in early bundle designs was replaced with brazed skewed split-spacers and bearing pads. The external design features of the CANDU fuel bundle (e.g., endcap profiles, bearing pad planes and endplate dimensions) have also changed to accommodate differences in fuel channel and fuel handling components among CANDU reactor designs.

More recently, two new fuel bundle concepts have been taken through the entire design process -- CANFLEX [2,3] with natural uranium fuel and LVRF [4,5,6]. AECL's ongoing experience in the fuel design process has been invaluable in the design of the fuel for the Advanced CANDU Reactor (ACR™) [7-10].

While the fuel design process has evolved with experience and the development of more sophisticated tools, the main elements of the design process have not changed. The process for a new fuel design notionally comprises of three phases: pre-conceptual design, conceptual design and detailed design. The pre-conceptual design phase involves the definition of high-level objectives, and broad scoping studies to identify candidates for the new fuel design. The bundle design at this stage considers only high-level aspects, such as bundle power, geometry and enrichment. In the conceptual design stage, one or more candidates are assessed in greater detail using the best available tools and all high-risk, high-impact aspects of the bundle design are defined. Optimization of the design generally takes place during this phase. In the detailed design stage, one determines/specifies all geometric, dimensional, and materials aspects -- including tolerances -- of the fuel bundle that have an impact on required fuel performance. The bundle is qualified in the detailed design stage, by showing that fuel design requirements and fuel design acceptance criteria have been met.

In Canada, fuel design is done according to the CAN/CSA-N286.2 quality assurance standard [11][1]. AECL has established a company-wide Design QA Manual and a set of related procedures that meet the requirements of CSA-N286.2.

INPUT TO NEW FUEL DESIGN: EXPERIENCE AND R&D

[1] Replaced in 2005 March by CSA Standard N286-05.

Any new CANDU fuel design is anchored in the experience base from the manufacture and irradiation of over 2.5 million fuel bundles in power reactors. This experience includes the fuel design itself (the bundle geometry and components -- pellet materials, fuel sheath, CANLUB coating, appendages, endcap and endplate), the operating conditions that the fuel experiences (power/burnup envelope, primary heat transport conditions and refuelling process), and the manufacturing processes (particularly those that influence fuel performance). This experience base provides confidence in, and an understanding of CANDU fuel performance, and helps to define the relationship between fuel performance and fuel design, manufacturing, and operating conditions. Relevant experience from LWR fuel may also be an input to new CANDU fuel designs.

While experience provides the foundation on which advanced fuels are built, R&D provides the technology that makes a new fuel design "new". Ideally, improvements to fuel design are based on R&D that has already been demonstrated to the largest extent possible. The degree to which the advanced technology has been proven is a major determinant in the risk in the new design, in terms of both schedule and technology: Will the fuel be qualified in time? Will the expected benefit be borne out by testing and analysis? Will it be accepted by the regulator? New technology that has largely been pre-qualified, or generically qualified represents a small risk. If R&D takes place in parallel with the fuel design process, there is a greater risk that there will be "discoveries" during the fuel design process that could necessitate changes in design, result in delays, or necessitate requalification. The further along in the design a discovery is made, the higher the impact; even if there is no technical impact, there can be impacts on cost and schedule.

As noted, ideally all of the R&D associated with advanced technology is completed before the start of the design process -- e.g., it is solely "input" into the new fuel design. The design would then be based only on fully proven technology, which would minimize the risks. However, it is sometimes necessary to perform R&D during the design process. Part of the reason for this is that the development of advanced fuel technology is a long, expensive process. Because of the long lead times involved, advanced fuel technology development must be proactive, rather than reactionary [5,12]. The development must anticipate customers' needs well in advance of their recognition or articulation of those needs, in order that the technology be available when needed. As a result, advanced fuel technology development is sometimes generic in application, and additional R&D may be required when the advanced technology is applied to a specific customer's application.

R&D is also used to obtain

- material properties data and other fundamental data to support the use of advanced materials in new fuel designs, and to develop and qualify design tools such as fuel performance models, correlations and computer codes; examples are properties of irradiated fuel sheath and endplate material, and in-reactor and out-reactor tests for modelling stress-corrosion cracking (SCC);

- validation data for computer codes; irradiation data from both power reactors and research reactors is usually used for this purpose; and
- a fundamental understanding of the relationship between fuel performance and fuel design, manufacturing and operating conditions; an example is an in-reactor test to examine the relationship between the pellet design and fuel performance.

Thus, R&D is a key input in the fuel design process.

COMPUTER PROGRAMS

Analysis using computer programs is an integral part of all stages of the fuel design process. In the pre-conceptual and conceptual design stages, analysis is done to assess various fuel design options, to determine high-level design features, to predict fuel performance within a broad operating envelope and to provide some assurance that fuel design requirements can be met. In the detailed fuel design stage, analysis is essential in establishing detailed geometry, dimensions and materials that will meet the design requirements, and to show that design requirements and fuel design acceptance criteria are met (e.g., to qualify the fuel). Even when qualification testing is performed as part of design verification, analysis may be required to extend the test conditions to power reactor conditions within all permitted design and operational tolerances.

Computer code development, qualification and use follow the CAN/CSA-N286.7 quality assurance standard [13]. Computer code qualification refers to the set of activities that show the computer program is suitable for the intended application. It includes documentation, such as the Theory Manual and Users Manual, verification, which shows that the coding has been done correctly, and validation (usually against experiments and independent analytical/numerical solutions) to establish the bias and uncertainty in key parameters. AECL has established a company-wide Software QA Manual and a set of related procedures that meet the requirements of CSA-N286.7. An early part of the design process is assessing the applicability of the computer programs to the intended application. Gaps in the models and computer programs, as well as in the validation database, must be identified and addressed. It is important that this be done early, as any tests necessary to address those gaps can be lengthy.

Ideally, the entire design process uses models and computer programs that have been fully validated for the intended application. Sometimes, however, fully validated codes are not available, and analysis is done using the best available tools. The project then assumes a risk, which may be reflected in the design margins. That risk can be minimized by doing spot checks of the design using more sophisticated tools. In the ACR, for instance, spot-checks of the physics design using the standard physics toolset (WIMS/DRAGON/ RFSP) [14] is done using the more theoretically rigorous MCNP code [15]. Analysis supporting the final detailed fuel design should use fully validated tools.

In reality, computer code validation is an ongoing process over time. The uncertainties in code predictions can be reduced as more validation data is obtained, from operating reactors and/or additional experiments after the design has been verified.

The ELESTRES fuel performance computer program [16] is the main code used by AECL in CANDU fuel design. In addition, the computer codes FEAT [17], FEAST [17], BOW [18] and INTEGRITY [19] are used for analysis of thermal/mechanical, compatibility and SCC aspects of the fuel element/bundle design.

FUEL DESIGN REQUIREMENTS, FUEL DESIGN OBJECTIVES, FUEL DESIGN ACCEPTANCE CRITERIA, AND FUEL SAFETY CRITERIA

Fuel design requirements arise from a number of reactor systems and operational considerations. These are classified as functional, reactor physics, heat transfer and transport, fuel channel system, fuel handling system, failed fuel detection and location systems, as well as safety and seismic. At a high level, the fuel design requirements are generally the same for all fuel designs and reactors (e.g., the fuel has to meet the power/burnup envelope from reactor physics, and it has to interface with the channel and the fuel handling system). Of course, the specific requirements (such as the actual power/ burnup envelope) depend on the details of the reactor design and application, and should be fully specified before the detailed fuel design phase. For a new reactor design, this is an iterative process since the reactor and fuel design constitute a system that is being optimized.

In the pre-conceptual and conceptual stages for a new fuel design, design objectives or targets are normally established. As described in Reference 5, fuel optimization is a complex, multi-disciplinary consideration of many, often conflicting objectives. The challenge in fuel design is that no single design can optimize all of these objectives simultaneously, so tradeoffs are required. While design requirements must be met, design objectives can be adjusted during the optimization process. Some examples of fuel design objectives are

- minimizing fuel bundle complexity, fuel cycle cost, fuelling machine usage, fuel bundle pressure drop, and peak linear element ratings;
- maximizing uranium content in the bundle, uranium utilization, bundle power, critical heat flux (CHF), and critical channel power (CCP); and
- targets for fuel discharge burnup, reactivity coefficients, and the use (or otherwise) of natural uranium fuel.

It goes without saying that in optimizing the fuel design, safety is a paramount consideration, and safety requirements must be met. New fuel designs usually seek to increase safety margins.

For the ACR, AECL plans to introduce up-front fuel design acceptance criteria, which would provide assurance that the fuel will not fail from any one of several damage mechanisms during normal operation or during anticipated operational occurrences (AOOs). These fuel design acceptance criteria will be based on fundamental laws of nature. The supporting analysis will also show that the fuel dimensions remain within operational limits and that functional capabilities are not reduced below those assumed in safety analyses. Consideration will be given to tolerances in the fuel and interfacing components, reactor operating conditions (the power/burnup history), uncertainties in the models and computer programs, and uncertainties in the data used to validate those models and computer programs.

The fuel design acceptance criteria will be organized into three specific categories – criteria to ensure:

a) thermal integrity of the fuel. These criteria protect the fuel sheath and pellet from potential overheating.
b) structural integrity of the fuel element and the fuel bundle. These criteria protect against potential cracks, breaks, or loss of structural stability in appropriate critical parts.
c) compatibility of the 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 the fuel system/element and other interfaces to within design allowances.

The detailed fuel design stage includes assessments that show how the fuel design requirements and the fuel design acceptance criteria have been met (how the fuel is qualified).

Fuel safety criteria are also specified for the fuel system for postulated accidents. Systematic fuel element failures are to be precluded in normal operation and in AOOs. For certain postulated accidents, fuel element failures may occur, and it must be demonstrated that the damage to the fuel system is limited and possible fission-product releases to the containment building and the environment do not exceed regulatory limits. Showing that fuel safety criteria are met has traditionally been done in the safety analysis reports (rather than in fuel design documentation).

THREE STAGES OF FUEL DESIGN

The three notional stages of the fuel design process will now be described in greater detail. These are not necessarily completely distinct phases, and there may be overlap between them.

<u>Pre-conceptual design.</u> If the new fuel is not based on an existing design, "pre-conceptual" design is the exploratory stage of a new fuel design, involving many scoping

studies. High-level objectives/targets are defined during the pre-conceptual design stage. The focus is on the broad aspects of the fuel design, such as power, geometry, enrichment and burnup.

As noted, the early stages of fuel design (pre-conceptual and conceptual) can be complicated if the final application is not known, or if the requirements are not well enough defined. This stage often involves only a few people, who must have a good understanding of the key disciplines involved in fuel design: fuel engineering (including manufacturability), reactor physics, thermalhydraulics, safety, and the interfacing systems (including the fuel channel and the fuel handling system). It is important that all of the high-level design objectives are considered.

The principal output from this stage is one or more fuel design concepts that are subjected to more detailed assessments in the next phase.

Conceptual design. In this stage, fuel design requirements and acceptance criteria should be fully defined. Assessments are conducted on all high-risk, high-impact aspects of the fuel, using approximations or best available tools if fully validated tools are not yet available. It is necessary to have some idea of the bias and uncertainty in the key parameters to ensure sufficient operating and safety margins. Many assessments and iterations are typically performed during this phase to optimize the design against the objectives, and to have confidence that all fuel design requirements can be met.

Many inputs are required for these fuel design assessments, including reactor physics, which provides the power/burnup envelope and the predicted power histories (steady state, transient powers during refuelling, and powers during postulated accidents such as LOCA); fuel handling, which determines the interface requirements during refuelling as well as the transient powers during refuelling; the primary heat transport system, which determines the flows and coolant conditions which are needed to assess thermalhydraulic margins; and the fuel channel components, which determine mechanical interface requirements. In a new reactor design, this step is significantly more complicated as the entire reactor design may be changing as the result of optimization. Therefore, the necessary fuel design inputs may not be available until later in the design process, or may be changing. If the fuel does not meet design objectives, then a change is made to the fuel design, the design of other components (including the safety systems), the operating conditions, and/or the design objectives.

The fuel design must consider

- pellet design: chemical composition, density, pellet length-to-diameter ratio, geometry of pellet ends (dish, chamfer -- as these determine both the inter-pellet sheath ridging and the internal void volume that is available to accommodate thermal expansion and fission gas release); special end-pellets may be necessary for end-flux peaking and for controlling sheath stresses;

- sheath: material, properties, thickness;
- appendages: location, number, attachment;
- endcap: material, properties, shape, weld profile;
- CANLUB coating: composition, thickness; and
- endplate: material, properties, thickness, design, and bundle-assembly welding.

Just as the capabilities of the computer codes are assessed against the requirements for the new fuel design, so too each of the fuel design features is similarly evaluated, and those features that need to be upgraded are changed to meet the requirements.

Manufacturing input is important in the conceptual fuel design stage for a new fuel design. This is to ensure that the design is manufacturable and cost-effective, that fuel design tolerances can be met by manufacturers (in both material compositions and geometries), and to ensure that any impacts from material compositions and manufacturing processes on fuel performance are known and reflected in fuel design documentation (drawings, specifications), as appropriate. It also allows the fuel manufacturers to design the jigs required in fuel manufacturing, both for manufacture of test elements for qualification testing, and for commercial manufacturing. In the CANFLEX development program, there were extensive interactions with manufacturers during this phase.

During the conceptual fuel design stage, there should be an initial assessment of all of the fuel operating and safety margins, using available information. As well as fuel design and performance analysis, preliminary safety analysis should be done to have confidence that fuel safety criteria will be met with the new fuel design. Linear element ratings (and the operating power history) are an important determinant in fuel performance margins (affecting fission gas release, sheath strain, internal gas pressure and SCC performance). While element ratings are also important in determining safety margins, bundle power is the key determinant in some postulated accidents. CHF is the key parameter in some AOOs and postulated accidents. Reactor power, bundle power, and linear element ratings will be limited by the most restrictive of these margins. Insufficient margins may necessitate a revisit of the fuel design, the design of other systems, the operating conditions, operational procedures, or the design objectives.

Typical outputs from the conceptual fuel design phase may include the following:

- Fuel Documentation Baseline: a list of all of the documentation required in fuel design and regulatory review;
- Fuel Design Requirements: initially these may be high level, but should be quantified before the detailed fuel design stage; the basis for the design requirements can be specified here or in a separate document;
- Fuel Design Acceptance Criteria;
- Fuel Design Concept Decision: gives the essential features of the fuel design;

- Preliminary Fuel Design Assessments: early fuel design-assist analysis using available codes to support the fuel design decisions and to provide confidence that design requirements will be met; and
- Software QA documentation for computer codes, such as Code Assessment, and Code Development and Qualification Plan.

The document titles here are illustrative of content, and there is flexibility in how the information is organized. There should be sufficient confidence in the design at this stage to allow procurement of hardware for long lead-time qualification tests.

<u>Detailed design.</u> The detailed fuel design stage finalizes all aspects of the fuel design. Assessments confirm the basis for fuel design decisions, document important fuel performance characteristics and show that the fuel design is fully qualified, e.g., that requirements and acceptance criteria have been met. The fuel analysis during the detailed design stage should account for the range of parameters that might be expected in-reactor, such as the high power envelope, the deviation of design dimensions from nominal dimensions, and uncertainties in computer code models and analyses. Analysis supporting the final design should use fully qualified tools.

It is important that all aspects of the design are specified in sufficient detail, including any manufacturing aspects that can impact on fuel performance. Hence, the drawings and specifications describing the fuel design must ensure that if fuel is manufactured according to the specifications, it will perform acceptably and meet all design requirements. Therefore, there must be a good understanding of the relationship between fuel performance and fuel design, manufacturing, and the operating conditions.

Typical outputs from this stage may include the following:

- Fuel Design Description: a detailed description of the fuel design; if the designs for the initial and transition cores are different from the equilibrium core, then these have to be described;
- Fuel Bundle Drawing;
- Fuel Technical Specifications;
- Analysis Basis Document: for each major analysis, a description of the analysis that will be done, what input is to be used, the version of codes that are to be used, how analysis is to be done, and how the analysis will be used;
- Detailed Fuel Design Assessments: documentation of analysis of important fuel performance characteristics, and analysis showing that the fuel design requirements and acceptance criteria have been met (qualification analysis); and
- Software QA documentation for computer codes (if not already produced), such as Theory Manual, User Manual, Verification Report, and Validation Manual.

FUEL DESIGN VERIFICATION

Fuel design verification is the process for confirming that the specified design requirements are complete and that the design satisfies those requirements. It is not a separate design stage, but an activity that takes place during each of the design stages. It provides confirmation that the design output meets design input requirements and that documentation is complete and adequate.

In the detailed fuel design stage, a key activity is to ensure that the final design meets all of the requirements and acceptance criteria. This is a subset of fuel design verification, and is often called fuel qualification. Fuel qualification is achieved through analysis using qualified methods and through qualification testing (which together establish the design adequacy).

In any stage of the fuel design, one common design verification method is the independent checking of analysis. This involves independent review by someone not involved in the original analysis, to confirm the adequacy of the assumptions, the input, the methodology, the results and the conclusions. Verification of analysis can also include simplified calculations and assumptions to yield approximate results.

In general, to quote from the standard (Reference 11, Appendix A, Section A.3.5), design verification involves review *"by persons other than those who did the work, to check that the design and its supporting information comply with the request for design and are complete and correct. Verifying methods include one or more of the following:*

a) *a review of the design information by one or more persons;*
b) *analysis by other methods to check the validity of the calculations; and*
c) *tests of manufactured samples for proving the acceptability of the design."*

Fuel qualification tests involve both out-reactor and in-reactor tests, and usually address one or more key features or phenomena in the fuel design. Out-reactor tests mainly address the mechanical performance of the bundle and its interface with the fuel handling and fuel channel systems. In-reactor tests mainly demonstrate the nuclear performance of the bundle, fission gas performance of the pellet and corrosion performance of the sheath. Qualification testing is done with components that are as true to the design drawings, and under test conditions that are as close to the required operating conditions, as can be achieved. However, since the fuel has to be qualified before it is introduced into an operating CANDU reactor, the tests can never be fully representative of the fuel design drawings and/or required operating conditions and their full ranges/combinations as a result of design and operational tolerances. Analysis may be required to extend the results from tests to CANDU reactor conditions to show that the design requirements are met.

For instance, out-reactor tests are performed on un-irradiated bundles, usually in the absence of radiation. So fuel design verification needs to address the effects of irradiation in extending the qualification test results to in-reactor conditions. In-reactor tests are often done in the NRU reactor, which is vertical (rather than horizontal as in CANDU power reactors), and in which the center element is removed to allow for a central tie-rod for mechanical support of the fuel string in the reactor. Any differences in operating conditions between the research reactor and the power reactor, such as pressure and temperature, must also be accounted for.

Typical out-reactor qualification tests include the following: axial sheath collapse, longitudinal sheath ridging, sheath corrosion, bundle strength, bundle compression, cross-flow, fuelling machine compatibility, refuelling impact, sliding wear, spacer interlocking, crevice corrosion, pressure pulsation and bundle endurance. Typical in-reactor qualification tests include a high power / high burnup envelope irradiation, and a steady-state power ramp test. These can be bundle and/or element tests. Irradiation tests are followed by post-irradiation examination (PIE) to confirm fuel microstructure, fission gas release and fuel element and bundle dimensional changes.

Qualification testing for fuel design verification also includes thermalhydraulics tests. Thermalhydraulics qualification testing usually includes CHF tests done both in freon and water using electrical heaters simulating the fuel bundles, as well as measurements of pressure drop and its components. Reactor physics tests are typically done in the ZED-2 critical facility and consist of measurements of reactivity, reactivity coefficients, reaction rates, device worths, and kinetics parameters. The tests planned to support the ACR are described in Reference 20. The physics tests provide validation data for the reactor physics toolset, rather than direct verification of fuel design requirements in the area of reactor physics.

Typical output from the fuel design verification activity may include the following:

- Fuel Design Verification Plan: a plan which shows how the design will be formally verified through qualification analysis and tests, checking and review of analysis (or performance of alternate analysis) and design reviews; the DVP is produced during the conceptual design phase or at the start of the detailed design phase;
- Checklists for analysis reports;
- Results from independent fuel design reviews;
- Component Verification Specification (CVS): for each qualification test, the CVS describes the purpose of the test, what is to be measured, acceptance criteria for the test, and a test matrix;
- Test Plans, Test Procedures and Test Reports: the design organization is responsible for the CVS and the CVR; the detailed test plan and test procedure meeting the requirements of the CVS and the test results are documented by the testing organization;

- Component Verification Report (CVR): for each qualification test, the CVR describes the test results and shows that the acceptance criteria for the test have been met. Dispositioning differences from in-reactor conditions may be done in this report, or in a separate assessment report.

FUEL DESIGN MANUAL (FDM)

The FDM is a summary of everything required to describe the fuel design, and to show how the fuel design requirements have been met. Ideally, the FDM will reference the CVRs and detailed fuel design assessment reports, and summarize their conclusions.

Some of the topics in the Fuel Design Manual may include

- Introduction
- Design requirements (and fuel design acceptance criteria)
- Detailed description of bundle
- Operational input to qualification activities
  - fuel-management systems, primary heat transport system, fuel channel, components, fuel handling system
- Design performance evaluation
  - summary of tests and analyses showing how fuel design requirements and the acceptance criteria are met, including analysis of thermal performance, structural integrity of fuel elements and the fuel bundle, and compatibility with interfacing systems
  - summary of overall bundle design performance.

DEMONSTRATION IRRADIATION (DI)

A demonstration irradiation is not part of the fuel design process, since the fuel must be formally qualified before it is introduced into a power reactor. However, a DI can provide additional reassurance to the utility customer, the regulator and even the designer of acceptable fuel performance. It can also provide further reassurance that all aspects of fuel performance that can be affected by fuel bundle manufacturing have been accounted for in the design. For new fuel that is being introduced into an operating reactor, a DI can be a prelude to full-core implementation.

CANFLEX

Some salient aspects of the fuel design process will be illustrated with CANFLEX and LVRF, two CANDU fuel concepts that have gone through the entire design process over the last 20 years.

Both CANFLEX and LVRF provide good examples of the pre-conceptual fuel design stage. The CANFLEX bundle development program was initiated in the mid-80s, originally as a “High Power Bundle Program” [21]. The key design objective was to achieve a peak bundle power of 1250 kW with peak ratings no greater than 65 kW/m, e.g., a 20% increase in bundle power compared to the 37-element bundle, with the same peak element rating. It was intended for use in existing and new CANDU reactors, with either natural uranium or slightly enriched uranium (SEU). Other considerations in the pre-conceptual design stage were that

- dryout first occurs in the interior of the bundle,
- CHF is increased with the addition of extra spacers and bearing pads,
- the design has “reasonable” fabrication costs, and
- the bundle has sufficient strength.

During the pre-conceptual design phase, the focus was on the fuel bundle geometry. Physics scoping studies were done for approximately two dozen bundle geometries using the WIMS [22] lattice-cell code -- an example of “circles on a sheet of paper”. Two burnups were considered, natural uranium, and 21 MWd/kg (1.2% SEU). Bundle designs were characterized by the peak linear element rating (for a given bundle power), and surface heat flux (SHF). Since the radial power profile across the bundle changes significantly with burnup with SEU fuel, linear element ratings and SHF were calculated for fresh, mid-burnup and discharge burnup. For the initial assessments, thermalhydraulic performance considered SHF, the size and distributions of the coolant subchannels, and the minimum distance between elements. Fuel cost was ranked considering burnup (in both MWd/kg and MWd/bundle), the number and types of fuel elements, and bundle complexity. The smallest element size was a consideration in bundle strength.

The considerations taken 20 years ago during this pre-conceptual design phase illustrate the complex multi-disciplinary, multi-dimensional optimization process that comprises fuel design, and are just as relevant today: *“Each design offers a different compromise for the optimization of the individual parameters. Bundle fabrication costs are minimized with the least number of pins, and with only one pin size; bundle strength favours large elements; dryout power will be increased with low peak SHF and large inter-element gaps; fuelling costs are reduced with a small burnup penalty; fuel performance favours a minimum peak linear element rating...”*

From the initial two dozen fuel concepts that were assessed, more detailed analysis was done on a handful: a 44-element design (having three element sizes, and the elements arranged in rings of 1, 7, 14 and 22 elements); a 43-element design (having two element sizes); a 48-element design having one element size; and a modification of that design having 51 elements of two sizes. Thermalhydraulics assessments were carried out using the ASSERT thermalhydraulics subchannel code [23], and physics analysis was extended to include calculation of coolant void reactivity. The final choice was a 43-element design having two element sizes, based on reactor physics, thermalhydraulics, and fuel engineering considerations. The two element sizes and the increase in the number of elements resulted in a reduction in linear element rating of 15 to 20% for either natural uranium or SEU with uniform enrichment, compared to a 37-element bundle. This pre-conceptual design phase took over a year.

The mechanical design of the CANFLEX bundle during the conceptual and detailed fuel design phases was straightforward. However, the thermalhydraulic performance of the bundle with extra planes of spacers or bearing pads was not sufficient to match the desired higher bundle power. In addition, the erosion of thermalhydraulic margins due to reactor ageing mechanisms was just then being recognized. As a response, CANFLEX became a bundle thermalhydraulic optimization program, to provide increased CHF and CCP to offset the deleterious effects of pressure tube creep and other ageing mechanisms. A range of CHF-enhancing techniques was tested over a 10-year period. A result of the CANFLEX program was a substantial increase in the fundamental understanding of fuel bundle thermalhydraulics, including the effects of axial and radial power profile on CHF and fluid-to-fluid modelling. Major improvements were made to the ASSERT subchannel code and to the NUCIRC [24] system thermalhydraulics code. The CANFLEX bundle design went through several iterations during this phase, although the changes were largely confined to the design and location of appendages on the fuel sheath in order to optimize the thermalhydraulic performance. The result was the development and testing of the current CANFLEX bundle design, with significantly improved CHF and CCP performance.

As noted earlier, the maximum bundle or channel power is determined by the most limiting of fuel performance, thermalhydraulics and safety margins. In a CANDU 6 reactor, thermalhydraulic limits and safety limits with the CANFLEX bundle are reached before fuel performance limits, so potential power uprating is less than the 20% suggested by the reduction in linear element ratings [25].

A DI of 24 CANFLEX natural uranium bundles in two channels was conducted in the Point Lepreau reactor between 1998 September and 2000 August [26, 27]. In 2001, a 24-bundle DI was initiated in the Wolsong 1 reactor in Korea [28]. Minor fine tuning of the fuel design took place after the Point Lepreau DI, with some of the spacer pad heights changed slightly to reduce the possibility of interlocking.

Reference 29 contains a full chronology of CANFLEX development, from pre-1986 to the present.

The CANFLEX development program underscores some salient features of the fuel design process:

- the importance of completing the necessary R&D in advance of the fuel design process, so that it is input into the design; conducting the thermalhydraulic R&D in parallel with fuel design prolonged the design process by several years;
- the importance of establishing the various margins (fuel performance, thermalhydraulics and safety) as early as possible in the design process; and
- given the long lead time for advanced fuel development, the final application of advanced fuel technology may be different from that initially envisioned. Advanced fuel development should be as flexible as possible.

LOW VOID REACTIVITY FUEL (LVRF)

The LVRF program was initiated in the early '90s to provide the capability of reducing coolant void reactivity. In the pre-conceptual design phase, several dozen concepts were assessed. Changes in fuel bundle geometry were considered, as well as the propitious location of neutron absorbers or fixed scatterers in the bundle. The latter option (such as the replacement of the central 8 elements in the CANFLEX bundle with graphite or D_2O-filled elements) provided only a small, fixed reduction in coolant void reactivity, but this option could be used with either natural uranium or SEU fuel, and maintained good uranium utilization. WIMS lattice calculations provided the basic reactor physics characteristics of the various bundle designs.

The concept chosen entailed the use of a neutron absorber (dysprosium, Dy) in the center of the bundle mixed with either natural or depleted uranium, with SEU in the outer rings of the bundle. This concept provided the greatest flexibility, since both coolant void reactivity and fuel burnup could be tailored to the specific application by varying the concentrations of Dy and SEU. CANFLEX was chosen as the preferred geometry, as this minimized the bundle development and qualification testing required and provided the other benefits of CANFLEX (improved CHF and reduction in peak linear element rating for a given bundle power with uniform enrichment).

Since a specific reactor application was not targeted in the early stages, a generic qualification testing program was undertaken by AECL. This was done for both 37-element and CANFLEX bundle geometries, for designs that would achieve negative coolant void reactivity in existing CANDU reactors. The SEU enrichments chosen for the 37-element bundle design resulted in natural uranium burnup, while the enrichments chosen for the CANFLEX bundle design had three-times natural uranium burnup (~21 MWd/kg). These designs represented a more extreme test than designs achieving a smaller reduction in void reactivity.

The generic qualification testing included fabrication development for Dy-doped fuel; irradiation testing in NRU of prototype bundles and a demountable bundle containing Dy-doped elements with different Dy-concentrations mixed with natural or depleted uranium (to give different operating powers); thermalhydraulics testing in freon and analysis using the ASSERT code; and physics measurements in the ZED-2 reactor and WIMS code validation. This generic qualification testing provided proof-of-principle, and confidence in the technology to both AECL as the designer and to potential customers. The pre-conceptual fuel design studies and the generic fuel qualification testing program are described in greater detail in Reference 5.

In 2001, Bruce Power expressed an interest to AECL in the LVRF concept as a means of reducing coolant void reactivity in the Bruce B reactors, to restore the reactors to full power operation. AECL worked with Bruce Power in the design and qualification of the fuel for this specific application, e.g., target burnup and void reactivity reduction, and power/burnup and other interfacing requirements specified by Bruce Power [6]. CANFLEX was chosen as the geometry, with Dy mixed with natural uranium in the central element, with uniform SEU in the outer 42 elements. Small changes were made to this CANFLEX-LVRF bundle design, such as bearing pad height and configuration and endcap profile, to meet the fuel channel and fuel handling requirements of the Bruce B reactors.

The time frame for the qualification of Bruce CANFLEX-LVRF was significantly shortened by having already completed the conceptual fuel design and generic fuel qualification testing. This is a counterpoint to the CANFLEX program, in which a significant R&D program was mounted to improve the bundle thermalhydraulic performance. References 6 and 30 summarize the qualification of the Bruce CANFLEX-LVRF bundle, while Reference 31 summarizes the safety analysis done to ensure that fuel safety criteria were met.

AECL's LVRF program provides a successful model for advanced fuel development, design and qualification, where the time required for customer-specific qualification can be significantly shortened through generic qualification testing.

SUMMARY

CANDU fuel design can be described in three phases: pre-conceptual, conceptual and detailed design. Design verification is an activity that occurs during each phase, and ensures that the design output meets the design input requirements and that documentation is complete and adequate for that phase. While the fabrication and irradiation of over 2.5 million CANDU bundles provides the foundation on which any new fuel design is based, R&D provides the technology that drives any advances in the design. To the extent possible, R&D should be completed in advance of the fuel design process, so that it is an input to the design. The LVRF program is an example of generic qualification testing of advanced fuel technology, which has significantly reduced the design and qualification time as well as the risk of the Bruce CANFLEX-LVRF project.

The Fuel Design Manual describes the fuel design requirements, the design itself and the results from the fuel design qualification analysis and testing that show how the fuel design requirements and acceptance criteria have been met.

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