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CANDU FUEL - FIFTEEN YEARS OF POWER REACTOR EXPERIENCE

by

G.R. FANJOY and A.S. BAIN

Paper IAEA-CN-36/184 presented at the IAEA International Conference on Nuclear Power and its Fuel Cycle, Salzburg, Austria, 2-13 May 1977

Chalk River Nuclear Laboratories
Chalk River, Ontario
May 1977

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G.R. Fanjoy
Central Nuclear Services
Ontario Hydro
Toronto, Ontario

A.S. Bain
Atomic Energy of Canada Limited
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Combustible CANDU employé dans les réacteurs de puissance: quinze ans d'expérience*

G.R. Fanjoy
Central Nuclear Services
Ontario Hydro
Toronto, Ontario

A.S. Bain
L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
Chalk River, Ontario

Résumé

Le combustible CANDU (Canada Deutérium Uranium) est employé dans les réacteurs de puissance depuis 1962. Les analyses des statistiques de performance, lesquelles ont été complétées par des examens de combustible ayant séjourné dans des réacteurs de puissance et dans des boucles expérimentales, ont donné les résultats suivants:

(a) une parfaite compréhension du comportement fondamental du combustible CANDU:
(b) des données montrant que la haute utilisation prédite pour l'uranium a été atteinte: le coût du combustible, en 1976, de la centrale Pickering est de 1.2 m$/kWh (dollars canadiens de 1976) pour un simple cycle de combustible, à passe unique, à base de bioxyde d'uranium naturel;
(c) des critères de fonctionnement ayant permis d'obtenir un très faible taux de défectuosité, à savoir 0.03% pour toutes les grappes et d'avoir le combustible CANLUB qui possède une intercouche de graphite entre le combustible et la gaine pour réduire les défectuosités lors des augmentations de puissance;
(d) la preuve que la courte longueur (500 mm) et la gaine repliable de la grappe CANDU sont une réussite et que le combustible peut fonctionner efficacement à haute puissance (la puissance linéique maximale des éléments extérieurs est 58 ± 15% kW/m).

La participation active des fabricants d'électricité à tous les stades du développement du combustible a permis d'appliquer efficacement cette connaissance fondamentale. On a pu, ainsi, obtenir des spécifications appropriées pour le combustible, de bons délais d'approvisionnement, un chargement en temps voulu du réacteur et des renseignements concernant la performance réelle du combustible ont pu être envoyés aux concepteurs, aux développeurs et aux fabricants. A la fin du premier semestre de 1976, plus de 3×10^6 éléments individuels avaient été fabriqués au sein d'une industrie bien établie commercialement et ne craignant pas la concurrence et plus de 2×10^6 éléments avaient été irradiés. Seulement six défectuosités ont été attribuées à des matériaux en mauvais état ou à une malfaçon. En employant de l'UO_2 à haute densité ayant une faible teneur en humidité on a évité les défectuosités que peuvent produire la contamination par l'hydrogène et la densification. Les travaux de développement concernant l'UO_2 et d'autres cycles de combustible (plutonium et thorium) sont poursuivis et du fait que les réacteurs CANDU sont rechargés en cours de marche, les grappes peuvent être insérées dans les réacteurs de

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puissance pour fins expérimentales. C'est pourquoi la conception des nouveaux combustibles peut être rapidement mise au point pour que la filière CANDU continue à fournir de l'énergie à bon compte avec une grande fiabilité.

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Atomic Energy of Canada Limited
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ABSTRACT

CANDU (Canada Deuterium Uranium) fuel has operated in power reactors since 1962. Analyses of performance statistics, supplemented by examinations of fuel from power reactors and experimental loops have yielded:

(a) A thorough understanding of the fundamental behaviour of CANDU fuel.
(b) Data showing that the predicted high utilization of uranium has been achieved. Actual fuelling costs in 1976 at the Pickering Generating Station are 1.2 m$/kWh (1976 Canadian dollars) with the simple once-through natural-UO_2 fuel cycle.
(c) Criteria for operation, which have led to the current very low defect rate of 0.03% of all assemblies and to "CANLUB" fuel, which has a graphite interlayer between the fuel and sheath to reduce defects on power increases.
(d) Proof that the short length (500 mm), collapsible cladding features of the CANDU bundle are successful and that the fuel can operate at high-power output (current peak outer-element linear power is 58 ± 15% kW/m).

Involvement by the utility in all stages of fuel development has resulted in efficient application of this fundamental knowledge to ensure proper fuel specifications, procurement, scheduling into the reactor and feedback to developers, designers and manufacturers. As of mid-1976 over 3×10^6 individual elements have been built in a well-established commercially competitive fuel fabrication industry and over 2×10^6 elements have been irradiated. Only six defects have been attributed to faulty materials or fabrication, and the use of high-density UO_2 with low-moisture content precluded defects from hydrogen contamination and densification. Development work on UO_2 and other fuel cycles (plutonium and thorium) is continuing, and, because CANDU reactors use on-power fuelling, bundles can be inserted into power reactors for testing. Thus new fuel designs can be quickly adopted to ensure that the CANDU system continues to provide low-cost energy with high reliability.

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1. INTRODUCTION

The Canadian nuclear-electric generation program [1,2] is based on the CANDU-PHW[1] reactor. The choice of heavy water as moderator and heat transport fluid provided the opportunity to develop a reactor with exceptional neutron economy. The fuel for CANDU-PHW reactors is 500 mm long bundles of natural uranium dioxide clad in Zircaloy-4 sheathing. The 0.4 mm thick sheathing depends on the support of the contained UO_2 to withstand heat transport system pressure. Each horizontal fuel channel contains 12 bundles in positions numbered 1 to 12 from the new fuel end. CANDU is eminently suitable for natural uranium fuel, and extracts more electrical energy per kilogram of uranium mined than any other commercial system.

CANDU-PHW operating experience in Canada is confined to the Ontario Hydro system. Generating station construction is adding new capacity in Ontario and introducing commercial nuclear generating stations in Quebec and New Brunswick, while other provincial utilities are considering CANDU installations. In addition CANDU-PHW stations are operating in Pakistan (KANUPP) and India (RAPP).

Ontario Hydro is a publicly owned utility serving Ontario with a dependable peak capacity of 20 300 MWe at the end of 1976. Its nuclear-electric generating program, consists of 2284 MWe of CANDU-PHW in-service

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[1] Canada Deuterium Uranium - Pressurized Heavy Water

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(Table I) and another 2881 MWe under construction or planned. This paper discusses the fuel development program and Ontario Hydro's experience over the past 15 years.

TABLE I

ONTARIO HYDRO FUEL PERFORMANCE DATA

(To end of September 1976)

STATION	IRRADIATED	DEFECTIVE	% DEFECTIVE[a]
	(Numbers of bundles)		
NPD (22 MWe)	3 844	12[b]	0.31
Douglas Point G.S. (206 MWe)	13 989	91	0.65
Before Jan. 1, 1972	7 169	66	0.92
After Jan. 1, 1972	10 492	25	0.24
Pickering G.S. (4 x 514 MWe)			
Unit 1	21 978	99	0.45
Before Nov. 1, 1972	6 938	91	1.31
After Nov. 1, 1972	19 720	8	0.04
Unit 2	20 406	1	0.01
Unit 3	15 128	6	0.04
Unit 4	12 592	4	0.03
Pickering G.S. Total	70 104	110[c]	0.16
Pick. G.S. Total After Nov 1, 1972	67 846	19	0.03

[a] Percent defective bundles = $\frac{\text{Total discharged defective bundes}}{\text{Total irradiated bundles}} \times 100\%$

[b] Only 4 bundles have defected under normal operating conditions. Remaining 8 were experimental fuel.

[c] Iodine concentrations indicate that there may be 1 or 2 defects in each Pickering reactor; these are not included in this total.

2. FUEL MANAGEMENT

In this paper the term fuel management encompasses all activities associated with the fuel cycle, including the commercial and technical activities associated with material purchases, inspection, transportation, use, storage, reprocessing and waste management.

The once-through natural uranium fuel cycle used in CANDU-PHW has been developed, and is being improved with an integrated "team" approach involving Atomic Energy of Canada Limited (AECL), Ontario Hydro, Canadian General Electric Company Limited and Westinghouse Canada Limited.

Much of the early part of this work was provided by the research and development laboratories, especially before the commercial stage of nuclear generating stations. As the program has grown, Ontario Hydro has expanded its capability in these areas and is now fully conversant with all aspects of fuel management as defined above. Very close liaison continues between all members of the team, and this close integration of the various groups has been a key ingredient in achieving economical, high performance fuel.

Working within the above team approach, Ontario Hydro's fuel management plan can be described as follows:

(1) Maintain staff knowledgeable in all aspects of fuel management.

(2) Define Ontario Hydro needs, providing ideas for research and development, funding specific programs, conducting tests of developmental fuel in nuclear-electric generating stations, selecting irradiated fuel bundles for post-irradiation examination and initiating the examination.

(3) Purchase uranium raw material on long-term contracts (about 10-15 years).

(4) Purchase the detailed design and the manufacturing service to convert the raw material to finished fuel bundles in commercially attractive quantities (about 2000 megagrams U).

(5) Inspect all phases of fuel manufacture.

(6) Establish and operate a nuclear materials accounting system to satisfy monetary, physical and governmental control needs.

(7) Develop and use methods for scheduling fuel through the reactors. Analyse potential problems and solve problems involving fuel in nuclear-electric generating stations.

(8) Store and transport irradiated fuel, including interim storage remote from generating stations.

(9) Assist AECL in the total programs for long term storage of irradiated fuel, waste management, and use of recycle fuel in CANDU reactors (including reprocessing).

3. FUEL USE

Before any fuelling schedule can be adopted, a system to determine the existing burnup and power output of bundles, and power changes that will occur during the fuelling operation, must be well established and readily available. The work then required to take finished fuel bundles and insert them into the reactor to extract the optimum heat involves many key steps:

(1) Define the fuel limitations such as bundle and channel power output.

(2) Establish in detail what channels should be fuelled. Normally eight new bundles are inserted so that bundles from the low-power positions 1 and 2 move to high-power positions, bundles from positions 3 and 4 move to low-power positions, and bundles from positions 5 to 12 are discharged.

(3) Solve actual fuel problems.

A staff group, normally remote from the actual generating station, must define the limitations within which fuel should operate. Criteria are specified for limitations of burnup, fuel bundle power, power change, heat transport system temperature and pressure, etc. Work continues to define defect probability as a function of fuel bundle power, power change and burnup [3].

To define which channels are to be fuelled [4,5,6] we must develop fuel scheduling ground rules that can be used by station personnel; develop and use three-dimensional computer codes that continuously follow each reactor's neutron flux shape and present timely and meaningful information, e.g., bundle powers and burnup, to the station personnel; and have knowledge of abnormalities affecting each reactor:

- fuel handling system abnormalities,
- fuel channels that temporarily cannot accept fuel,
- extraordinary needs for reactivity,
- other generating unit system abnormalities that affect fuel scheduling.

Station personnel use the fuel limitations, defect criteria and fuel scheduling ground rules to write detailed instructions to station shift personnel for moving new fuel into reactor channels and irradiated fuel to storage. The defect criteria are key tools because they provide the station with quantitative information on the probability of fuel defects which can be balanced against the other aspects of station operation.

The station operator should clearly understand the interaction between the fuel and other parts of the generating station, for example the steam generators. He should be able to recognize unexpected problems and be able to call on expert help from manufacturers, designers and research personnel who can quickly diagnose the problem, perform examinations, tests and analyses and recommend practical and timely solutions. Optimum fuel performance demands this type of knowledge and the ability to bring good talent to bear when required. One example, involving Pickering NGS Unit 1 is discussed later in this paper.

4. FUEL PERFORMANCE

4.1 Development Program

The program to develop fuel for the CANDU reactors started with single element irradiations in loops in the NRX reactor at Chalk River Nuclear Laboratories [7] then tests of full size fuel bundles [8]. During this program, 304 bundles and 445 individual elements have been irradiated at low or high power to burnups up to three times that expected of natural uranium fuel in the CANDU-PHW reactors.

Fuel specifications were written, and enforced, that ensured there would be no defects due to localized hydriding of the sheath, densification of the UO_2 or unacceptable collapse to form sharp ridges in the thin-walled sheathing. Of the over two million individual elements that have been irradiated in the CANDU-PHW reactors, only six are known to have defected due to manufacturing faults. No defects have been observed in the zironium - 5% beryllium braze of the nine million brazed appendages.

The short bundle, and the horizontal orientation, eliminated concerns such as pellet stack slumping, longitudinal ratchetting, and problems associated with large fission gas plenums.

4.2 Power Reactor Fuel Performance

The performance of the fuel in the CANDU-PHW reactors operated by Ontario Hydro is given in Table I.

Over 80% of the total number of defective bundles in all 4 units of Pickering NGS to date, occurred in 1971-1972. Since November 1972, only 19 bundles have defected in Pickering NGS corresponding to a rate of 0.03%, well within the operating target of 0.1%. The effect on station operation has been negligible. Typically, the defects are small cracks affecting only one or two of the 28 elements in a bundle.

Concentrations of I-131 in the heat transport system are measured routinely and, at steady reactor power, typically range from 10-15 μCi/kg (0.4-0.6 MBq/kg) of heavy water [9]. Iodine content is not easily related to defective elements and any such relation depends largely on engineering judgement. However, it is estimated that typically there are about two defective elements in each reactor.

It must be emphasized we regard the 10-15 μCi/kg (0.4-0.6 MBq/kg) range of I-131 content as tiny. We take no specific actions to determine the location of the defective bundles nor to discharge them. Their effect on station operation is negligible, and the iodine is safely contained within the heat transport circuit.

The majority of fuel defects occurred during the early operation of Douglas Point and Pickering 1[2]. The operating staff were directly involved with devising operating procedures to minimize problems resulting from fuel defects, determining the defect causes, changing fuel scheduling to eliminate the defects and systematically discharging the defective bundles. This involvement and the ability of operating staff to react was clearly demonstrated in 1971-1972 with the Pickering NGS Unit 1.

Unit 1 went critical in February 1971, and towards the end of the third quarter of 1971 the iodine concentration in the heat transport system had increased substantially due to fuel defects. The cause was believed to be out-of-sequence movement of cobalt control rods. The immediate action taken was to revert to the intended sequence, which produced smaller fuel power increases. In mid-1972 revisions to the sequence further reduced the associated power increases and have virtually eliminated cobalt control rod movement as a defect cause. Analyses of bundle powers led to two predictions: which channels should contain defective fuel; and that defects should be in positions 5 to 8.

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[2] These acute occurrences resulted in only minor perturbations to the successful operation of the stations.

Channels considered to contain defective bundles were fuelled by 8-bundle fuelling. However iodine levels continued to increase. This indicated that new fuel defects were occurring: due to power increases resulting from 8-bundle fuelling; and unusually high channel powers because of the increased neutron flux due to insertion of new bundles in neighbouring channels which were fuelled to discharge previous defects.

In May 1972, Pickering NGS Unit 1 was shut down as planned for reasons other than fuel defects. Weeks before the shutdown, when the power histories of individual bundles first became available, it was apparent that fuelling in power-peaked channels may have resulted in defects in bundles shifted from positions 1 and 2 to positions 9 and 10. Since a deliberate design decision had been made not to install equipment to locate defective bundles in the reactor, analysis of operating history was the major tool for their location.

A list was produced of bundles suspected of being defective, in decreasing order of probability, based on the defect criteria, and the calculated burnup and powers of the bundles in the reactor before and after fuelling. Channels were fuelled in the order defined by the list during the unit shutdown to remove fuel defects. All relevant bundles discharged were inspected in the spent fuel bay. Defects were found in bundles from positions 9 and 10 in the predicted channels. When three successive channels did not contain defective bundles, fuelling was stopped. Virtually all the defects in Unit 1 were located and discharged, as indicated from the extremely low iodine level measured during the unit's startup.

Many lessons were learned from the Pickering NGS incident: prominent amongst these were

- the value of being able to analyse bundle operating experience with sufficient accuracy to predict defective bundle location,
- the necessity of vigilant monitoring of radioactivity in the heat transport system to provide early warning of a problem,
- the value of on-site inspection capabilities,
- the value of supporting research and development that gave an early lead to the cause of the defects, and the utility involvement that allowed the information to be applied immediately.

The fuel defect data were analysed statistically. Criteria were developed which correlated the probability of a defect with the fuel burnup, maximum power, power increase and time at power [3]. Use of these correlations significantly lowered the defect rate to its present 0.03%.

4.3 Current Studies and Development

The changes in fuel management virtually eliminated fuel defects in Pickering NGS, but the need remained to understand why defects occurred, and to develop a fuel more tolerant to power increases, which would provide wider operating margins. In 1971 a program was launched which showed that the defects were most probably due to iodine induced stress corrosion cracking of the sheath at positions of stress concentrations - e.g., at pellet cracks, pellet chips or circumferential ridges formed at pellet/pellet interfaces [10, 11].

About 20 alternative designs to the then reference fuel were irradiated in AECL research reactors. Several were quickly eliminated, since their defect rate was similar to the reference fuel. Higher initial ductility of the sheathing was called for in new fuel for the Douglas Point NGS but test and power reactor fuel performance [12] subsequently showed that such a change was not a solution to the problem. In 1972 tests indicated that the deposition of a graphite layer on the inner surface of the sheath resulted in defect-free performance, see Figure 1, and fuel with the graphite interlayer - designated CANLUB - became the reference design.

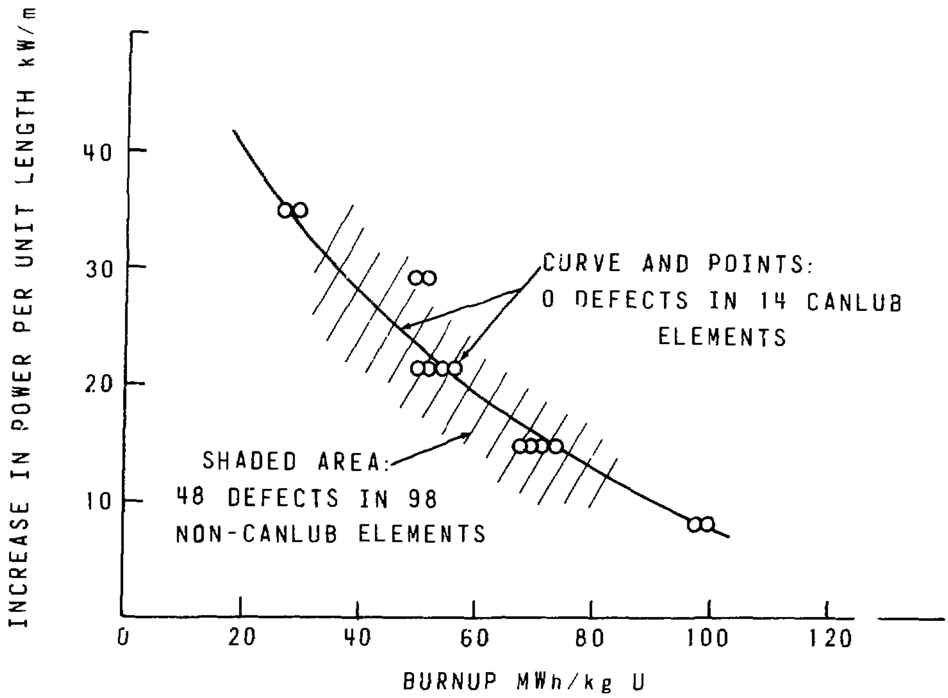

Fig.1. NRU Tests to Compare Power-Ramp Defects in CANLUB and Non-CANLUB Elements

There are not yet sufficient data to quantitatively define CANLUB fuel performance. However, it is clear CANLUB improves fuel performance. Our current challenge is to define the improvement. In parallel with the development of CANLUB graphite fuel, testing is underway on alternative designs: a siloxane layer instead of the graphite [11], changes in pellet geometry [13], and graphite discs between pellets [14].

5. FUELLING COST

Fuel procurement has involved competitive fixed price bids for the detailed design and manufacturing service. This competition has been healthy and has resulted in the actual cost of Pickering NGS fuel in 1976 of 67$/kg U, including the UO_2, and an actual fuelling cost of 1.2 m$/kWhe, both numbers in 1976 Canadian dollars.

These fuel and fuelling costs are based on the natural uranium, once-through cycle where the irradiated fuel is valued at zero. No credit is taken for the potential worth of the contained plutonium.

The CANDU reactor has very low parasitic material in the reactor core. The resulting high utilization of uranium, expressed in kWhe per unit mass of natural uranium mined is established to a high level of confidence. Even with escalation of uranium prices the CANDU fuelling costs will remain competitive with alternative reactor concepts.

6. ALTERNATIVE FUEL CYCLES

The neutron economy, on-power fuelling, and short bundles of CANDU reactors provides excellent flexibility to accommodate new fuel cycles and designs. Initial studies show that plutonium and thorium [15] fuel cycles can be accommodated in existing reactors with minimal modifications to reactor control elements and control systems. Fuel irradiations are in progress. These are leading to development of alternative fuel cycles involving thorium and plutonium for possible use in the 1990's.

7. CONCLUSION

Fifteen years of experience has demonstrated that CANDU fuel performance has met the demands of operating reactors. From the results of development programs now in progress we have full confidence that fuel for future reactors, whether based on natural uranium or recycled fuel, will have equally high performance.

The fifteen years experience has proven the real value of the team approach. It has emphasized the importance of communication and contribution to a single objective by all team members: the operators, the manufacturers, the designers and the researchers.

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