CANDU Fuel Performance

by

Song Wenhui* and A.M. Manzer**
*Shanghai Nuclear Engineering Design & Research Institute
**Atomic Energy of Canada Limited

1. OVERVIEW

One of the recognized strengths of the CANDU (CANada Deuterium Uranium) nuclear reactor is the excellent performance of its fuel. Of the more than 1 300 000 fuel bundles that have been irradiated to 1996 in Canada, less than 0.1% have developed defects(1). Since most defective bundles have single-element failures, the cumulative fuel element defect rate is approaching 10^{-5}. The defect causes tend to fall into three categories: manufacturing flaws, operational and system design related fuel defects. In recent years, there have been very few system design related defects.

The low defect rate of CANDU fuel is attributed to the fuel element and bundle designs that meet all requirements, as demonstrated by qualification programs that include extensive out-reactor tests and in-reactor irradiations. Equally important factors are the specialized manufacturing processes and systems that have been developed to produce fuel within the design specifications and under good quality assurance.

When a fuel element becomes defective, it does not impose an immediate risk to station operation because

1. The systems and/or techniques for detecting and locating defective fuel do not normally require reactor shutdowns. At most stations, operators find the defects while they are small and usually before they contaminate the primary circuit.

2. The fuel handling systems have the capability for removing defective fuel using normal operating procedures at full power.

On the other hand, if there are several defective elements in the core resulting in high releases, there is a risk that regulatory limits will be exceeded, requiring a reactor shutdown.

There are 22 CANDU power reactors in Canada:

- 20 reactors in 5 four-unit stations (Pickering A and B, Bruce A and B, and Darlington, which are owned and operated by Ontario Hydro); and
- 2 reactors in single unit CANDU 6 stations (Point Lepreau and Gentilly 2, which are owned and operated by New Brunswick Power and Hydro Quebec, respectively).

Besides the power reactors, Canada had three prototype CANDU reactors that began operations in the 1960s and 1970s. These included the Nuclear Power Demonstration (NPD), Douglas Point, and Gentilly 1 prototype reactors. All three have now been decommissioned. Except for the Gentilly 1 reactor, all CANDU reactor cores contain horizontal fuel channels, which are fuelled on a once-through natural uranium fuel cycle that requires heavy water moderation and cooling. The Gentilly 1 reactor used natural uranium fuel, contained vertical fuel channels, and had heavy water moderation and boiling light water coolant.

CANDU fuel bundles are small, simple assemblies that do not require structural components such as grid spacers, support rods or endfittings to contain the fuel rods or elements. The fuel elements and the thin endplates serve as structural components. The bundles are loaded and removed from fuel channels by fuel handling systems that operate at the full range of reactor power, pressure and temperature.

The fuel handling system has two fuelling machines that operate as a pair while refuelling a fuel channel. One machine loads new bundles into one end of a channel while the other unloads irradiated bundles from the other end. Each CANDU reactor has one of two types of fuelling machines, depending on the fuelling direction relative to the coolant flow direction:

- The "fuel-against-flow" machines load new bundles into the downstream end of the channel. Each channel contains latches to support the fuel against the drag force generated by the coolant, and the fuelling machine uses fuel carriers to transport bundles to and from the channel (Bruce and Darlington reactors); and
- The "fuel-with-flow" machines load new bundles into the upstream end of the channel. Each channel uses shield plugs to support the fuel against the coolant drag, and the fuelling machine uses sidestop separators to separate bundles from the fuel column during removal from the channel (Pickering and CANDU 6 reactors).

The Pickering and CANDU 6 designs were derived from Douglas Point prototype reactor that also permitted fuelling in the direction of coolant flow. The Bruce and Darlington designs were derived from NPD prototype reactor that permitted fuelling against the direction of coolant flow.

The pressure tubes used in fuel channels of all CANDU power reactors in Canada have a common inside diameter of 100 mm. This sets the diameter of all three fuel bundle designs built today in Canada. The current fuel designs include

- a 28-element bundle for the Pickering reactors,
- a 37-element bundle for the Bruce and Darlington reactors, and
- a 37-element bundle for the CANDU 6 reactors.

The fuel element subdivision was selected on the basis of the specific power requirements. The 37-element bundle has 13 mm diameter fuel elements that are smaller than those in the 28-element bundle. The Pickering bundle has 15 mm diameter elements that are the same size as those in the 19-element bundles previously used in the NPD and Douglas Point reactors. Since both sizes of fuel elements are qualified to operate at the same high linear powers of about 60 kW/m, the 37-element bundle delivers about 30% more power than that delivered by the 28-element bundle.

The two 37-element bundle designs are very similar, with the exceptions of the small differences in the end-cap profiles and bearing pad positions along the fuel elements, as shown in Figures 1 and 2. These differences are needed to ensure compatibility with the different fuel handling systems and fuel channel configurations.

2. KEY DESIGN FEATURES

With a natural uranium fuel cycle, the excess reactivity of the core is quite small, and it is easily controlled with on-power fuelling. The average fuel bundle discharge burnup varies from about 7200 to 8300 MWd/MgU, depending on the reactor design, fuel type, heavy water isotopic purity, and fuel management strategies. The corresponding natural uranium consumption for CANDU 6 reactors is about 170 MgU_n per GWy electrical.

The capability to replace fuel on-power has led to a unique fuel design that is quite different from those reactors that use enriched uranium and require off-power fuelling. The CANDU fuel design consists of 0.5 m long fuel elements assembled into a standard bundle configuration. The fuel bundles are inserted into specific reactor fuel channels as required by the fuel management system to control the excess core reactivity. Because of the low fuelling costs of less than about 1.5 mils/kWh, fuel bundle reconstitution is not economically attractive to replace defective elements, and is not practiced by CANDU utilities.

2.1 FUEL ELEMENT COMPONENTS

The CANDU fuel element is comprised of UO_2 ceramic pellets, Zircaloy-4 cladding, graphite coatings on the inner sheath surface, and Zircaloy-4 end-caps.

The geometric parameters and material properties of the fuel pellet are chosen and controlled to

a. Maximize the amount of fissile material present in the fuel element,

b. Minimize the pellet volumetric changes during fuel in-reactor life,
c. Ensure that fission gas release is within acceptable limits,
d. Ensure that the pellet design meets the requirements imposed by production capability and economy, and
e. Minimize circumferential ridging of the sheath.

The UO_2 properties that bear the strongest influence on the pellet thermal behaviour are density and oxygen-to-uranium ratio. These characteristics determine the thermal conductivity of the oxide and are maintained within the specified ranges to ensure acceptable UO_2 temperatures and, hence, fission gas release.

Pellet ends are designed with spherical indentations, or dishes, to accommodate thermal volumetric expansion of the plastic core of the pellet and to accommodate fission product gases. The pellet ends are chamfered on the corners of the flat pellet surfaces to minimize pellet chipping during loading and during subsequent element handling. Chamfering also reduces sheath strain at pellet interfaces.

Zircaloy-4 is used in fuel sheath production because of its low neutron absorption. It also has good corrosion resistance and low hydrogen or deuterium pickup performance under CANDU coolant conditions. Material properties and heat treatments are specified so that the material will retain acceptable ductility at high irradiation levels.

Fuel element sheath diameter is locally reduced in the region of the sheath-to-endcap weld. To eliminate the possibility of sheath damage in this region from pellet-sheath interaction, a non-standard pellet is placed at the each end of the fuel stack.

As in all CANDU fuel designs, the sheathing is designed to collapse into contact with the UO_2 at reactor coolant conditions. The thin sheath provides fission product containment while ensuring minimum neutron absorption and resistance to heat transfer. The as-fabricated diametrical clearance between the UO_2 pellet stack and the sheath is chosen and controlled to be in the appropriate range to

a. Prevent the formation of longitudinal ridges in the sheath,
b. Facilitate pellet loading during fuel element manufacturing, and
c. Accommodate some of the pellet diametrical expansion and minimize sheath strain.

Before pellet loading, a thin layer of graphite (CANLUB) is applied to the inner surface of the fuel sheaths to reduce pellet-sheath interaction. The void within the fuel elements is filled (unpressurized) with a He/air or He/inert gas mixture prior to end-cap welding. The presence of helium within the fuel element allows for leak detection during fabrication and provides some improvement in the pellet-to-sheath heat transfer.

Fuel element closure is provided by two end-caps that are resistance-welded to the ends of the sheath. The end-cap material is specified and inspected to ensure adequate strength and lack of porosity, which is needed for fission product containment.

2.2 FUEL BUNDLE COMPONENTS

The fuel bundle components are made of Zircaloy-4 and include endplates, end-caps, interelement spacers, and bearing pads.

There are two endplate designs available for 37-element bundles and one for the 28-element bundle. All designs have been fully qualified for use in CANDU reactors. The endplates hold the fuel elements together in a bundle configuration. They have to be strong enough to maintain the bundle configuration and to allow axial loads to be distributed among many elements rather than being concentrated on a few. Simultaneously, they should be flexible enough to allow differential axial expansion among the elements and to permit bending and skewing of the bundle. The endplates should also be thin to minimize the quantity of neutron absorbing material and to minimize axial separation between the fuel pellets in adjacent bundles.

While the endplates maintain separation of the elements at the bundle extremities, interelement spacers maintain separation at the bundle midplane. The spacers are rectangular with an aspect ratio of about 3.5. They are mounted with their major axis slightly angled (skewed) with respect to the element axis, such that the spacers on any two adjacent elements are skewed in the opposite direction. This skewing increases the width of possible contact between spacer pairs and decreases the probability of spacer interlocking.

The bearing pads, brazed to the outer element sheaths near the element ends and at the midplane, support the bundle inside the fuel channel and fuel handling systems. They protect the fuel sheaths from any mechanical contact throughout the fuel bundle lifetime. The pads must be profiled to minimize pressure tube surface damage during the in-reactor residence time of a fuel bundle and during fuelling operations. The pads must also be designed to minimize local corrosion of the pressure tube.

Two basic end-cap designs are available for CANDU bundles. Each has an external profile that is designed to interface with the fuel channel and fuel handling system components.

3 FUEL DEFECT EXPERIENCE

Most of the fuel defects found in CANDU reactors have occurred in small batches in situations termed as "defect excursions". CANDU reactors have had 12 defect excursions, as shown in Table 1; most of these are described in References 2 to 10. Nine of the excursions occurred in

Canada. Figure 3 shows the historical defect rate for 37-element fuel irradiated in Canada over a 10 year period. Although the fuel defect trend for the 28-element fuel is similar, detailed statistics are not available.

With the exceptions of the early power ramp fuel defects in the early 1970s and the mechanical fuel failures at the Darlington NGS in the 1990s, there have been no system design related defects. Most defects from all CANDU reactors are attributed to manufacturing and operations.

The manufacturing flaws that have caused fuel defects among CANDU power reactor fuel include

- incomplete end-cap welds,
- porous end-cap bar stock,
- insufficient volume,
- excess hydrogen gas within the element, and
- fretting through the sheath from end-cap weld flashings.

The causes of operational defects include:

- sheath fretting that is due to debris from the coolant,
- stress corrosion cracking (SCC) of the sheath that is due to power ramps associated with abnormal operations, and
- mechanical damage that is due to abnormal fuelling.

The causes of system design related defects include

- SCC of the sheath that is due to power ramps associated with normal operations, and
- bundle disassembly that is due to resonant vibration in acoustically active channels.

This section summarizes the characteristics of defective fuel as observed from previous defect excursions.

3.1 MANUFACTURING FLAWS

Of all defect causes that are due to manufacturing flaws, an incomplete endcap weld predominates over all the others, listed in the previous section. Manufacturing flaws caused by fretting from weld flashing are extremely rare and tend to have the same characteristics as defects due to fretting by debris. Therefore, this section focuses on the first four of the five types of defects that are due to manufacturing flaws.

3.1.1 INCOMPLETE WELDS AND ENDCAP POROSITY

Flaws that are due to incomplete end-cap welds or porosity in the end-caps have common characteristics and have similar performance in reactor. The initial breach in the cladding begins as a small hole near the end of the fuel element. Because of the small size of the hole, the amounts of coolant entering the fuel element and of fission products released to the coolant are limited. With low fission product release, defects can remain undetected until the hole becomes larger. With coolant inside the element, a source of hydrogen (or deuterium) is available to attack the Zircaloy cladding and cause secondary hydriding (or deuteriding) damage. When this happens, local hydrided regions of the cladding become brittle and begin to crack open.

The incubation period for secondary damage depends on the initial size of the primary hole and the fuel temperature (or element linear power)(11). From previous experimental irradiations conducted at the Chalk River Laboratories, it has been shown that the defects with very small holes do not open up and release fission products in detectable quantities. The release rate tends to increase after the fuel element achieves a burnup of about 40 MWh/kgU(11). This burnup represents about one month of operation for a high powered element. Moreover, the small hole tends to remain stable at element linear powers below about 40 kW/m. Because of these power and burnup thresholds, defects associated with manufacturing flaws are not normally detected within the first few weeks after loading them into the core. Also, they tend to preferentially occur in high power regions of the core.

The deterioration rate of fuel elements that initially contain small holes is also influenced by other parameters, particularly

- element linear power (or fuel temperature), and
- inside sheath temperature.

Therefore, these types of fuel defects preferentially occur in these locations:

- the downstream half of the channel where the inside sheath temperature is the highest,
- the outer ring of fuel elements where the linear powers are the highest, and
- in high power channels near reactivity control devices.

The preferential distribution of defects was observed in 1981-1982 at the Douglas Point reactor during a defect excursion. At the time, the core contained many bundles with elements that had incomplete closure welds. The bundles were randomly distributed in the core, but the defects were preferentially located at high power positions towards the outlet end of the channel. (See Figure 4.)

In recent years, endcap porosity has been virtually eliminated by a change in the material specification that now requires 100% ultrasonic inspection of endcap barstock material.

3.1.2 EXCESS HYDROGEN GAS

In 1991-1992(2), at least 20 defective bundles, mostly from high power positions, were discharged from the Point Lepreau core. The investigation concluded that the cause was due to excess hydrogen gas, made available during irradiation. About 4 to 5 mg of excess hydrogen gas was measured inside new fuel elements built at the same time as the defective bundles. During this time, the CANLUB graphite coatings were insufficiently cured. This amount of hydrogen gas inside the fuel element exceeded the technical specification of 1 mg.

The defective elements failed at linear powers exceeding about 50 kW/m. At these high powers, a small hole is believed to have developed within a day or two after initial insertion of the bundles into the core. The ^{133}Xe activity concentrations in the coolant gave the first sign of defective fuel in the core. In some cases, noble gas escaped within a few days of the initial loading of the defective element. The ^{133}Xe concentration increased by about 3 MBq/kg per defective element to steady levels of about 150 to 250 MBq/kg when several defective elements were in the core. The release-to-birth rate ratio of ^{133}Xe was estimated to be about 20%(2). The hole was large enough to allow the noble gases, particularly ^{133}Xe, to escape, but small enough to prevent coolant ingress and halogen release. Without halogen release, the defects could not be located with the failed fuel location system. The hole size was believed to have increased several weeks later, generally after the element achieved a burnup of about 50 MWh/kgU. When that happened, the iodines escaped in detectable quantities and the defects were found with the failed fuel location system.

Defective elements that are due to excessive hydrogen gas display the same characteristics as those that were discussed in the previous section for incomplete welds. The only difference is that the thresholds for secondary damage appear to be slightly higher than those that were observed for manufacturing flaws, that is, about 50 MWh/kgU and 50 kW/m, as shown in Figure 5. Because of the 50 kW/m threshold, defects are only expected among fuel elements located on the outer ring of the bundle. All other elements in the core will operate at linear powers below this threshold.

3.1.3 INSUFFICIENT VOLUME

In December 1983 and early 1984(3), a large defect excursion occurred at Bruce A Unit 3. Increasing levels of radioiodine in the coolant provided the first signs of fuel defects in the core. Within one week, the ^{131}I levels in the coolant rose by 10 times and remained high for several months at about 4 MBq/kg. The noble gas levels at Bruce are not normally reported. At least 43 defective bundles containing 140 defective fuel elements were located by the failed fuel location system. Dry sipping in the fuel transfer mechanism and visual inspections in the bay confirmed that the defects were discharged.

Most of the defective bundles (37 out of 43) had been made by the same manufacturer and had been irradiated in Unit 3 at Bruce A. They had been shifted from low power position #3 along the fuel channel to high power position #7 in the central region of the core. The defect appeared to be confined to a circumferential region in the endcap weld that is closest to the end bearing pad. In some cases, the cracking resulted in complete separation of the endcap from the element.

A review(4) of the manufacturing processes indicated that the affected fuel may not have conformed to the original AECL technical specifications that control the gap volumes within the elements. The suspected non-conformances were

1. The axial gap between the fuel stack and endcaps was below the minimum limit;
2. The diametral clearance between the pellets at the ends of the fuel stack and the sheath was below the minimum limit; and
3. The UO_2 density was above the maximum limit.

In addition, there is some evidence(4) that suggests that there was excess hydrogen gas within the fuel elements.

These non-conformances contributed to high stresses in the sheath, particularly at the ends of the elements. The excess hydrogen gas may have entered the sheath at the local regions of high stress where the diametral clearance was insufficient. The additional increase in the stresses during the refuelling power ramp combined with the presence of fission products in the gap likely led to SCC(4). One explanation for the these failures having occurred in only one of the Bruce units may be due to slight differences in the power distributions among the Bruce units.

3.2 OPERATIONAL DEFECTS

3.2.1 STRESS CORROSION CRACKING DURING ABNORMAL OPERATION

One of the most common operational defects among CANDU fuel is SCC of the sheath because of power ramps. These types of failures have only occurred during defect excursions among the Pickering size fuel elements (15 mm diameter). High sheath stresses associated with a sudden increase in power combined with a high concentration of corrosive fission products within the pellet-to-sheath gap can lead to failure.

In November 1988(5), a reactor trip occurred at Pickering A Unit 1. During trip recovery, all adjusters were withdrawn from the core and the reactor power was raised to 87% for 40 min. This was outside the range of normal operation; reactor power is normally limited to 65% in this situation. As a result of the transient, about 200 fuel bundles in 40 central channels sustained large power ramps. Following the transient, the radioiodine and noble gas levels in the coolant indicated the presence of many defective elements. Subsequently, fuel was discharged from these channels and inspected in the bays. Thirty-six defective bundles contained about 290 outer fuel element failures. Some of these experienced failures in all elements of the outer ring. No failures were observed among the non-outer elements that operate at significantly lower powers than the outer elements.

The defective fuel bundles caused by SCC usually have multiple fuel element failures in the outer ring which is the ring that experiences the highest linear powers. The defective elements usually display extensive damage such as: local swelling of the sheath because of UO_2 oxidation, uranium deposition downstream of defect sites, secondary deuteride damage at several sites, and irregular cracking patterns on the sheath. The primary defect site is not usually found during inspections in the bay nor in the hot cells. In previous controlled experimental irradiations, the rate of secondary degradation of the defective elements was rapid, generally within an hour of the power transient(11). Although the initial degradation rate is high, it diminishes quickly with time as indicated by the condition of the defects. Defective bundles discharged shortly after the transient appeared to have the same extent of damage as did those that were discharged weeks later.

3.2.2 DEBRIS FRETTING

The other most common type of operational defect in CANDU reactors is sheath fretting by debris. Debris within the primary circuit can be circulated through the core by the coolant. Often new CANDU reactors experience several fuel defects because of debris being trapped within fuel bundles. Depending on the size and location of the debris, the coolant velocity can cause it to vibrate and damage the fuel sheath. The main source of debris found within the primary circuit comes from the construction stage of new reactors. Other sources of debris can be made available to the primary circuit after startup when reactors are shut down for routine maintenance and inspection of primary circuit components.

For commissioning of Pickering B Unit 5, the core was loaded with first charge fuel and strainers were installed on the *pump discharge lines* to collect debris(6). After the pumps were started, the strainers broke up and some of the pieces eventually became trapped in the fuel. The subsequent fretting led to fuel failures. To reduce the risk of having fretting defects during the initial startup, strainers are now normally installed in *specific channels* during commissioning to remove debris.

Unlike other defect types, fretting defects are not power related. Defective elements can appear anywhere in the bundle and anywhere along the fuel channel, depending on the size of the debris.

If the fretted hole is small, the deterioration rate can be slow until the fuel element achieves a burnup threshold, similar to that identified for the fuel elements with manufacturing flaws(11).

Previous experience has shown that the defects caused by debris fretting are usually single element failures. The defective elements may have: local areas of swelling because of UO_2 oxidation, uranium deposition downstream of the defect, and small amounts of secondary deuteride damage. The amount of secondary damage depends on the burnup or time duration in the core while defective. Primary defect sites are usually found during inpections in the bays: shiny surfaces indicate where the fretting has occurred.

The Wolsong 1 fuel defect experience in the mid 1980s appeared to be associated with debris fretting. The evidence seemed to suggest that the debris was small enough to circulate within the primary circuit and fall into inlet feeders located along the bottom of the headers near the pump discharge lines. Channels with inlet feeders connected to the headers at these locations are more susceptible to debris fretting failures.

The primary circuits in CANDU reactors, which have a figure-of-eight configuration have two separate loop halves. This means that fuel defects tend to appear in the loop half that is downstream of the point where debris is introduced.

At the onset of a fuel defect excursion where many pieces of debris are caught among several bundles within the core, defects do not necessarily occur at the same time. Instead, they occur over a long time depending on the variability in fretting rates. This means that the fission product levels in the coolant would increase slowly with time.

3.2.3 MECHANICAL DAMAGE

The third operational defect is mechanical damage that is due to fuelling. The events when bundles have been mechanically damaged are extremely rare and have been attributed to human error or abnormal operations. Fuel bundles have been occasionally damaged during fuelling at the Bruce and Pickering reactors. Two examples are briefly described below:

1. At Bruce A, the fuelling direction is against the flow that requires pairs of bundles to be transported to and from the fuel channel in "fuel carriers". In 1979, a fuel bundle had escaped or "washed-out" from the carrier at the upstream end of Channel P13 in Unit 1. This bundle was subsequently crushed when an empty carrier was returned to the channel to remove the next pair of bundles. The problem was corrected with a minor change to the fuelling sequence to avoid bundle washout.

2. Because of an interruption to fuelling operations at Pickering A, bundles resided for several days in the cross flow region near the liner holes of the inlet end fitting of the fuel channel. Under these conditions, the endplates broke causing a bundle to partially disassemble in the end fitting. Normal residence time in cross flow is about 2 min. On these rare occasions, bundle damage can be extensive and requires a reactor shutdown to recover broken fuel components.

3.3 SYSTEM DESIGN RELATED DEFECTS

3.3.1 STRESS CORROSION CRACKING DURING NORMAL OPERATION

In 1971-1972(7), the early operation of Pickering A Unit 2 resulted in many defects from power ramping associated with adjuster rod movements and fuelling shifts. These failures occurred before the introduction of graphite CANLUB that provides protection against SCC failure. The event at Pickering was the largest fuel defect excursion in CANDU history. The core contained over 400 defective elements.

Most of the fuel defects were discharged during the four month shutdown in 1972. The fuel bundles were moved while they were exposed to low coolant temperature and pressure. Although no fuel handling difficulties were reported, the defective bundles appeared to be badly damaged(11). The reasons for the severe damage have never been fully resolved. In particular, it is unclear whether or not the degradation took place in the reactor during full power operation or in the fuel transfer system at low temperature and pressure. However, several observations point to the latter, as suggested below:

1. Because of the high deuteride content of the cladding of the defective elements, the Zircaloy was likely brittle at the low temperatures when the fuel was removed from the core while the reactor was shutdown.

2. Most of the secondary damage was preferentially located at the upstream end of bundle #9 (high power end); and downstream end of bundle #10 (low power end). The degradation at the bundle ends is likely attributed to the high deuteride content and to the fuel handling system that handles bundles in pairs. Since these two bundles were discharged together, the damage was located at the ends that were in contact with the fuelling machine rams and side stops during transfer to the bay.

This experience along with other events involving SCC defects at Douglas Point (early 1970s) and at Pickering (1988), have shown that power ramp failures are "systematic". The defective bundles were generally had more than one defective element among the outer ring of the bundle. (See Figure 6.)

3.3.2 ENDPLATE FATIGUE

In November 1990(8), a routine fuelling operation on channel N12 of Darlington Unit 2 was aborted because of difficulties encountered while inserting a pair of fuel bundles recycled from another channel. The follow-up investigation later showed that the centre seven elements from the downstream bundle had broken loose and had interfered with normal fuelling operations. These elements had been carried past the fuel latch by the coolant flow through the channel and had obstructed other bundles from being completely inserted into the channel. The bundle was extensively damaged during the attempted fuelling operation. The damage increased the activity levels for most fission products in the primary circuit. The increased activity levels were difficult to quantify at the time since the failed fuel detection system was not fully commissioned.

Inspections of other outlet bundles in the Darlington fuel bays showed the presence of endplate cracks. The post irradiation examinations of the damaged fuel revealed that the endplate cracks were the result of high cycle-low amplitude fatigue. Prior investigations demonstrated that the 5-vane impellers of the primary circuit pumps introduced pressure pulsations that were acoustically amplified within certain fuel channels. The pulsation frequency of 150 Hz coincided with the resonant frequency of the inner seven fuel elements of the 37 element bundle. With latch support of the fuel column, which is unique to the Darlington and Bruce reactors, the non-outer fuel elements are unrestrained and are free to vibrate in the axial direction. Axial vibration at the resonant frequency led to endplate cracking.

To eliminate the acoustic amplification of the pressure pulsations in the fuel channels and to decouple the axial resonant response of the fuel, the 5-vane pump impellers were replaced with 7-vanes. This change shifted the pressure pulsation frequency from 150 to 210 Hz and eliminated the end plate cracking problem at Darlington.

4 FUEL ELEMENT OPERATING THRESHOLDS

4.1 CENTRELINE MELTING

Experimental irradiations of CANDU type fuel elements indicate that centreline melting of the element occurs at element linear powers that exceed 70 kW/m. The fuel performance codes also predict centreline melting at these linear powers for fuel elements operating under normal heat transfer conditions of a CANDU reactor. The maximum fuel element linear powers corresponding to operating bundle power envelopes (and bundle power licensing limits) for all CANDU reactors, are less than 65 kW/m. There has been no evidence of centreline melting in CANDU power reactor fuel.

4.2 STRESS CORROSION CRACKING

The power histories of fuel defects caused by SCC of the sheath have been extensively studied. Empirically derived thresholds are used to limit the ramped power and change in power that bundles can undergo during fuelling and reactor power maneuvers. These curves were empirically derived from the fuel defect experience at Pickering and Douglas Point(7) and from the experimental reactors in Chalk River(12). The fuel defect database for the power reactors includes 15 mm diameter fuel elements only. With the possible exception of the high burnup Bruce bundles, there have been no SCC failures among the 13 mm diameter sheaths of the 37-element bundle. The risk of SCC fuel failure increases if the ramped power and power increase of a fuel element exceed BOTH thresholds.

The lower set of SCC thresholds used for CANDU 6 fuel is shown in Figure 7. These curves bound the power/burnup histories of 37-element fuel that has operated under load following conditions at Bruce B, Embalse and Gentilly 2(13,14). The upper set of thresholds in this figure bounds the power histories of bundles successfully irradiated under base load conditions at Bruce A. The difference in the two sets of thresholds reflect the differences in operating power envelopes among the CANDU reactors that experienced either base load or load following conditions. It is interesting that the recent SCC fuel failures at Pickering A Unit 1 in 1988(5) operated at powers and burnups that exceeded the upper set of SCC thresholds in Figure 7.

The thresholds used for Ontario Hydro are similar. All normal operations at the CANDU stations are conducted in such a manner that the power conditions of all bundles in the core do not exceed these thresholds.

5 FUEL DESIGN BASIS FOR NORMAL AND ACCIDENT CONDITIONS

For normal operating conditions, CANDU fuel is so designed that systematic fuel failures do not normally occur. To avoid continued operation with many defects in the core, the nuclear regulator imposes reactor shutdown limits, based on fission product isotope concentrations in the coolant.

For many accidents, particularly those of moderate predicted frequency, fuel element sheath failures should not be systematic. In such transient conditions leading to high temperatures, the fuel element is considered to remain intact if the following criteria are satisfied:

a. No fuel centerline melting. A fuel element will be assumed to have failed if its centreline temperature exceeds the UO_2 melting temperature of 2840^0C;

b. No excessive strain. A fuel element will be assumed to have failed if the uniform sheath strain exceeds 5% for sheath temperatures less than 1000^0C or 2% for the temperatures higher than 1000^0C; and

c. No oxygen embrittlement. A fuel element will be assumed to have failed if its oxygen concentration exceeds 0.7 wt% over half the sheath thickness.

For other, less frequent accidents (for example, large LOCA, single channel events), some fuel element failures are permitted.

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Table 1: Fuel Defect Excursions* That Have Occurred In CANDU Reactors

YEAR	CANDU	FUEL DEFECT TYPE	Ref.
1969-72	Douglas Point	Stress Corrosion Cracking	7
1972-72	Pickering A Units1 and 2	Stress Corrosion Cracking	7
1976-77	Bruce A Unit 2	Incomplete welds, debris fretting	NA
1981	Douglas Point	Incomplete welds	NA
1984	Bruce A Unit 3	Endcap weld cracking	3, 4
1985	Pickering B Unit 5	Debris fretting due to strainer breakup	6
1984-85	Wolsong 1	Debris fretting	NA
1985	Embalse	Incomplete welds	9
1988	Pickering A Unit 1	Stress Corrosion Cracking	5
1990-92	Darlington 2	Endplate fatigue	8
1991-92	Point Lepreau	Excess Hydrogen	2, 4
1991	Wolsong 1	Debris fretting	NA

* A fuel defect excursion refers to a period of operation when many fuel elements fail because of a common cause.