Canadian Fuel Development Program in 1997/98

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Abstract

This paper describes the CANDU® fuel development activities in Canada during 1997 through 1998. The activities include those of the Fuel Technology Program sponsored by the CANDU Owners Group. The goal of the Fuel Technology Program is to maintain and improve the reliability, economics and safety of CANDU fuel in operating reactors. These activities, therefore, concentrate on the present designs of 28-element and 37-element fuel bundles. The Canadian fuel development activities also include those of the Advanced Fuel and Fuel Cycle Technology Program at AECL. These activities concentrate on the development of advanced fuel designs and advanced fuel cycles, which among other advantages, can reduce the capital and fuelling costs, maintain operating margins in aging reactors, improve natural-uranium utilization, and reduce the amount of spent fuel.

Introduction

CANDU fuel has an excellent performance record. More than 1.3 million fuel bundles were irradiated in Canada by 1996. Of these, less than 0.1% had defects. As most failed bundles have single-element failures, the cumulative fuel element defect rate is about 0.003%. The defect rate is even lower if the failures from the earlier years of the CANDU program are excluded. For example, the cumulative bundle defect rate for fuel irradiated in Canada from 1991 to 1994 is about 0.02%. Moreover, from 1992 through 1997, the Gentilly-2 reactor operated without any single fuel bundle failure. All of these indicate significant improvements in performance over the years.

The successful performance of CANDU fuel is the result of a number of contributing factors, including a simple and robust fuel design with conservative design margins, reliable and specialized manufacturing processes developed over the years, and fuel operations conforming to the fuel operating limits.

Another reason for the success of CANDU fuel performance is the openness and cooperation with which the fuel designers, the reactor operators, fuel procurement staff, the fuel manufacturers, and the UO_2 suppliers disclose and discuss fuel-related problems. When a fuel problem occurred at a particular nuclear station, the reactor operators, the fuel designers and the manufacturers collaborated to identify the root cause and eliminate the problem.[1,2] Such openness and cooperation enable the industry to learn and benefit from the fuel failure incidents and avoid reoccurrence.

The need for continuous improvement is also recognized by the industry. The industry cannot afford to be complacent because of the good fuel performance record to date. It has to actively maintain and improve the fuel performance. Fuel defect excursions have occurred periodically, and effort must be exerted to avoid re-occurrence. Under the auspices of the CANDU Owners Group (COG), Hydro Quebec, New Brunswick Power, Ontario Hydro and Atomic Energy of Canada Ltd (AECL), jointly or in part, sponsor work programs under the Fuel Technology Program to maintain and improve the reliability, economics and safety of CANDU fuel in operating reactors. The work programs centre on the present fuel designs of 28-element and 37-element CANDU fuel bundles, and address issues related to fuel operation and performance.

In addition, to be competitive with other reactor systems and, in fact, with other energy generating systems, there is a need for continuous advancement of the CANDU fuel products. AECL has maintained an integrated development program to develop advanced fuels and fuel cycles.[3,4,5,6] The goal of the Advanced Fuel and Fuel Cycle Technology Program is to develop fuel and fuel cycle products that can reduce both capital and fuelling costs, increase the operating margins, improve natural-uranium utilization and provide synergy with other reactor systems to improve resource utilization and spent fuel management.

This paper describes the fuel development activities in Canada during 1997 through 1998. The activities are discussed in two parts: the work packages in the COG Fuel Technology Program and the work packages in the AECL Advanced Fuel and Fuel Cycle Technology Program.

COG Fuel Technology Program

The COG Fuel Technology Program has the goal of maintaining and improving the reliability, economic and safety of CANDU fuel in operating reactors. The program has been in existence for many years, originating in the late 1970s when it was a part of the Common Development Program. The scope of the program, or work packages, is defined and agreed to by the sponsoring organizations at the beginning of each fiscal year. Some work packages are multi-year programs, whereas some work packages span one or two years. In the following, the 1997 through 1998 program is described:

Data on Failed Fuel

In CANDU stations, failed fuel bundles can be removed while the reactor is on-power, then canned and stored in the fuel bay. To determine the root cause of failure so that remedial action can be taken, the fuel bundles may be inspected at the fuel bay. Bundles or elements may also be shipped subsequently to a hot-cell facility for detailed destructive examination. Our experience has shown that the manufacturing data for these bundles, the operating conditions under which the bundles have been irradiated, and the inspection or examination results will be useful in determining the cause of failure. Also, the information, when compiled over time, will be useful for monitoring whether there have been any changes in the fuel behaviour, brought on by changes in operation conditions, manufacturing processes, or other causes.

A work package in the Fuel Technology Program will compile the operating conditions to which failed fuel has been exposed in Canadian nuclear stations. As the first step, a reporting specification had been prepared for use at stations to report data regarding failed fuel. The specifications recommend important parameters that should be reported, for example, the power burnup histories, locations of the fuel in the channel, fuel manufacturers and gross fission-product signals. This year, the cumulative failed fuel data from a CANDU station will be compiled according to these specifications. This database will then be used to define the conditions for which the fuel has been exposed in the station and for which fuel failures resulted.

A companion work package is to compile and examine the post-irradiation examination (PIE) data obtained in hot cells for power reactor fuel. Reference 7, presented at this conference, shows an application of such a database. It determines the range of sheath strains and fission-gas releases from power reactor fuel over the last 20 years. Recently, under this work package, the PIE of fuel that had experienced load following in the Bruce B Nuclear Generating Station was documented and compared with a reference fuel examination. It confirmed that the load-following power transients applied had no negative effect on the fuel performance. Reference 8, also presented in this conference, uses the database to evaluate the effect of uranium mass increase in CANDU fuel bundles in Canada over the years.

Fuel Design Experience and Methodology

Another work package in the Fuel Technology Program is the preparation of the Fuel Engineers Manual. This is a "sequel" to the Fuel Encyclopedia that was prepared in 1988. The Fuel Engineers Manual covers in detail all aspects of the present CANDU fuel bundles, including CANLUB coating, design development testing, fuel materials, fuel manufacture, as well as design evolution and history. The Manual is being prepared by authors in their field of expertise, and the document is expected to be a valuable resource to help to understand design and operational problems regarding fuel. It can also be used as a training tool for new members entering the nuclear fuel industry. This manual is expected to be ready for industry use by mid-1998.

Fuel Specifications Update

From the many years of fuel operating experience, fuel PIE and development work, the knowledge on fuel behaviour, fuel design and fuel manufacturing have significantly advanced. To ensure that new important information is captured in the fuel technical specifications, the Fuel Technology Program has a work package to review and update the specifications. The fuel specifications are the working documents for fuel design and procurement. To date, the review of the specifications of Zircaloy tubing and UO_2 powder have been completed. Reference 9, presented in this conference, describes the review and the conclusions. During 1997 through 1998, additional specifications including "UO_2 pellets" and "Beryllium Metal for Brazed Joints" will be reviewed.

Special Bundles Irradiation and Examination

To guide the designers to confirm, and refine if required, the fuel specifications, the Fuel Technology Program also sponsors the irradiation and PIE of special bundles. To date, well-characterized bundles manufactured at the specification limits of density and pellet/sheath radial gap have completed their irradiation at Point Lepreau Nuclear Generating Station. They have been shipped to the hot-cells at the Chalk River Laboratories (CRL) where they are awaiting destructive examination. Two additional bundles with and without the CANLUB coating have also been irradiated, discharged and will be shipped to CRL after the required cooling period. The irradiation of fuel at the specification limits of density and gap can provide information that may affect the uranium mass in a bundle, and hence the fuel burnup and the fuelling cost. The CANLUB irradiation will provide further insight into the chemistry of CANLUB in-reactor and the active ingredient of CANLUB in protecting the sheath from stress-corrosion cracking.[10]

In-Bay Fuel Inspection

Fuel behaviour is often the first indicator of a performance problem in the reactor. Therefore, defects in the fuel need to be found and the root cause determined as soon as possible. In addition, safe response of the fuel in any safety assessments requires that the fuel condition be in a defined state. All of these often require fuel examination in a hot-cell facility, which tends to be time-consuming, relatively expensive, and therefore rather infrequent. For example, fuel bundles normally cannot be transported to hot-cells until after a cooling period of about 3 to 6 months after discharge. There is an incentive to maximize the information gained by inspection at the fuel bay, thereby increasing the value and the frequency of data collection on the condition of fuel. A new work package is being set up and implemented to develop, design, and construct prototype equipment for in-bay inspections. The first step in this work package is to identify the type of inspection required and develop the specifications for the prototype equipment.

Fuel Failure Maps

For postulated fuel-handling accidents, irradiated fuel is held up during its transfer from the reactor to the fuel bay. As a result of this delay that may cause degraded cooling, a fuel bundle may heat up at decay power. The time to sheath failure governs the response time that cooling should be restored to the fuel bundles. The time to failure is dependent on the bundle power and the specific heat transfer environment in which the bundle is located. To provide the operator with realistic estimates of the response time, several work packages have been implemented in the Fuel Technology Program. In one package, electrically heated fuel bundle simulators have been used to assess the heatup transients of the sheath under various cooling conditions. Work this year will deal with heatup in a fuelling machine. In another package, the failure criteria of the fuel sheath that is due to sheath oxidation and hydriding were confirmed by laboratory oxidation tests. This year, a work package is underway to combine the results of the two programs into fuel failure maps. The maps provide the predicted failure times as a function of decay power and various cooling conditions.

Fuel Performance Modelling

For reactor operation, fuel performance models can be used to assess whether certain power transients may have a greater chance of causing fuel defects, or whether certain fuel manufacture deviations may have an adverse effect on the fuel performance. For design, a model can be used to evaluate the performance of a new fuel design, and reduce the total cost of implementing changes that would otherwise require expensive laboratory tests to simulate the fuel performance. The Fuel Technology Program has been supporting the fuel modelling effort for a number of years. Because of development history and priority, two fuel performance models are now available, each focusing on different aspects of fuel behaviour. The ELESIM code [11,12] concentrates on the behaviour of the UO_2 and fission-gas release during irradiation. The ELESTRES code [12,14] concentrates on the pellet hourglassing behaviour and local ridge strain on the sheath, while using similar UO_2 and fission-gas release models as ELESIM. Both ELESTRES and ELESIM are mature codes, and have been used in design and safety work in their areas of applications. The work package in this current year is to physically combine the two codes into one integrated package (ELESTRES-IST) with a common numeric solution scheme. This new Industry Standard Tool (IST) will then be subjected to validation using the databases that have been or are being compiled within the Fuel Technology Program. Further code development will be based on ELESTRES-IST.

Advanced Fuel and Fuel Cycle Technology Program at AECL

Present CANDU fuel bundle designs, based on natural uranium, have been successful in meeting the needs of the CANDU reactor program. The excellent performance record, the simplicity in design and the ease of manufacture localization have made the CANDU fuel one of the distinguished features of the CANDU reactor system. All countries that have CANDU reactors have also developed the capability to manufacture their own fuel. However, at some point in the future, the incentives for using the current fuel bundle design and natural uranium may be outweighed by the advantages of advanced fuel bundles and fuel cycles, on the basis of either economics, resource utilization or performance.

To advance CANDU fuel products, AECL has maintained an integrated Advanced Fuel and Fuel Cycle Technology Program. Figure 1 shows a schematic of the program. The program consists of the development of specific fuel products such as the CANFLEX bundle, the development of generic fuel technologies such as an improved CANLUB coating and improved welding technology that are independent of fuel type and geometry, and the development of advanced fuel cycles such as enriched uranium, thorium, or plutonium.

CANFLEX is the next step in the evolution of the CANDU fuel bundle geometry. The CANFLEX bundle has been developed jointly by AECL and KAERI since 1991, and before that by AECL since 1986.[15]The CANFLEX fuel bundle has lower linear element rating for the same bundle power as a result of the greater element subdivision and the use of two element sizes, and is therefore is well suited for use in advanced fuel cycles, particularly those that can attain high fuel burnup. The CANFLEX bundle has also incorporated the latest critical heat flux (CHF) enhancement technology developed by AECL and therefore can also be used in existing reactors to offset the reduction in dryout margins when the reactors age.

Because of the lower linear element rating and higher CHF performance, AECL's vision is that the CANFLEX bundle will be the preferred carrier of advanced fuel cycles. Successive improvements in the CANFLEX bundle will continue. Beyond the improved CANFLEX bundles, an advanced CANDU bundle is being developed as the fuel bundle for the next generation of CANDU reactors.

Complementing the fuel product development is the development of generic fuel technologies. This includes improved welding techniques to replace beryllium brazing as the attachment method for the bundle appendages (i.e., bearing pads, spacers); low void reactivity fuel (LVRF) concept that can reduce void reactivity to any given value; the cool fuel concept to reduce the fuel operating temperature; CHF enhancement techniques to further enhance the CHF performance; improved CANLUB coating and optimized internal element design to enable the fuel to operate at high burnup. These technologies will be selectively incorporated into the CANFLEX bundle as the needs for their applications are required.

The CANDU reactor system has the highest neutron economy of all commercial power reactors, and is the only commercial reactor capable of using natural uranium. The on-power refuelling feature also allows flexibility to adjust reactivity and to shape the flux without reactor shutdown. The CANDU reactor system is therefore well suited for the use of advanced fuel cycles. The Advanced Fuel and Fuel Cycle Program contains work packages in slightly enriched uranium (SEU)/recovered uranium(RU) fuel, plutomium mixed-oxide (MOX) fuel, the DUPIC cycle (Direct-Use of spent PWR fuel in CANDU), thorium and inert matrix fuel.

Fuel and fuel cycle development involves a multidisciplinary effort. The program therefore integrates work activities in many disciplines, including fuel design, fuel bundle thermalhydraulics, fuel materials, reactor physics and fuel manufacture. In the following, the program activities for 1997 through 1998 are briefly described.

CANFLEX (natural uranium) Bundles

The CANFLEX natural-uranium bundle, with its CHF enhancement, is able to offset the reductions in dryout margins that occur as the reactor ages. The CANFLEX bundle design and qualification are now near completion. Enhancements in the critical heat flux have been confirmed in the thermalhydraulic test loop at the Chalk River Laboratories (CRL).[16] The tests were performed with a 12-bundle-length CANFLEX heater string in Freon. Prototype bundles have been irradiated successfully at the NRU reactor at CRL. All mechanical tests to qualify that the bundle meets its requirements have been completed at KAERI and AECL, except for the 3000-h endurance test that is targeted for completion by the end of 1997.[17,18] Work activities in Canada this year include the completion of the safety and licensing analysis, bundle fabrication, demonstration irradiation of 24 CANFLEX natural-uranium bundles which is planned for the Point Lepreau Nuclear Generating Station, and preparation for the critical heat flux tests in water.

SEU/RU Fuel

The easiest first step in the CANDU fuel cycle evolution is the use of SEU fuel with ^{235}U content between 0.9% and 1.2%. Generally, enrichment between 0.9% and 1.2% can increase the burnup in a CANDU reactor by a factor of 2 to 3, and reduce the fuel cost by 20 to 30%.[3] Alternatively, reactor power can be uprated by flattening the channel power distribution across the reactor core with the use of enriched fuel.[19]

A variant of the SEU fuel cycle is the use of RU. Recovered uranium is a by-product of conventional reprocessing of spent fuel from light-water reactors (LWRs). Recovered uranium has an enrichment of about 0.9%, with the actual enrichment depending on the spent fuel that it originated from. The fuel cost savings with RU, which is a by-product of reprocessing, will be greater than for conventional SEU.

AECL has established bilateral programs with British Nuclear Fuel Limited (BNFL) and KAERI to demonstrate the use of RU in the CANFLEX bundles in CANDU reactors. Reactor physics studies were completed confirming that existing CANDU reactors can change to the use of RU fuel.[20] BNFL has identified that for RU, the integrated dry route (IDR) process is their preferred "conversion route" from uranyl nitrate solution to UO_2.

AECL has extensive experience with the irradiation of enriched fuel over the years. The enriched UO_2 was obtained by the ammonia di-uranate (ADU) process. Because the RU uses the IDR process, an irradiation program to compare fuel from the two types of powder is planned. In this year, CANFLEX bundles with RU (IDR) pellets and SEU (ADU) pellets will be fabricated for irradiation in the NRU reactor at CRL. Other works related to the RU program this year include the development of a model to study the economics of using RU fuel in an existing CANDU reactor.

DUPIC

The DUPIC cycle involves converting spent PWR fuel into CANDU fuel using a dry process. The process avoids selective element removal, and with the remaining high radiation field, offers a very high level of protection from proliferation. The DUPIC program is a joint program supported by AECL, KAERI and the US Department of State. The objective is to confirm the technical feasibility of the processes, process optimization, and obtain technical information for cost evaluation. A detailed discussion of AECL's progress in DUPIC fuel development is provided in Reference 21, a paper presented at this conference. The program this year centres on the fabrication, using the OREOX process[21] (i.e., oxidation/reduction of the spent PWR pellets), of several DUPIC elements at AECL's Whiteshell Laboratories for test irradiation in the NRU reactor in Canada and the HANARO reactor in Korea.

Low Void Reactivity Fuel

Positive void reactivity is an inherent feature of the current CANDU lattice design. It is accommodated through the reactor design in such features as the provision of two independent fast-acting shutdown systems, each having a high degree of reliability and each being able to act alone to effectively shut down the reactor. Nonetheless, some countries may require reduced or even negative void reactivity for licensing, political or other considerations. As a response, AECL has a development program for this type of fuel.

The LVRF bundle uses a combination of fuel elements containing enriched fuel and elements containing depleted uranium with dysprosium, which is a neutron absorber. The enrichment and dysprosium levels can be adjusted to result in a given value of void reactivity. The LVRF concept can be embodied in a number of geometries, including the 37-element and the CANFLEX bundle. Testing related to 37-element bundles for natural-uranium burnup applications is being performed this year. This includes thermalhydraulic testing, reactor physics assessments, and irradiation and PIE of two prototype bundles and elements in a demountable bundle geometry. Testing of CANFLEX geometries intended for higher burnups is in progress. For the longer term, more advanced options are also being developed, that would achieve a significant reduction in void reactivity while preserving good neutron economy.

Thorium Fuel

AECL has many years of experience with thorium fuel, ranging from scenario studies of the different thorium cycles, fuel management studies, reactor physics measurements with ThO_2 fuel and the fabrication and irradiation of the ThO_2 fuel. The program this year includes re-analysis of earlier reactor physics measurements using more updated core physics methods, evaluation and improvement of core physics methods for treating flux-history dependence of cross sections in reactor, fuel cycle scenario studies to obtain the fuel management strategies in thorium cycle implementation, and the continuation of ThO_2 fuel irradiations in the NRU reactor.

MOX Fuel and Dispositioning of Weapons Plutonium

The higher initial enrichment and discharge burnup of LWR fuel, compared with the CANDU fuel, result in a higher concentration of plutonium in the spent fuel. Moreover, the CANDU reactor is a more efficient burner of fissile material. Twice as much energy can be derived from the plutonium in spent LWR fuel by burning it in a CANDU reactor than by recycling it in a LWR. These features form the basis for the plutonium MOX fuel cycle in which plutonium MOX fuel is used in the CANDU reactor, with the plutonium coming from the reprocessing of LWR fuel. A variation of this is the dispositioning of weapons grade plutonium, in which plutonium from the weapons programs could be fabricated as MOX fuel and burned in the CANDU reactors. Details of the plutonium dispositioning programs that AECL participates in are discussed in References 22 and 23, both of which are papers presented at this conference.

Actinide Burning

This is a fuel cycle in which transuranium actinides separated by reprocessing can be fabricated into fuel and burned (transmuted) in a CANDU reactor. To ensure that no further plutonium is generated in the process, a suitable inert material needs to be selected to contain the actinides for irradiation. The AECL program on actinide burning focuses on silicon carbide as a candidate matrix material, and is described in Reference 24, a paper presented at this conference.

Generic Technology Development

Generic improvements in fuel technology are being developed, which can be exploited by a range of fuel cycles and bundle geometries. For example, elements with various CANLUB coatings have been fabricated and will be irradiated and power ramped in the NRU reactor to test the stress-corrosion resistance of the coatings. Elements with optimized internal element designs had been fabricated and are under irradiation in the NRU reactor. Freon tests will be performed later this year to further improve the CHF enhancement technology.

Conclusions

Present CANDU fuel bundle designs, based on natural uranium, have been successful in meeting the needs of the CANDU reactor program. To further enhance the competitiveness of operating and new CANDU power stations, fuel development activities are continuing in Canada. The Fuel Technology Program, sponsored by the CANDU Owners Group, has the goal of maintaining and improving the reliability, economics and safety of CANDU fuel in operating reactors. The Advanced Fuel and Fuel Cycle Technology Program at AECL concentrates on the development of advanced fuel designs and advanced fuel cycles.

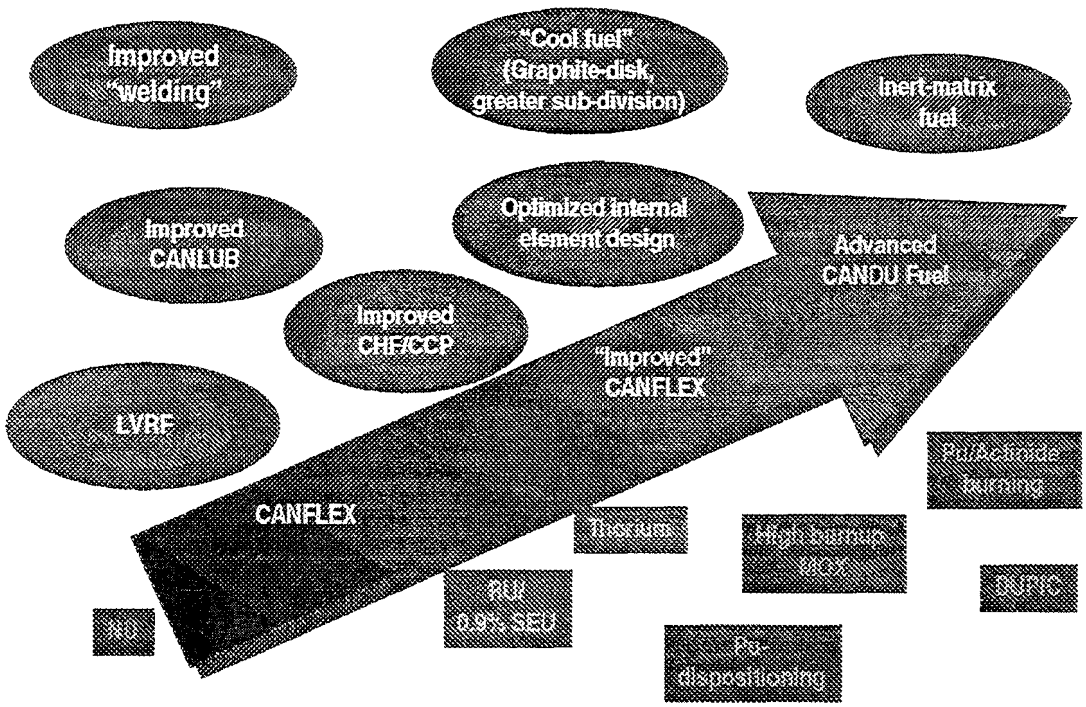

Figure 1
Schematic of AECL's Advanced Fuel & Fuel Cycle Technology Program

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