CANADIAN FUEL DEVELOPMENT PROGRAM AND RECENT OPERATIONAL EXPERIENCE

D.S. COX[1], E. KØHN[2], J.H.K. LAU[3], G.J. DICKE[2], N.N. MACICI[4] and R.W. SANCTON[5]

[1]AECL, Chalk River Laboratories, Chalk River, Ontario K0J 1J0
[2]Ontario Hydro, RSOAD, Toronto, Ontario M5G 1X6
[3]AECL, Sheridan Park, Mississauga, Ontario L5K 1B2
[4]Hydro-Québec, Gentilly, Quebec G0X 1G0
[5]New Brunswick Electric Power Commission, Point Lepreau, New Brunswick E0G 2H0

ABSTRACT

This paper provides an overview of the current Canadian CANDU® fuel R&D programs and operational experience. The details of operational experience for fuel in Canadian reactors are summarized for the period 1991-1994; excellent fuel performance has been sustained, with steady-state bundle defect rates currently as low as 0.02%. The status of introducing "long" 37-element bundles, and bundles with rounded bearing pads is reviewed. These minor changes in fuel design have been selectively introduced in response to operational constraints (end-plate cracking and pressure-tube fretting) at Ontario Hydro's Bruce-B and Darlington stations. The R&D programs are generating a more complete understanding of CANDU fuel behaviour, while the CANDU Owners Group (COG) Fuel Technology Program is being re-aligned to a more exclusive focus on the needs of operating stations. Technical highlights and realized benefits from the COG program are summarized. Re-organization of AECL to provide a one-company focus, with an outward looking view to new CANDU markets, has strengthened R&D in advanced fuel cycles. Progress in AECL's key fuel cycle programs is also summarized.

INTRODUCTION

The current economic downturn, particularly in Ontario, has brought extreme pressure to the price of electricity and corresponding pressures on the nuclear industry to improve economics, re-organize for improved efficiency, and reduce funding to some R&D programs. With the backdrop of economic pressures, it is heartening to note that in 1994, Pickering Unit 7 broke the world record for continuous operation, with an on-power run of 894 d. Also, in Ontario, about 60% of the electricity generation was nuclear in 1994; 19% of Canadian generation. These achievements can be attributed in some measure to the sustained excellent performance and economics of natural-uranium CANDU fuel. In spite of this success, there is a continued drive to improve fuel performance and reliability, and to contribute to the resolution of operational issues. In addition, AECL's Advanced Fuel Cycle Technology Program is helping the marketing of new CANDU reactors by developing advanced fuel cycles to exploit the flexibility of the CANDU reactor, and to provide potential benefits in capital cost reductions, safety and operating margins and security of indigenous fuel supplies.

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RECENT OPERATIONAL EXPERIENCE

Fuel Performance

Natural-uranium fuel continues to demonstrate excellent performance in the 22 CANDU power reactors operating in Canada. More than 1.2 million CANDU fuel bundles have now been irradiated in these reactors, and less than 0.1% have developed defects.

Most of the failures continue to occur during periodic "defect excursions" attributed to manufacturing flaws or non-standard operation; the steady-state defect rate (excluding excursions) is about 0.02%. Table 1 summarizes the number of defects that were reported at each station during the 4-a period 1991-1994. The defect rate and average discharge burnups recorded in 1994 are also shown for each station. The relatively high number of defects at the Point Lepreau station were due to underbaking of the CANLUB coating [1], resulting in failures because of excess hydrogen (22 defects in 1991 and 1992).

The cause of about half of the defects remains attributable to manufacturing flaws (or unassigned causes), including primary hydriding, and the other half of the defects are related to debris fretting wear or stress–corrosion cracking (SCC). The proportion of fretting defects is higher in recent experience, relative to SCC failures, as shown in Table 2. This observation may be attributable to skewing of the recent data by the start-up operation of the 4 Darlington reactors; a higher frequency of fretting failures is typically observed during the early period of new reactor operation.

The 1994 burnup data listed in Table 1 are typical of recent operating experience at most stations. Darlington Units 3 and 4 reached equilibrium near mid-1994 and late-1994 respectively. The recent trend in burnup at Pickering has been downwards to the current levels, which are regarded as optimal with respect to fuel performance. The recent trend at Gentilly-2 has been a slight increase in burnup, due primarily to improved isotopics in the heavy water. The average uranium weight of bundles irradiated at Gentilly-2 has risen to about 19.31 kgU, without deleterious consequences in fuel performance, as shown by the recent lack of fuel failures.

Operational Constraints

Several operational issues that have an effect on the fuel became prominent during the last three or four years. These issues include

- outlet bundle end-plate cracking,
- abnormal fuel support (pressure-tube fretting), and
- fuel string relocation ("power pulse").

These issues are all interrelated, and a variety of successful solutions has been implemented at the different affected stations.

In November 1990, fuel damage occurred during refuelling in Ontario Hydro's Darlington Generating Station, Unit 2. The fatigue damage to the end plates was determined to be a result of acoustic pressure pulsations caused by the main coolant pumps [2,3]. The pumps generated a pressure pulse in the coolant at 150 Hz because of the 30-Hz pump rotation frequency multiplied by the 5 pump impeller vanes. Moreover, the acoustic response of the piping amplified the pressure pulses in the headers and feeders. This system response had not been anticipated in the primary heat transport system design, nor was the fuel designed for those pressure pulse conditions. Thus a small number of fuel channels were subjected to unexpectedly high levels of pressure pulsation.

The pressure pulses resulted in axial and radial vibrations of the fuel. The axial vibrations were complex; the centre 7 elements moved axially relative to the outer elements, causing fatigue damage of the end plates, and some fretting wear of the end plates [4,5]. Most fatigue damage occurred downstream where the fuel string is supported by the latches. These latches support only on the outer-element end caps, and hence the hydraulic and fatigue loads were applied mostly to the last bundle.

The movement of the fuel also resulted in fretting wear of the spacers within the bundle, and caused damage to the pressure tubes. The damage to the pressure tubes was of most concern at the inlet end of the channel at the rolled joint–burnish mark location. At this location, the fretting caused by the bearing pads would threaten the life of the pressure tubes, if left uncorrected.

At the Darlington station, changing the number of impeller vanes from 5 to 7, and hence the coolant pulsation frequency from 150 Hz to 210 Hz, greatly reduced acoustic pressure pulses reaching the fuel. Thus the causes of this incident were identified, isolated, and corrected in Darlington.

In addition to the pump impeller changes at the Darlington station, a decision was made in 1993 to change from 13- to 12-bundle fuel channels in both Darlington and Bruce-B, to eliminate fretting of the pressure tube by the 13th bundle. Bundles with rounded bearing pads (corner radius increased from 0.1 to 0.5 mm) were also introduced at both stations to reduce the severity of pressure-tube fretting. However, implementation of the 12-bundle channels was halted when safety and licensing analyses discovered that an unacceptable power pulse could result from an inlet header break, with flow reversal causing the fuel string to shift to the inlet side, introducing sudden positive reactivity into the core. This resulted in derating of all Bruce reactors to 60% of full power. The Darlington reactors do not suffer from the power pulse problem to the same extent because of the two-loop primary heat transport system. Other CANDU reactors are also unaffected because their direction of fuelling is with the flow (FWF) rather than against the flow, so that a similar accident scenario results in a negative reactivity insertion.

At the Bruce-B station, a small number of channels were also identified to have an acoustic response causing a minor amount of end-plate fatigue, and wear on the pressure tube. About 13 bundles with cracked end plates have been found in Bruce-B reactors, but none were found in Bruce-A reactors.

Two solutions are in the process of being implemented to overcome the combined problems of fuel string relocation and pressure-tube fretting at the burnish mark. The Bruce-B and Darlington stations are now fuelling specific channels with bundles that are 12.7 mm longer than the normal 37-element bundle, in order to control the position of the inlet bundle and eliminate concern about the power pulse and pressure-tube wear. Long bundles are added, as required, to control the inlet gap and to accommodate pressure-tube elongation. At Bruce-B, a flow-straightening inlet shield plug (FSISP) has also been introduced in certain channels to control the gap and reduce bundle vibration; at Bruce-A, the implemented solution has been to change the direction of fuelling in 12 bundle channels to FWF. This change has required modification of the shield plugs so that the downstream irradiated bundles are supported in a manner that does not cause end-plate cracking [6]. The change to FWF at the Bruce-A station is now in progress.

Status of Operational Solutions

Extensive out-reactor handling tests for long bundles were completed, and loading in Bruce-B reactors began (21 bundles) in 1993. The long-bundle program was extended in 1994 to 1710 bundles in Bruce-B reactors and 337 in Darlington. No performance problems have been identified.

Rounded bearing pad bundles have been tested on a trial basis in both Bruce-B and Darlington reactors in 1993 and 1994. The effectiveness of the rounded pads will require assessments through fuel inspection and examination of the marks on pressure tubes.

CANADIAN CANDU FUEL R&D PROGRAMS

A key factor in the success of CANDU fuel has been effective co-operation in the Canadian fuel industry between research, design, manufacture and operation. The CANDU Owners Group (COG), a partnership between AECL, Ontario Hydro, Hydro-Québec and New Brunswick Electric Power Commission, has facilitated this cooperation. COG has provided most of the funding for R&D related to operating fuel technology, and for safety-related studies and experiments. In recent years, there has been a continuation of the trend to focus COG R&D on current station issues. In addition to COG R&D, AECL directs a vigorous Advanced Fuel Cycle Technology Program, which builds upon the unique capability and flexibility of the CANDU reactor to utilize a number of advanced fuel cycles.

COG Fuel Technology Program

A strategic plan for the overall COG organization has been developed and has undergone further evolution in recent years. The principal Safety and Licensing issue that is addressed by the Fuel Technology Working Party is

Maintain and Improve the Reliability, Economics, and Safety of CANDU Fuel.

The Fuel Technology Working Party directs applied R&D with the following 5 objectives:

- determine and extend fuel operational limits;
- provide fuel performance models;
- relate fuel performance to fundamental fuel properties;
- determine fuel behaviour under degraded cooling conditions; and
- develop fuel designs that improve safety, economics and reliabilit.y

In addition to meeting these objectives, the various activities undertaken by the Working Party facilitate the maintenance of an R&D infrastructure and response capability necessary to meet the demands of our CANDU industry. Also, many of the projects provide understanding, data or tools that are useful for addressing the AECB generic action item on "impact of fuel bundle condition on reactor safety". Some of the recent technical highlights from the Fuel Technology Working Party are described below.

T-Pad Bearing Pads:
- A total of 20 bundles with T-pad bearing pads have now been irradiated in Bruce-A and Point Lepreau reactors. T-pad bearing pads are nearly "qualified", following satisfactory examination of fuel from Bruce-A reactors. Examination of the Point Lepreau fuel is in progress. The T-pad design offers the possibility of eliminating crevice corrosion in the pressure tube–bearing pad contact area, by reducing heat flux across the modified geometry of the bearing pad.

Post-Irradiation Examination Capabilities:
- Techniques for quantifying the radial profile of UO_2 density in irradiated fuel have been developed.
- Post-irradiation examination procedures have been standardized and qualified for profilometry and H/D analysis.
- Techniques for quantifying the radial profile of UO_2 stoichiometry in irradiated fuel have been developed.
- Response capability has been maintained for CANDU industry needs.

Data to Address AECB Generic Action Item on Fuel Condition:
- Sheath strains in high uranium-mass bundles have been confirmed to be a maximum of 1%.
- The thermal conductivity, specific heat and melting temperature of high-burnup SIMFUEL has been measured.
- Preliminary measurements of high-burnup CANDU fuel indicate that the increasing O/U ratio is buffered by oxidation of fission product Mo, thus preventing large increases in the O/U ratio.

Fuel Operational Limits Defined:
- Determination of Specification Extremes:
  - Well-characterized bundles with high- and low-density UO_2 and a range of pellet-sheath radial gaps have completed their irradiation at Point Lepreau and await shipment for post-irradiation examination (PIE).
  - Well-characterized bundles that have alternating elements coated with CANLUB await irradiation.
- Examination of highly irradiated NPD-40 experimental fuel (1200 MW•h/kg HE) infers that inaccessible outer channels of CANDU reactors could be irradiated to burnups as high as 1000 MW•h/kg HE at linear powers < 20 kW/m without danger of fuel defects.

Other Realized Benefits:
- Improved physical models of UO_2 behaviour are aiding the quantification of fuel design changes and licensing analyses.
- Behaviour of fuel in a real incident involving loss of pump flow was quantified, with fairly benign consequences noted.
- The Fuel Engineers Manual continues to be used for operational problems.

AECL Advanced Fuel Cycle Technology Program

The CANDU reactor has the unique flexibility to use a number of fuel cycles. The driver for advanced fuel cycles has traditionally been even further improvements in uranium utilization, for example, through the use of 1.2% slightly enriched uranium (SEU), which can yield a 30% improvement in fuel cycle costs and uranium utilization, while reducing spent fuel volumes by a factor of 3. However, other potential benefits are also important in pursuing advanced fuel cycles:

- reduced plant capital costs (e.g., the use of SEU to flatten the power distribution in the core and thereby increase rated output for the same core size);
- simplified plant design; and
- increased operating and safety margins (e.g., lower peak element ratings and higher critical channel power in CANFLEX (CANDU FLEXible) fuel; reduced or negative void reactivity as required in some markets).

Other incentives for advanced fuel cycles include:

- exploiting pressurized light-water reactor (PWR)–CANDU synergism (DUPIC, Direct Use of Spent PWR Fuel In CANDU, and civilian mixed-oxide (MOX) fuel cycles that utilize the spent or reprocessed PWR fuel),
- destruction of military plutonium from excess weapons stockpiles (e.g., as MOX fuel)
- destruction of Pu and actinide wastes (e.g., in an inert-matrix fuel design)
- maximization of energy derived from indigenous fuel materials (e.g., thorium fuels in countries without uranium reserves).

The goal of AECL's Advanced Fuel Cycle Technology Program is to develop fuels and fuel cycles to improve the performance of existing CANDU plants, to reduce capital and operating costs in new CANDU plants, to enhance resource utilization and reduce waste handling volumes, to enhance reactor safety, to overcome effects of component aging, and to exploit fuel cycle flexibility in CANDU reactors.

The recent re-organization of AECL, with merging of the former Research Company and CANDU Operations, has strengthened the Advanced Fuel Cycle initiatives, and yielded a mix of short- and long-term development programs. Some the key projects are outlined below, or elsewhere in these proceedings.

<u>CANFLEX:</u> The CANFLEX fuel bundle is the next stage in CANDU fuel evolution, and features greater subdivision (43 elements) and 2 element sizes to reduce peak ratings by 20%, and critical heat flux (CHF)-enhancement appendages to gain up to 7% improvement in critical channel power. The status of the CANFLEX program is given elsewhere in these proceedings [7].

<u>DUPIC:</u> DUPIC is a joint project between AECL, KAERI and the US Department of State to develop the technology to fabricate CANDU fuel from spent PWR fuel, using only dry processes. Each organization funds its own activities. The project consists of several tasks, including optimization of the OREOX (OXidation-REduction-OXidation) process, fission-product immobilization studies, waste management studies, assessment of decladding options, reactor physics evaluations, and input to the International Atomic Energy Agency's safeguards assessments. The OREOX process has been optimized in the laboratory using kilogram-sized batches of unirradiated SIMFUEL [8], leading to the production of fuel pellets that meet the specifications of CANDU fuel. Two experiments have been completed in hot cells to examine the effect of temperature and environment in the OREOX process and to conduct trial sintering tests of DUPIC fuel pellets. There have been a number of reactor physics activities including a reassessment of the burnup of DUPIC fuel in a CANDU reactor, the representation of PWR fuel

in codes and the anticipated power level of DUPIC elements in the NRU reactor. Work is proceeding towards fabrication and irradiation of DUPIC fuel elements in the next two years.

Low Void Reactivity Fuel (LVRF): While positive void reactivity is an inherent feature of the current CANDU core, it has been accommodated through several features in the CANDU design, such as 2 independent fast-acting shutdown systems. As a consequence, the CANDU reactor has an extremely high degree of safety. Nevertheless, some markets require zero or negative void reactivity, and AECL has developed a fuel concept to meet those needs. The concept involves incorporating dysprosium absorber in the central pins of a 37-element or CANFLEX bundle. The amount of absorber, and the level of enrichment in the outer rings of the bundle can be varied to achieve any desired level of discharge burnup and void reactivity [9].
A fabrication campaign in 1994 produced 35 LVRF bundles for physics testing in the ZED-2 reactor, including hot-channel and fine-structure measurements. Initial thermalhydraulic measurements to determine CHF in Freon-22 have also been performed.

Irradiation in NRU of fuel elements with various Dy concentrations began in 1994 and 2 protoype 37-element LVRF bundles are also being irradiated. Demonstration of a high-burnup (HB) 43-element CANFLEX version of the LVRF bundle concept (HB-LVRF) is also well underway. As with the LVRF bundle, activities include fabrication, reactor physics, thermalhydraulics and irradiation in a research reactor. The HB-LVRF bundle uses the latest Mk IV CANFLEX geometry and is designed for a discharge burnup of 21 MW•d/kg U, with a slightly negative void reactivity at mid-burnup.

MOX : Several CANDU MOX fuel irradiations are currently on-going in the NRU reactor. Details of AECL's fabrication and irradiation testing program are given elsewhere [10,11].

Actinide Waste Annihilation: This work addresses the potential of CANDU reactors to either burn excess military plutonium, without generating additional plutonium, or to burn (transmute) transuranium actinides, termed *actinide mix*, generated in all reactors, but separated and concentrated by reprocessing of LWR fuels. Although there are a number of candidate materials to hold the Pu or actinide mix, in 1994 AECL began to focus on SiC. At the same time, AECL is investigating other candidates materials, such as spinel. The studies include accelerator simulations of in-reactor irradiation, and compatibility tests with water coolant and cladding materials. Details are given elsewhere in these proceedings [12].

Thorium: The current thoriun fuel program builds on many years of prior work at AECL, and is focussed on the once-through thorium fuel cycle. The program focuses on fabrication of new fuel (and associated technology required to fabricate controlled microstructures), irradiation of new and existing thorium fuels, and reactor physics and fuel management simulations.

Plutonium Dispositioning: With the end of the Cold War, and strategic disarmament treaties in place, there is a growing international stockpile of weapons-grade Pu, derived from dismantled nuclear warheads. AECL participated in a study by the US Department of Energy, to assess the feasibility of dispositioning this excess Pu as MOX fuel in commercial power reactors, one option being the CANDU reactor[13]. The feasibility of the CANDU MOX fuel option was established in the study, which addressed technical and strategic issues, schedule, and cost related parameters, with the objective of identifying a strategy permitting consumption of 50 t of ex-weapons Pu as MOX fuel in CANDU reactors over 25 a. Aside from a hardened MOX fuel reception area, the study concluded that no major modification would be required for 2 Bruce-A reactors to undertake such a mission.

SUMMARY AND CONCLUSIONS

CANDU fuel performance continues to be excellent in Canadian power stations. Recent operational constraints such as fuel string relocation and pressure-tube fretting are being addressed through minor changes to the fuel (e.g., "long" bundles and rounded bearing pads). A more complete understanding of natural-uranium CANDU fuel behaviour is being gained through COG projects that investigate fuel performance at the limits of current specifications.

Advanced fuel cycles are being developed to exploit the flexibility of the CANDU reactor and provide potential benefits in capital cost reductions, safety, operating margins and security of indigenous fuel supplies.

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Table 1: Canadian CANDU Fuel Performance Summary

Station	Number of Defects (1991-1994)	Defect Rate (defects/bundles discharged) x 100 1994	Average Discharge Burnup† (Mwh•/kg U) 1994
Bruce-A	19	0.	215
Bruce-B	13	0.	190
Pickering-A	11	0.02	215.3
Pickering-B			193.2
Darlington	16	0.02	192.5
Gentilly-2	2	0.	180.5
Point Lepreau	28	0.04	178.8

† Average values for all bundles discharged. Does not discount early discharge of channels for inspection purposes.

Table 2: Causes of Defects

Defect Mechanism	Percentage of Total	
	1991 - 1994	All Data
Debris Fretting Wear	39	16
Stress–Corrosion Cracking	12*	35
Manufacturing and Unassigned Causes	49	49

* Includes 7 observations of circumferential end cap cracking (not confirmed to be SCC-related)