FUEL CONDITION IN CANADIAN CANDU 6 REACTORS

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Abstract

The cornerstone of the CANDU concept is its natural uranium fuel, and the success of its reactor operation hinges on the fuel condition in the reactor. Neutron economy, on power refuelling, and simple fuel design are among the unique characteristics of CANDU fuel.

In Canadian CANDU 6 reactors (Gentilly 2 and Point Lepreau), the 37-element fuel has provided an enviable record of safe, economic and reliable plant operation for 29 reactor years to date. The fuelling cost is among the lowest in the world - a corollary of high neutron economy, simple fuel design, and judicial fuelling scheme. The reliability of fuel is high: only 21 of the 60000 bundles discharged from Gentilly 2 were confirmed defective and the five-year period from March 1992 to February 1997 saw no defect at all at Gentilly-2. Also, thanks to the inherent on-power refuelling capability and an effective defect detection and removal system, the primary coolant loops are kept extremely clean (very low activity level) - benefitting both maintenance and safety. Moreover, the inventories of fission products in the core and in the channel are maintained within the safety analysis envelope, due to on-power fuelling and sophisticated fuel management.

In this paper, CANDU 6 fuel performance is reviewed against the feedback from post-irradiation examinations, and the findings from our ongoing R&D program. The results suggest that the fuel behavior in reactor are basically as originally anticipated, despite an evolutionary 3% increase in bundle uranium mass in the 1980's. For operating conditions within the CANDU 6 37-element experience, the average strains are typically 0.09%; and fission gas release, 2.7%. The UO_2 fuel remains stoichiometric after irradiation. In-core measurements of pressure tube fretting are generally low. All these observations are consistent with the excellent fuel performance statistics coming out of the two Canadian CANDU 6 reactors.

Additionally, this paper will briefly discuss our experience in some situations which are not normally encountered by the fuel, such as return to full power after a long period of low power operation, response to the loss of electric power, and sustained shim-mode operation.

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1. Introduction

Over the past 15 years, Canada's two pioneer CANDU 6 reactors (Gentilly 2 and Point Lepreau), together with their two overseas contemporaries (Korea's Wolsong 1 and Argentina's Embalse) have provided a solid technical and performance base for AECL's CANDU 6 family to grow worldwide. CANDU 6 reactors are now in operation or under construction in Europe (Romania) and in Asia (Korea and China), in addition to North America and South America. The CANDU Station Performance Newsletter (Reference 1) published by CANDU Owners Group (COG) for December 1996 reported the gross capacity factors since in-service date of these four reactors as follows: Gentilly 2, 80.2%; Pt Lepreau, 88.0% (Figure 1); Wolsong 1, 84.6%; Embalse, 82.1%. A note may be in order here that in the early four years of operation, Gentilly 2 was not allowed to produce full power because of the grid surplus situation. Table 1 contains a summary of all CANDU units in the world: their gross ratings, their in-service dates, and their gross capacity factors since in-service and for the past five years (Reference 1).

The initial need for an assessment of fuel condition in CANDU 6 was occasioned by the fuel defect excursion in Darlington, which was later diagnosed as due to accoustic pressure pulsations peculiar to their pumps and the problem was resolved by installing 7-vane impellers.

On the CANDU 6 front, in response to a regulatory action, a joint study on the fuel condition was launched at AECL by Hydro-Québec and New Brunswick Power in 1995. The main conclusion of this study, completed in late 1996, suggested that fuel related problems identified by the regulatory body are not a concern for CANDU 6, and that the integrity of the fuel and fuel channels is not challenged by in-service fuel degradation. Since the CANDU 6 channels are not acoustically active, and CANDU 6 fuel strings are supported by shield plugs rather than latches, the damage mechanisms which had occured in Darlington would not be present in the CANDU 6 reactors Therefore, no severe vibration and fretting wears were observed on either the pressure tubes or the fuel, no worn-out pads or spacers, and no end plate cracking. A companion paper (Reference 2) for this conference will feature a historical perspective on post-irradiation examinations (PIE) of CANDU power reactor fuel sheath strain and fission gas release, based on this joint study.

The motivation of this paper is to present a general assessment of the fuel condition in these two Canadian CANDU 6 reactors, with focus on normal operations and potential impact on safety assessments. More specifically, this paper will make an attempt to link fuel design and performance to reactor safety concerns.

The presentation will begin with a brief review of fuel performance in Canadian CANDU 6 reactors, with special reference to current heavy uranium mass bundles. This will be followed by a general treatment of relevant post-irradiation examinations, current operating practices, safety considerations, fuel operating flexibility, as well as COG R&D program of special interest to CANDU 6 fuel. Finally, a discussion section will be devoted to the main findings, before the conclusions are drawn for this paper.

It is worth mentioning at the outset that because of the principal author's deep involvement and easy access, Gentilly 2 infomation and experience will be largely called upon for presentation of the argument.

2. Fuel Conditions

2.1 Performance

Normal Operation

High performance fuel has been the cornerstone of CANDU 6's enviable record of safe, economic and reliable operation. The defect rates in the two Canadian reactors have been very low. Of about 60 000 bundles which have been irradiated in Gentilly 2 to this date, only 21 bundles are found defective, for a defect rate of 0.035% on bundle basis, or 0.001% on element basis. Most of these few defects occurred in the early two years of operation (Reference 3). In a five-year period (March, 1992 to February 1997), Gentilly 2 was operating at high capacity practically defect free (Figure 2). At Pt Lepreau, the number of defects is slightly higher because of the 20-bundle defect excursion in 1991/92 which resulted from the residual hydrogen left in the fuel elements due to under-curing of CANLUB coating during manufacture (Reference 4).

Common to the two reactors, the known defects have been attributed to manufacturing faults or debris fretting (Figure 3). There have not been any defects attributable to sheath stress-corrosion-crack (SCC) associated with power ramps.

The average bundle exit burnup has been around 180 MWh/kg U since 1986. This is achieved through: upgrading of heavy water, decrease of excess reactivity, increase in uranium contents in fuel, and judicious fuelling scheme.

In the final analysis, the excellent fuel performance has been made possible by a combination of sound design, quality fabrication, strong R&D support, prudent reactor operation, and rapid response from industry to prevent problem escalation: a genuine industry effort and achievement.

High Uranium Mass Bundle

The excellent fuel performance record also speaks eloquently for the current high uranium mass fuel. Here, high uranium mass (19.2 to 19.3 kg U per bundle) is a relative term, relative to the slightly lower mass fuel produced in the early 1980's (18.7 kg U). Because of improved manufacture process and better economics (mainly, cost and burnup), the 37-element bundles, manufactured since1986/87, contain about 3% higher uranium mass; yet, they are all within the specified limits for internal dimensions.

Higher mass comes mainly from higher density of the UO_2 pellets. It was expected, in our previous internal analysis, that higher density would result in higher thermal conductivity, lower UO_2 temperatures and fission gas releases, thus outweighing the minimal adverse effect of reduced porosity and increased sheath strain.

Ten years (or many many thousands of defect-free heavy bundles) later today, in retrospect, the high performance of the heavy fuel might have also benefitted from the CANDU 6 8-bundle refuelling scheme which requires all fresh bundles to travel past the highest flux region before returning to their normal in-reactor positions (Figure 4). This in essence is equivalent to an early preconditioning of the fresh fuel for improved tolerance to later power ramps: the benefit of which has long been postulated (Reference 5). Within limits, the small difference in dimension due to higher mass might have been "benignly" absorbed by the initial "high-power" fuel expansion. It is not surprising that only a weak correlation (Reference 6) was found between the content of uranium and the fuel sheath strain and the database for CANDU 6 offered no evidence to suggest that fuel performance was adversely affected by the increase in uranium mass to 19.3 kg .

2.2 Post Irradiation Examination

Dimensional stability, the key to reliable and safe fuel operation in reactor, is usually confirmed by post-irradiation examinations (PIE) in AECL's hot cells under the auspices of COG or utilities directly involved. As reported in Reference 2, review of all available PIE data obtained over the past 20 years indicates that the 37-element fuel's sheath strain, and fission gas releases were generally mild and small under operating conditions applicable to CANDU 6. For typical Gentilly 2 and Pt Lepreau conditions, the average tensile sheath strains on the outer elements remained at about 0.09%, while the intermediate and inner elements saw small compressive strains only. It was noted that higher strains in the data bank were always associated with higher power rating and/or higher burnup that were beyond the normal range of Gentilly 2 and Pt Lepreau. Meanwhile, the distributions of fission gas releases averaged about 2.7% for outer elements, 0.2% for intermediate elements and 0.2% for inner elements. Severe wear of spacers was observed only on fuel discharged from reactors having acoustically active channels. As noted earlier, the CANDU 6 reactors are not acoustically active.

The inference from CANDU 6 operation is : there is no large sheath strains or severe inter-element spacer wear that would lead to significant coolant subchannel area reduction and element bowing. Thus, CHF should not have been affected to any great extent. The maximum measured outward bow for acoustically inactive channels in Darlington, according to the review, is about 0.3 mm. Gentilly 2 and Pt Lepreau channels are acoutically inactive. The absence of end plate cracking and severe fretting wear on inspected Pt Lepreau bundles also corroborates our belief that resonant acoustic vibrations, if present, must be negligible in both reactors. It should be noted that Gentilly-2 and Pt Lepreau have 7- and 5-vane implellers and have different acoustic driving frequencies.

2.3 Fuel Failure Detection

Equipped with an effective system to detect, locate and remove fuel defects, CANDU 6 operators are able to remove defective fuel as early as optimally possible. The fuel status of the core is continuously monitored by the failed fuel detection system, commonly referred to as the Gaseous Fission Product (GFP) system. It provides the first indication of defect in either of the two HTS loops. Coolant samples are analyzed at the chemistry laboratory daily. The failed fuel location system, referred to as Delayed Neutron (DN) system, helps pin down which bundle pair contains the defect by measuring the delayed neutrons emitted from sample lines attached to the outlet feeder of each channel. The Gentilly-2 experience suggests that Xe-133 is the most reliable indicator for onset of a defect; Kr-88, for indicating deterioration of sheath; I-134, for uranium release; I-131, as monitor for public safety; and Xe-135, for information about iodine release when the purification system is operational.

To keep the loop activity low for operational safety and for accidents such as iodine spiking coinciding with a small LOCA, Gentilly 2 has kept activity levels well below the target values. Take I-131 for example, the target level is <10 μci/kg D_20, as compared to 13500 μCi/kg D_20 for shutdown limit. The actual I-131 level, as shown in Figure 4 with other isotopes (Xe-135, Xe-133, and Kr-88), was maintained below 2 μCi/kg D_2O for four consecutive years, the period covered by the plot. From coolant activity viewpoint, this is a clean heat transport system for both daily operation and maintenance as well as for any eventuality of accident. The radioactive release to the public has been maintained well below 1% (i.e. 0.05 mSv) of the limits stipulated in the Canadian standard, i.e. 5 millisieverts (mSv) per year (Table 2). In CANDU 6, normal operation has ensured favorable initial conditions in case any postulated accident transient occurs.

3. Safety Considerations

In any postulated accident, evolution of the event and hence the consequence will start from the intitial condition of the fuel in the reactor. In practical terms, this initial conditon is reflected by the sheath and UO_2 temperatures and deformations, fission gas release, UO_2 stoichiometry, radionuclide distribution in the element, and whether there is any defected fuel already in existence; all these combine to impact on the source term. The ability to detect and remove defective fuel helps to ensure that coolant fission product inventories are low, and that the consequence of defective fuel in accidents is minimal. Based on the excellent performance of the fuel in normal operation in terms of the number of defects and the PIE results on sheath strain and fission gas release, there is no evidence to suggest that the intitial condition is not equal or better than that originally anticipated. The strict enforcement of restrictions on bundle and channel powers, as discussed later, further lends support to our view in this regard.

Insofar as initial conditions for CANDU 6 are concerned, our safety analyses have been based on maximum bundle power of 935 kW and maximum channel power of 7.3 MW. To account for uncertainties involved in the calculation of reactor power, Gentilly-2 introduced in 1996 stricter operating targets of 882 kW and 6.95 MW (for high power channels), respectively. The record for the year of 1996 showed that the target for maximum bundle power was met throughout the year, while the maximum channel power of 6.95 MW was exceeded three times, each resulting in an imposed reduction of reactor power until the operating target was again met. These statistics demonstrate that the fuel has been operated strictly within their analyzed limits.

To ensure that the source term is within the boundaries of the safety analyses, calculations were done for the total core fission product inventories and the quarter core free inventories. The results indicated that the maximum gap inventory for the quarter core from the postulated failed elements based on actual power and burnup histories was within the safety analysis release value (Reference 7).

To check against very unlikely event of flow blockage in the channel, monthly verification is made of all channel outlet temperatures at 80% full power. Also, routine check of channel pressure drop is done during refuelling to provide early warning against any unlikely intrusion of foreign matter when the channel is open to the fuelling machines.

4. OPERATION FLEXIBILITY

Low Power Operation

During the first four years of Gentilly operation (1983 to 1987), an over-capacity existed in Hydro-Québec's power system and Gentilly-2 was operated at only 50% of its rated capacity over long periods of time. There was concern that each return to full power would entail some fuel failures. Mainly through prudently managing power rise from low power, Gentilly 2 went through several high-low-high cycles without any fuel failure (Reference 3).

Loss of Class IV Power

Prior to 1995, Gentilly-2 had experienced several loss of Class IV power events; none of which had resulted in any significant power transient. In September 1995, an overpower trasient due to loss of electric power occurred where all four PHT pumps tripped simultaneously at full power, with the coincident loss of liquid zone system pumps. The station was automatically shut down within two seconds by Shutdown System No 1 (SDS 1). Subsequent analysis (Reference 8) placed maximun overpower at 10 % (well below the safety analysis value of 24%) in a period of 1.6 second. There were no reported fuel failures in this worst-ever loss of electrical power excursion.

Shim Mode

One unique CANDU feature which is not well publicized but deserves credit is "shim" operation (Reference 9). Shim capability permits continued reactor operation near full power or at substantially reduced power, depending on the duration of the fuelling machine unavailability. The process involves using the adjusters to add or remove small amounts of reactivity. The local power perturbations caused by adjusters' withdrawal must not cause systematic fuel failures. Shim operation was necessary on two occasions at Gentilly. The first lasted about ten days in late 1989, with reactor power down to 87%. The second lasted four months starting in February 1990. During this period, reactor operation continued at various power levels, including a five bank shim operation for two months at 50% power. In view of the relatively high burnup of the fuel in the core, some consideration was given to the rate of power rise when Gentilly-2 was returned to full capacity following the sustained shim operation. No fuel defects occurred during adjuster removal, or during the return to full power in June 1990.

5. Research and Development

Hydro-Quebec and New Brunswick Power, together with Ontario Hydro and AECL, are founding members of COG. Like all other reactors in Canada, Gentilly 2 and Pt Lepreau operations are supported by COG ongoing R&D for better understanding of system and material behavior, and for resolving safety concerns and issues. In the area of fuel, under the Fuel Technology program (Working Party 9), COG sponsors studies aimed at improving the reliability, economics and safety of CANDU fuel (Reference 10). More specifically, the fuel programs under COG range from correlating fundamental properties to fuel performance, reviewing fuel specification (Referece 11), to pursuing applied research into fuel operating limits and root causes of defects. Among the topics undertaken by COG R&D, the following are of particular interest to current CANDU 6:

- As an industry effort to gain better knowledge in reactor aging effect on fuel behaviour, two Gentilly 2 bundles discharged from its highest crept channel (P 16) will be shipped to Chalk River this year for post irradiation examinations in the hot cells next year.

- Special bundles built to different UO_2 densities, to lower specified limits of internal clearances or built with alternate elements without standard CANLUB treatment, have been irradiated without any incident at Pt Lepreau. Some bundles have already been shipped to Chalk River for PIE. The results are expected to shed some light on fuel tolerance to internal manufacturing variations.

- There was concern expressed that as fuel increases in burnup, fission liberated oxygen may turn UO_2 into hyperstoicheometric UO_{2+x} thereby degrading its thermal conductivity, increasing fuel temperatures and accelerating fission product diffusion. Recent studies at CRL indicate that, even though the CANLUB coating may have prevented the sheath from gettering oxygen, one of the fission products, molybdenum, binds oxygen into MoO_3, acting as an oxygen buffer in the fuel. Therefore, UO_2 remains near stoichiometric for current normal burnups; and the concern over fuel operating at higher temperature due to fuel oxidation has not been borne out by experimental evidence.

- Fuel bowing has received considerable attention since badly worn-out spacers permitting large element bow were observed on fuel discharged from reactors having acoustically active channels. Experimental bowing investigations were launched by COG at three laboratories: Whiteshell, Stern, and Chalk River. The Whiteshell experiments, using helium gas as cooling medium, involved single fuel element simulator (FES) heated on one side to 600° C and 300° C on the other. The results showed that circumferential temperature distribution, pellet/sheath interaction, and creep were the three major factors affecting transient and permanent bows. The Stern program, still in Phase 1 of three Phases, had similar temperature gradient, but consisted of a trefoil arrangement and with more reactor representative thermalhydraulic conditions in steam. The Stern experiments may eventually arrive at a well-defined threshold of element bow above which CHF and post dryout characteristics would become seriously affected. It is worth pointing out again that severe spacer wear observed on Darlington fuel has been eliminated and CANDU 6 has not seen any severe spacer wears on their discharged fuel. CRL tests, conducted in Freon-134a with an element of the 37-element bundle mechanically bowed towards the pressure tube showed very small effect on CHF. A moderate 3% decrease in dryout power occurred as the gap size was reduced from nominal (1.07mm) to about 40%. These three programs are each represented by a paper presented at this conference (References 12, 13, and14).

- As part of the experimental program investigating fuel damages at Darlington and Bruce due to coolant pressure pulsation, a series of tests were done by COG at Stern Laboratories, comparing fuel string resonance characteristics and amplitudes of CANDU 6 fuel with those of Bruce type fuel. The results (Reference 15) indicate that the response of the CANDU 6 end plate displacement to the pressure pulse at the shield plug ring, over a wide range of frequency (15 to 270 Hz), was substantially less; static deflection of the end plate was 50% less, and the pressure pulse amplitudes were generally lower.

- Ethyl cellulose left in CANLUB after baking appears to be the ingredient immobilizing the corrosive species and preventing SCC. Baking at too high a temperature would drive off this ingredient, leaving the sheath vulnerable to iodine attack. Baking at too low temperatures could lead to residual hydrogen in the sheath.

- There are two completed COG programs which promise some long-term benefit to fuel economics or channel performance. These are thin-wall fuel (Reference 16) and improved "T-type" bearing pad (Refernce 17).

6. DISCUSSION

- The theme of our last international conference on CANDU fuel, according to the summary published in the CNS bulletin (Reference 18), was that CANDU fuel is safe, reliable and economic. In reviewing the normal operation, the departures from normal operations (sustained low power operation and shim mode) as well as the operational transients (such as power excursion due to loss of Class IV) experienced over the years, we find the fuel not only safe, economic and reliable, but also flexible: flexible in the sense it has coped with such unusual situations with considerable tolerance and resilience.

- A word about economics. CANDU is known for its low fuelling cost. This is obvious because of high neutron economy, high resource utilization, simple fuel design, low fabrication cost and on-power fuelling. However, we have to enrich the water (to D_2O) as a one-time capital cost, while LWR needs enriched uranium throughout the reactor life: both enrichments are expensive undertakings. Meanwhile, using slightly enriched (1.2%) fuel in CANDU reactors would provide potential for further reduction (29%) in uranium consumption and in fuelling cost (Reference 19). As a result, the total unit energy is a trade-off between the two enrichments. A comparison of CANDU (natural uranium) vs PWR fuelling costs and trade-off was made in 1980 (Reference 20). The world economic situation has changed tremendously since. A more recent study of fuel cycle economics by the OECD/NEA show that CANDU fuelling costs are about half those of PWR fuel (Reference 21). Because of good neutron economy, enrichment in CANDU can further reduce CANDU fuelling costs by 20-30% compared to natural uranium (Reference 22). For this presentation, fuelling cost has not been estimated because of commercial proprietary restrictions. In an open literature (Reference 23), however, it was reported that in 1993 the unit energy cost for Gentilly-2 was 5.3 ¢/kWh, broken down as follows:

Operating, maintenance and decommissioning** cost:	2.2 ¢/kWh
Depreciation costs, interest and taxes	3.1 ¢/kWh

** funds set aside for dismantling the station and for disposal of spent fuel

- A caveat about fuel performance. The excellent fuel record reported in the foregoing has been intimately associated with the normal range of power rating and burnup for the CANDU 6 fuel. The average discharge burnup is about 180 MWh/kgU; and the maximum burnup recorded in the Gentilly 2 history was 382 MWh/kg U. It has been reported (Reference 24) that bundles with higher burnup (> 500 MWh/kgU) and high power have shown sheath strains and fission gas releases that are higher than would be expected for natural uranium burnups. Even though this 500 MWh/kg U is far above the normal range of CANDU 6, it is nevertheless important to point out that the high performance of CANDU 6 fuel owes a great deal to reactor operations which respect the range and limitations of the fuel. Continued vigilance in daily operation is always in order.

- From safety point of view, CANDU fuel in general has several inherent advantages over other reactor fuels. The fuel temperatures, for the same rating, are lower because of thin, collapsible sheath and high density UO_2. On-power fuelling permits operation with minimum excess reactivity and with an essentially constant power shape. Due to the lower burnups, the total fission product inventory is somewhat less for CANDU reactors. The prompt neutron lifetime is longer and the delayed neutron fraction is high: hence the power pulse is less severe in a large LOCA and spontaneous fuel breakup is not a safety concern (Reference 25). UO_2 dissolution in molten zircaloy in high temperature transient (in the 2000° C range) is smaller because of the higher UO_2/Zr mass ratio (Reference 26). The UO_2 volume expansion associated with fuel frothing in a severe accident would be lower in the low burnup CANDU fuel due to the lower gas quantity generated in the fuel matrix (Reference 27). Detailed listing and comparison is beyond the scope of this paper.

- In reviewing the fuel condition in the two Canadian CANDU 6 reactors, it has become obvious that because of geographical proximity and effective feedback and exchange among the operators, the fabricators, the designers, the inspectors, the analysts, and the researchers from various organizations, a process is in place whereby any fuel-related problem or safety concern occurring in Canada can be monitored, reviewed, tested and resolved in an efficient and effective manner.

7. CONCLUSIONS

From a brief review of fuel condition in the CANDU 6 reactors, the following conclusions can be drawn:

- The current heavy uranium mass, 37-element fuel has demonstrated high reliability in Canadian CANDU 6 reactors: defect free for five consecutive years in Gentilly 2. Fuel defect rate since inception has been very low (0.035% at Gentilly-2); heat transport system is clean, public release is well within 1% of the allowable dose limit. Fuel design has proved to be robust and resilient to operational transients.

- CANDU 6 fuel has maintained a high degree of dimensional stability, partly due to absence of pulsating flow in the heat transport system; partly due to support of fuel string by shield plugs. As a result, the interaction with pressure tube and the effect on CHF due to strain or wear are held to a minimum.

- Fuel condition in Canadian CANDU 6 has been enhanced by carefully observing bundle and channel power limits and operating within the normal burnup range. The excellent CANDU 6 performance should be attributed to the combination of sound design, quality fabrication, strong COG R&D support, and prudent reactor operation: a genuine industry collaboration and achievement.

- There is a process in place where fuel condition is closely monitored, fuel inspected, performance feedback analyzed, root cause of defect determined, corrective actions taken, irradiated bundles selected for post-irradiation examination, fundamental properties studied, and safety impact of fuel behavior evaluated. It is recognized that this is a dynamic feedback process; further review may identify a few links in the chain which require some strengthening.

- There are four keywords to characterize CANDU 6 fuel operation: safe, reliable, economical, and flexible.

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REFERENCES

1. CANDU Owners Group, "CANDU Station Performance Newsletter", November/December 1996 issue.

2. Purdy, P.L., Manzer, A.M., Hu, R.H., Gibb, R.A., and Kohn, E. "Assessments of Sheath Strain and Fission Gas Release Data from 20 Years of Power Reactor Fuel Irradiations", Paper presented at the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

3. Hu, R.H., Cloutier, L., Macici, N., and Aubin, D. "Gentilly 2 Fuel Performance" Paper presented at the Annual CNS Conference, Ottawa, 1985.

4. Manzer, A.M., Sejnoha, R., Steed, R.G., Whynot, T., Graham, N.A., Barr, A.P., and Carter, T.J. "Fuel Defect Investigation at Point Lepreau" Paper presented at the Third International Conference on CANDU Fuel, Chalk River, 1992 Oct 4-8.

5. Hu, R.H., "Further Analysis of Possible Fuel Failures in the Proposed Gentilly-2 Near Term Operation", Hydro-Québec, 1983 December 14.

6. Palleck, S.J., and Sejnoha, R. "Uranium Content and Defect Thresholds of CANDU Fuel", Paper presented to the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

7. Beaudet, M. "Historique de 0 a 1977 JEPP des inventrires de produits de fission a Gentilly 2, en configuration normale", G2-RT-90-12, 1997-05-20.

8. Baudouin, A, Nguyen, C.H., Hotte, G., Harvel, G.D., Shad, M., and Soulard, M. "Gentilly 2 Overpower Transient initiated by a Loss of Electric Power", Paper presented to the Fifthe International Conference on Simulation Methods in Nuclear Engineering, CNS, Montreal, Sept 8-11, 1996.

9. Manzer, A.M., Dennier, D., Hu, R.H., and Young, E.G. "CANDU 6 Reactor Shim Operation: Fuel Performance Guidelines", Paper presented to the CNS Conference 1991.

10. Lau, J.H., Kohn, E., Sejnoha, R., Cox, D.S., Macici, N., Steed, R.G. "Canadian Fuel Development Program in 1997/98", Paper presented at the 5th Internationbal Fuel Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

11. Sejnoha, R. "Technical Specifications and Performance of CANDU Fuel", Paper presented to the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

12. Mathew, M. "Quantifying the Main Factors governing Thermal Bow of Fuel Element Simulator" Paper presented to the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

13. Kohn, E., Hu, R.H., Hadaller, G.I. and Fortman, R.A. "Understanding CANDU Fuel Bowing in Dlryout: An Industry Approach", Paper presented to the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

14. Sutradhar, S.C., and Schank, J.R., "The effect of Element Bow on Dryout Power and PDO Heat Transfer in CANDU Fuel Bundles", Paper presented at the 5th International Conference on CANDU Fuel, Toronto, Sept 21-25, 1997.

15. Sandig, P.F., Hadaller, G.I. "Effect of Pressure Pulsations on CANDU-6 Fuel", COG-96-250, Stern Laboratories Inc. Investigative Test SL-079, May 1996.

16. Tang, T.L. and Hu, R.H. "Gentilly-2 Type Standard and Thin-Wall Fuel Element Behavior during Large LOCA (Using ELESIM/ELOCA), paper presented at the 10th Simulation Symposium on Reactor Dynamics and Plant Control, St. John, N.B. 1984 April 8-10.

17. Sejnoha, R., Oldaker, I.E., Lim, D., Archinoff, G.H., Gacesa, M., and Hu, R.H. "Elimination of Crevice Corrosion of Pressure Tubes in CANDU Reactors", Paper presented to the 5th Annual CNS Conference, Saskotoon, 1984 June 4-5.

18. Canadian Nuclear Society, "4th International Conference on CANDU Fuel", Canadian Nuclear Society Bulletin, Vol. 16, No.3, Autumn 1995.

19. Hu, R.H., "Economic Feasibility of Utilizing Slightly Enriched Fuel in CANDU Reactors", Paper presented at the 18th Annual International Conference of Canadian Nuclear Association, Ottawa, June 11-14, 1978.

20. Hu, R.H. and Tang, T.L."A Comparison of CANDU and PWR Fuelling Costs", Paper presented at CNS Annual Conference, Montreal, 1980 June 18.

21. OECD/NEA, "The Economics of the Nuclear Fuel Cycle", 1994.

22. Boczar, P.G., Fehrenbach, P.J., and Meneley, D.A., "CANDU Fuel Cycle Development Potential", Paper presented at Fifth International Topical Meeting on Nuclear Thermal Hydraulics, Operations, and Safety (NUTHOS-5), Beijing, China, 1997 April 14-18.

23. Hydro-Quebec, "Overview of Gentilly-2 Nuclear Generating Station", ISBN 2-550-31086-2, Legal Deposit - 4th quarter 1996.

24. Floyd, M.R., Chenier, R.J., Leach, D.A., O'Brien, D., Moeller, R.E. and Elder, R.R. "Behavior of Bruce NGS-A Fuel Irradiated to a Burnup of 500 MWh/kg U" Paper presented to the Third International Conference on CANDU Fuel, Pembroke, Canada, 1992 October 4-8.

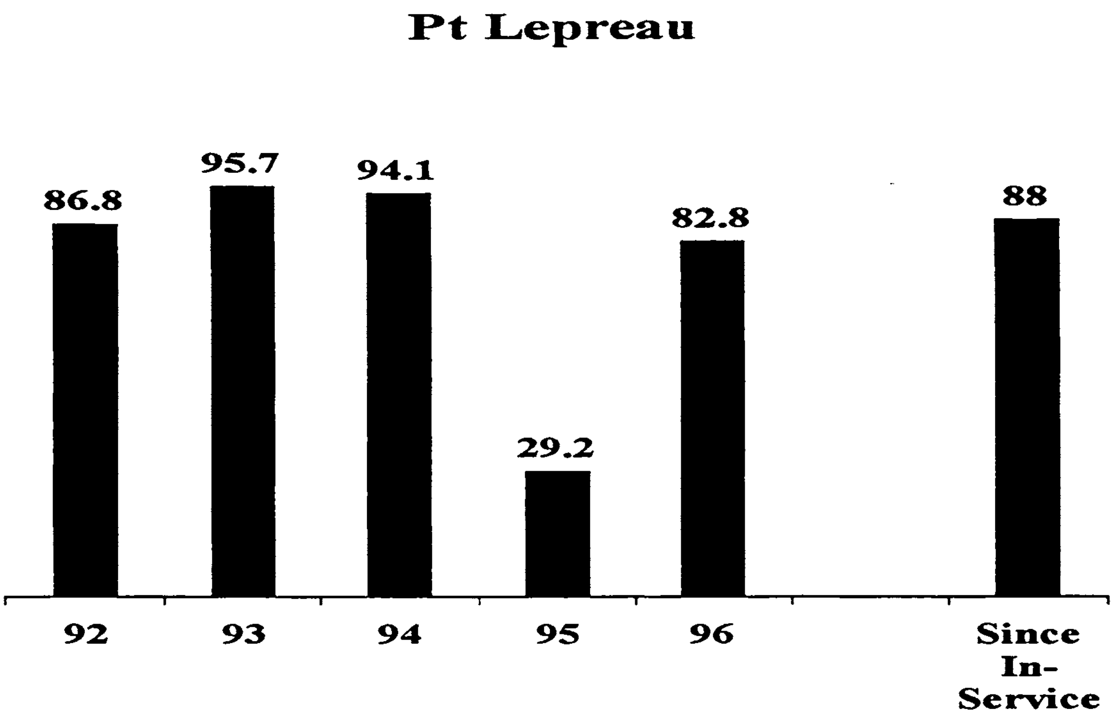
25. Kugler, G. "Distinctive Safety Aspects of the CANDU-PHW Reactor Design", AECL Report 6789, 1980 January.

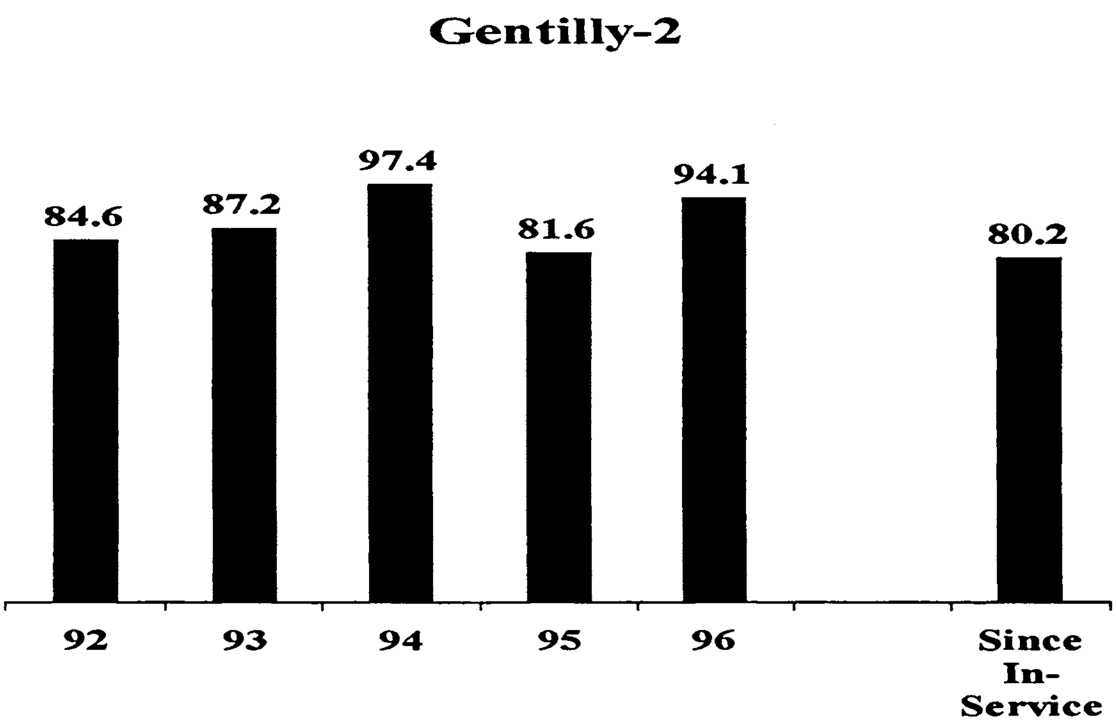
26. Hayward, P.J. and George, I.M. "Dissolution of UO_2 in Molten Zircaloy-4, Part 3: Solubility from 2000 to 2500° C", J. Nuclear Materials, 232 (1996) 1-12.

27. Iglesias, F.C., Brito, A.C., Liu, Y., Petrilli, M.A., Hu, R.H, Richards, M.J., Gibb, R.A., Reid, P.J., Elder, P., Cox, D.S., and Lewis, B.J. "Fission Product Release Mechanisms and

Groupings" Paper presented to the 4th International Conference on CANDU Fuel, Pembroke, Ontario, 1995 October 1-4.

Figure 1 Gross Capacity





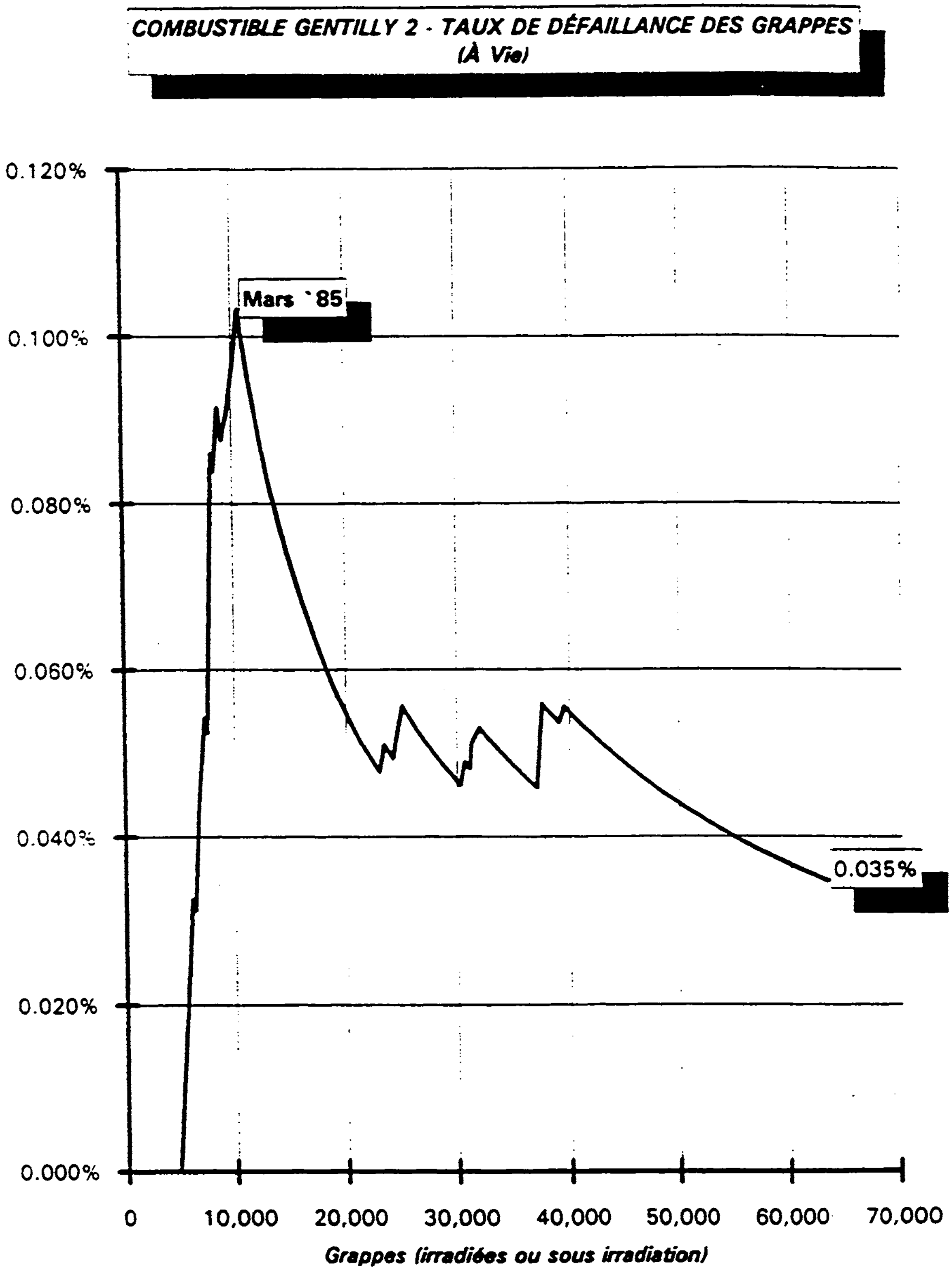
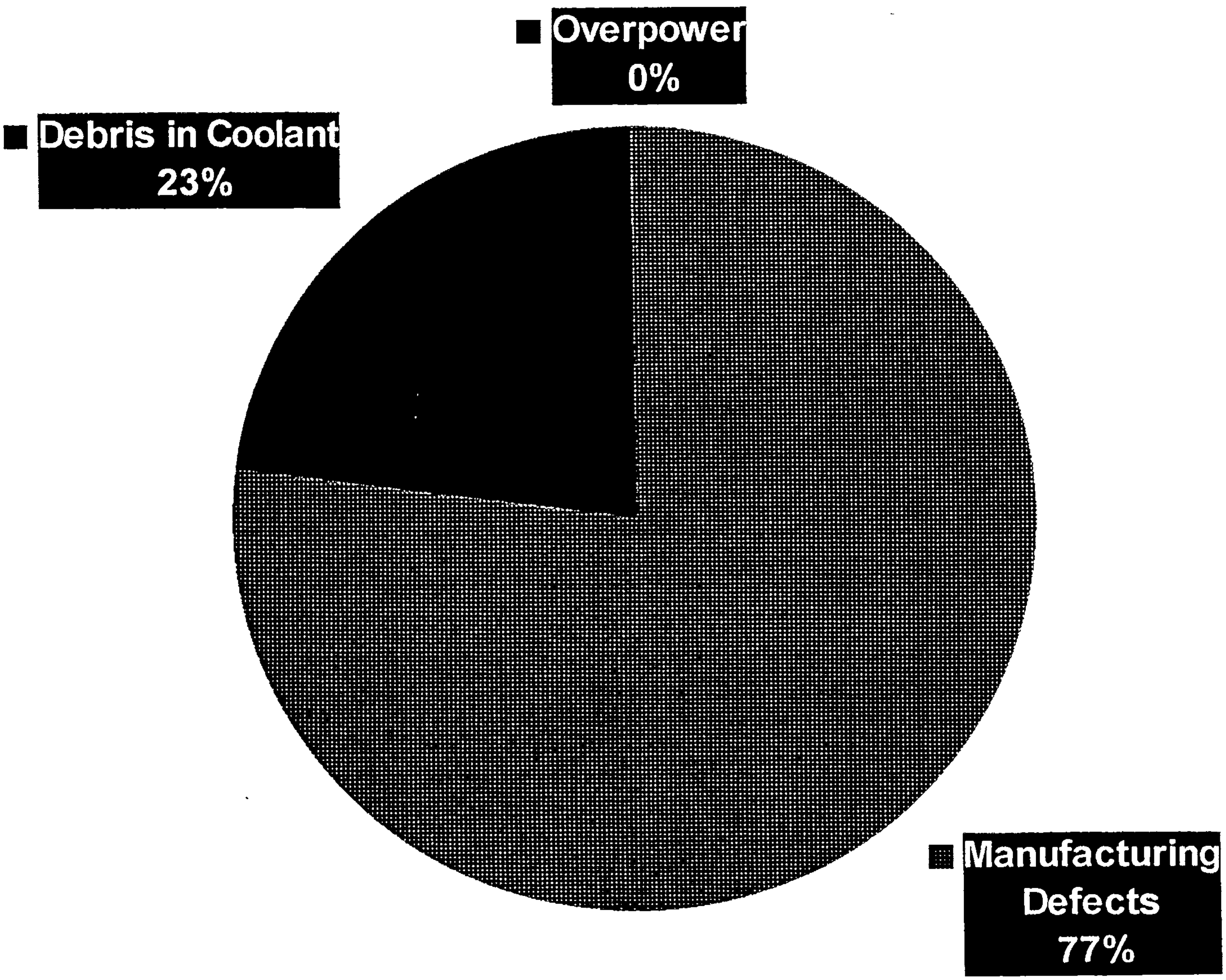


Figure 2 Gentilly-2 Fuel Defect Statistics

Source: Gentilly 2 Bilan Technique 1996: Indicateurs de performance

Figure 3 Gentilly-2 Fuel Defect Causes

Source: Gentilly-2 Bilan Technique 1996: Indicateurs de performance



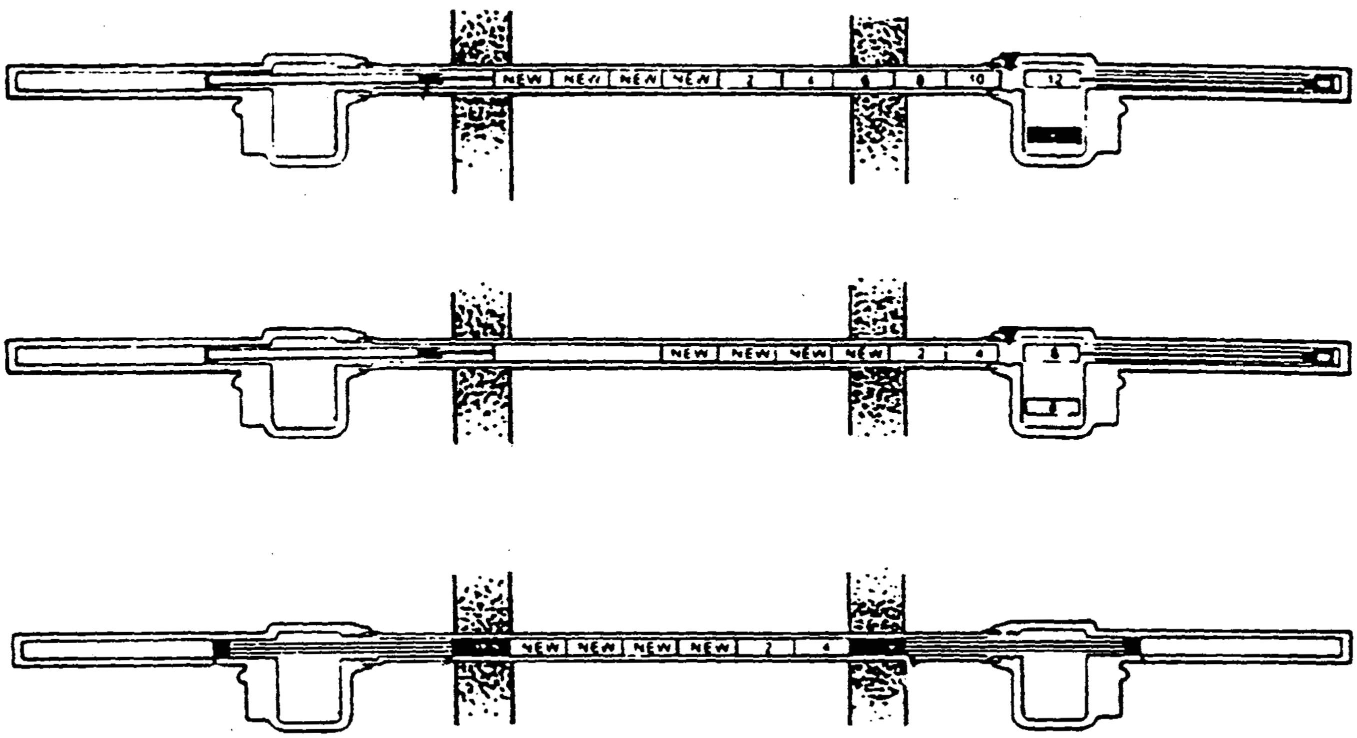
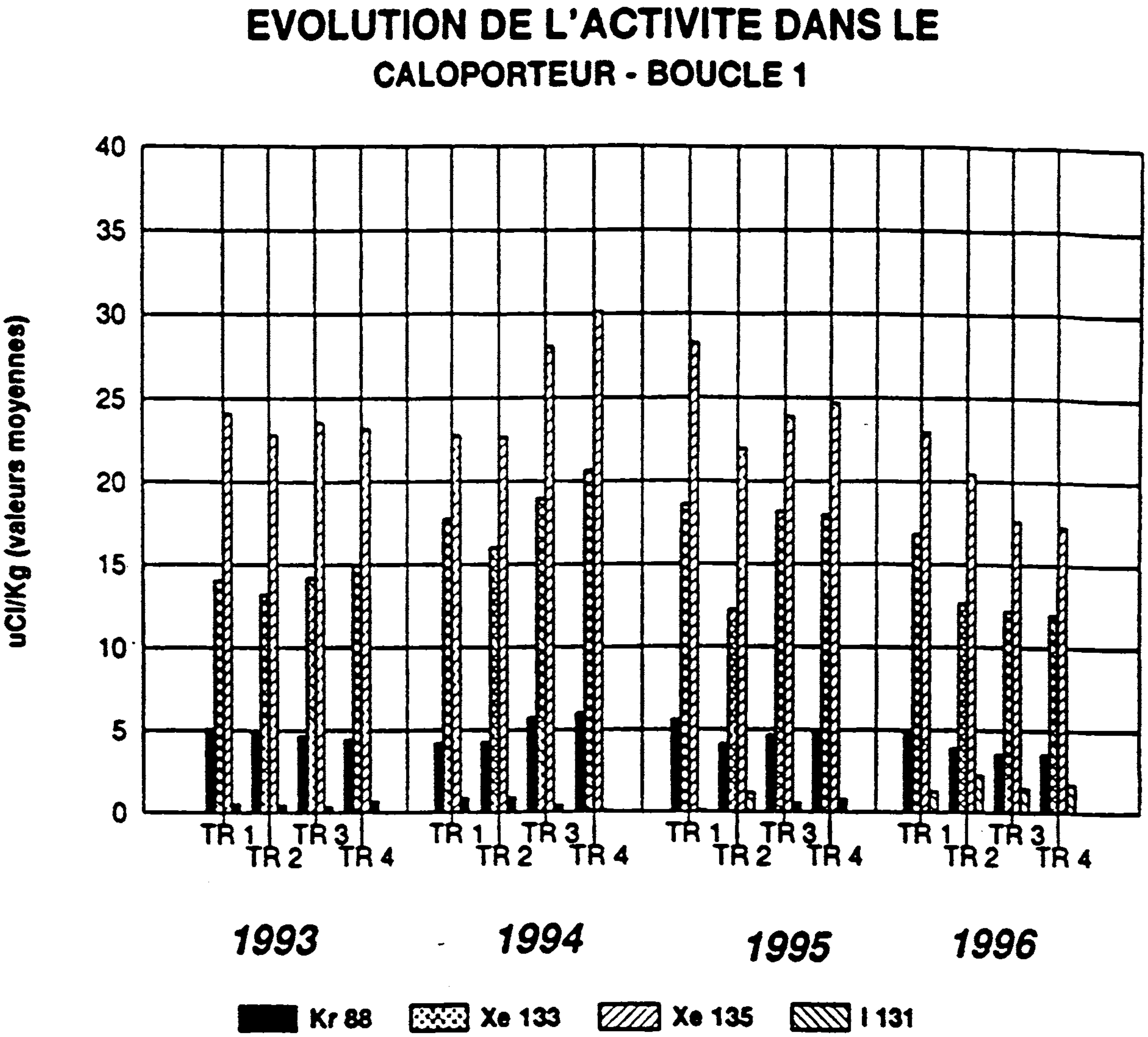


Figure 4 Fuel Changing at Gentilly-2 (Final Steps)



1. Objectif 1996: Garder l'activité des produits de fission à des valeurs cibles basses, au-dessous des seuils d'alarme.

	Valeur cible
I 131	< 10uCI/Kg
Xe 135	< 100 uCI/Kg
Xe 133	< 80 uCI/Kg
Kr 88	< 20 uCI/Kg

Figure 5 Evolution of Activity in Gentilly-2 Coolant Loop # 1

Source: Gentilly 2 Bilan Technique 1996: Indicateurs de performance

Table 1

SUMMARY OF CANDU UNITS TO 1996 DECEMBER 31

Unit	Gross Rating Electrical MWe	Gross Rating Electrical + Steam MWe	In-Service Date	Gross Capacity Factor Since In-Service %	Since In-Service EFPD*	1996 %	1995 %	1994 %	1993 %	1992 %
Pt.Lepreau	680		83 Feb 01	88.0	4475	82.8	29.2	94.1	95.7	86.8
Gentilly-2	675(1)		83 Oct 01	80.2	3884	94.1	81.6	97.4	87.2	84.6
Wolsong-1	678.68		83 Apr 22	84.6	4234	81.0	83.7	82.6	100.8	86.8
Embalse	648		84 Jan 20	82.1	3882	92.6	74.3	97.7	90.4	82.6
Cernavoda-1	708		96 Dec 02	100	30	100**				
Pickering-1	542		71 Jul 29	62.3	5787	67.0	44.8	20.0	76.7	64.7
Pickering-2	542		71 Dec 30	60.1	5489	29.1	0	86.6	95.0	90.8
Pickering-3	542		72 Jun 01	69.3	6223	24.4	60.0	91.5	75.9	89.8
Pickering-4	542		73 Jun 17	69.6	5982	25.1	61.9	88.9	73.6	0
Pickering-5	540		83 May 10	76.3	3802	68.0	75.5	68.7	86.2	29.9
Pickering-6	540		84 Feb 01	82.0	3867	57.6	78.0	90.2	60.1	90.2
Pickering-7	540		85 Jan 01	84.3	3697	45.8	90.5	82.7	98.5	83.0
Pickering-8	540		86 Feb 28	83.1	3290	28.9	89.5	96.8	81.7	93.5
Bruce-1***	825	904	77 Sep 01	67.4	4821	59.1	48.3	53.0	46.9	62.0
Bruce-2***	825	904	77 Sep 01	60.2	4047	(2)	67.5	53.4	41.8	4.8
Bruce-3***	825	904	78 Feb 01	72.6	5065	45.3	57.8	37.6	43.8	77.9
Bruce-4***	825	904	79 Jan 18	70.5	4662	72.2	41.5	50.6	4.7	78.9
Bruce-5	915		85 Mar 01	82.8	3581	75.0	81.5	75.1	68.8	85.5
Bruce-6	915		84 Sep 14	80.5	3618	90.5	62.2	86.3	58.8	70.4
Bruce-7	915		86 Apr 10	81.4	3189	72.7	83.6	73.7	78.1	85.0
Bruce-8	915		87 May 22	81.6	2865	92.2	81.4	86.4	63.0	72.3
Darlington-1	935		92 Nov 14	81.8	1235	74.8	89.4	82.5	78.7	96.7**
Darlington-2	935		90 Oct 09	61.5	1399	87.2	90.7	88.2	83.3	17.5
Darlington-3	935		93 Feb 14	90.7	1286	96.2	92.2	85.2	89.2**	
Darlington-4	935		93 Jun 14	84.2	1092	79.3	88.0	91.8	72.3**	
RAPS-1***	100		73 Dec 16	22.6	1898	0	0	0.9	24.7	9.4
RAPS-2***	200		81 Apr 01	59.7	3111	0	0	33.1	73.1	55.5
MAPS-1	170		84 Oct 27	49.6	2361	47.1	5	47.7	31.9	63.8
MAPS-2	170		86 Mar 03	48.9	1994	81.0	20.9	60.1	56.5	39.4
NAPS-1	220		91 Jan 01	36.0	943	67.4	55.4	0	19.9	45.7
NAPS-2	220		92 Jul 01	48.3	852	71.5	60.7	46.3	10.3	66.7**
KAPS-1	220		93 May 06	46.9	688	77.1	56.5	8.7	44.3**	
KAPS-2	220		95 Sep 01	75.8	466	77.6	70.3**			
KANUPP	137		72 Nov 28	28.6	2520	29.4	43.6	48.8	33.9	45.8

Notes:
- * Equivalent Full Power Days
- ** Gross Capacity Factor for the year since in-service date
- *** Gross Capacity Factor is for electricity + steam production
- (1) Gross Rating of Gentilly-2 revised from 685 to 675 MWe, retroactive to in-service date
- (2) Bruce-2 taken out of service indefinitely on 1995 October 8

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Source: CANDU Station Performance Newsletter (December 1996), published by COG

Table 2 Average Radiation Doses From Gentilly-2 Releases

1983	0.0045 mSv
1984	0.0022
1985	0.0105
1986	0.0061
1987	0.0067
1988	0.0073
1989	0.0069
1990	0.0077
1991	0.0095
1992	0.0185
1993	0.0171
1994	0.0128
1995	0.0175
1996	0.0172
1% of Max Allowable	0.0500 mSv
Max Allowable	5.0000 mSv