A 61-ELEMENT FUEL DESIGN (HAC) FOR VERY HIGH BURNUPS

M. TAYAL*, J.W. LOVE*, D. DENNIER*, M. GACESA*, S. SATO**, J. MACQUARRIE*, B.A.W. SMITH*, S-D. YU*, M. TANAKA**, B. WONG*, C. MANU*

* Atomic Energy of Canada Limited, Ontario, Canada
** Electric Power Development Company Limited, Tokyo, Japan

ABSTRACT

To meet the economic and safety specifications of Electric Power Development Company Limited (EPDC), Japan, a new fuel bundle is being designed for a Highly Advanced Core (HAC) CANDU® reactor. The design core-average burnup is 40 GW.d/tU, which is about five times the burnup of current CANDU 6 reactors. With the proposed new fuel design, the void reactivity of the HAC reactor is essentially zero.

From evaluations of fourteen potential bundle designs, a 61-element bundle has been selected for further development and assessment. The bundle contains enriched uranium, depleted uranium, and burnable poison. The bundle is sized to fit in the current CANDU 6 pressure tubes.

The bundle's performance has been assessed from the perspectives of corrosion, vibration, fretting, fatigue, and buckling. Overall, the HAC 61-element bundle appears promising, and no serious feasibility issue has been uncovered.

INTRODUCTION

EPDC has set a goal to enhance the competitiveness of the CANDU* reactor design with respect to the next generation of advanced large Light Water Reactors (LWRs) being developed for Japan. To realize this objective, specific targets were established for lower capital cost, lower operating cost, and higher safety during postulated accidents. Improvements in these areas will help position this Highly Advanced Core (HAC) CANDU reactor as an attractive option within the Japanese market.

The HAC reactor contains 640 fuel channels and its gross electrical output is in the range of 1300 MWe.

---

* CANDU®: Canada Deuterium Uranium is a registered trademark of AECL.

Presented at the Fourth International Conference on CANDU Fuel, Pembroke, Canada, 1995 October 1-4. Sponsored by CNS, COG, IAEA.

This paper summarizes the status of the fuel design for the HAC CANDU reactor. The text first discusses the requirements imposed by the HAC reactor on the fuel design. This is followed by a description of the HAC fuel bundle design. Subsequent sections outline the expected performance of the HAC bundle in the areas of corrosion, vibration, fretting, fatigue, and buckling.

BACKGROUND

The requirements set by EPDC on the HAC fuel bundle include: core-average burnup of 40 GW.d/tU or higher; maximum element burnup less than 55 GW.d/tU (1300 MW.h/kgU); core-average uranium enrichment less than 3.25%; half-core void reactivity of essentially zero; target maximum element rating of 45 kW/m or less; and channel powers in the range of 7.4 MW.

In particular, note that the core-average burnup (40 GW.d/tU) is about five times that achieved in the current CANDU 6 reactors.

The existing 37-element fuel bundle performs extremely well for core-average burnups in the range of 7-8 GW.d/tU. The slightly enriched uranium (SEU) version of the CANFLEX bundle is currently targeted for core-average burnups of about 21 GW.d/tU. Physics, Process, and Fuel assessments showed that these existing fuel designs (37-element and CANFLEX) could not simultaneously satisfy all the specifications of the HAC CANDU reactor. Hence, it was necessary to develop a new fuel design for the HAC CANDU reactor.

In current commercial CANDU reactors, reactivity of the natural uranium fuel limits the core-average burnup to 7-8 GW.d/tU. By using enriched uranium and advanced internal designs in test reactors, experimental CANDU fuel bundles have already demonstrated satisfactory irradiation performance to burnups of 50 GW.d/tU. Lead test assemblies of LWR fuel have also been successfully irradiated to burnups of 55 GW.d/tU. This gives us confidence that, with enriched uranium and advanced internal designs, commercial CANDU fuel can be designed for the HAC burnups.

BUNDLE DESIGN

Fourteen concepts of fuel bundle designs were surveyed for use in pressure tubes of several diameters. These included the 37-element and CANFLEX bundles, as well as new fuel design concepts containing up to 86 fuel elements.

The survey showed that a 61-element bundle, named the 61 MK3, meets all the EPDC specifications simultaneously. Hence, it was chosen for further development and assessment.

Figure 1 shows the cross-section of the 61 MK3 bundle. It fits inside a standard CANDU 6 pressure tube. Also, it is designed to interface with components very similar to those used in CANDU 6 reactors.

The 61 fuel elements of this HAC bundle are arranged in five concentric rings. The fifty-four fuel elements in the outer three rings contain slightly enriched uranium (SEU). The remaining seven elements in the inner two rings contain depleted uranium and a burnable poison.

The bundle contains fuel elements of two different diameters. The outer 54 SEU elements have slightly smaller diameters than the inner seven depleted uranium elements. All 61 fuel elements of the HAC bundle have smaller diameters than CANDU 6 elements.

FEATURES OF THE HAC BUNDLE

The major design features of the HAC 61 MK3 fuel bundle are summarized below, along with their corresponding benefits :

- Judicious use of slightly enriched uranium, depleted uranium, and burnable poison, in conjunction with optimized refuelling schemes and with the bundle layout noted above, permits the core-average burnup to reach 40 GW.d/tU. The high burnup means that proportionately less fuel bundles are required to produce a given amount of energy. This reduces the volume of spent fuel and the associated cost of waste disposal.

- The above features also permit flattening the radial and axial distributions of power through the reactor core and through the cross-section of the fuel bundle. This increases the maximum channel power to 7.4 MW, and reduces the capital cost per installed kW. The large number of fuel elements in the bundle help maintain the margin to dryout at the elevated channel powers.

- The core-average enrichment in the HAC CANDU reactor is kept below the nominal of 3.25% used in the advanced LWRs of similar burnups. This provides a competitive advantage to the HAC CANDU reactor against the advanced LWRs in the area of resource utilization.

- Half-core void reactivity is essentially zero. This enhances the safety of the reactor during postulated accidents. It is achieved by combining enriched and depleted uranium with burnable poison in the fuel[1].

- Maximum element burnup is about 50 GW.d/tU (1200 MW.h/kgU). Thus, the element burnup is within the range for which satisfactory experience is available from experimental CANDU fuel and from lead LWR fuel assemblies.

- Element ratings are kept below 45 kW/m. The comparatively low ratings limit fission gas release and pellet expansion. This helps fuel retain its structural integrity at the higher burnups.

- Element diameters are within the range of current fabrication and irradiation experience in the fuel industry.

- Collapsible sheaths are used, as in current CANDU fuel. This promotes the transfer of heat from the fuel pellets to the coolant. This also enables us to take advantage of the accumulated knowledge, experience, and analytical tools pertaining to CANDU fuel. At the same time, preliminary assessments show that the HAC sheath is strong enough to withstand axial compressive loads during on-power fuelling.

- The penetration distance of the fuelling machine sidestops has been maximized. This minimizes the eccentricity of the axial load on the sheath during refuelling. This in turn reduces the bending stresses in the sheath. To achieve this, the width of the outer endplate ring was optimized, and additional radial ribs were added to the endplate.

- The geometry of the endplates has been designed to minimize endplate stresses and to facilitate bundle fabrication while considering the consequences on coolant flow. Thus a balanced combination of strength, coolant flow, and fabricability is expected.

- The bearing pads are slightly closer to the endcaps in the HAC fuel compared to CANDU 6 fuel. This compensates for the greater flexibility of the HAC fuel elements, and ensures good dimensional compatibility between the bundle and the pressure tube.

- The axial "skew" angle (at which the spacers are attached to the sheath relative to the element centreline) has been reduced in HAC fuel compared to CANDU 6, while preserving the contact surface area of the spacers. This facilitates fabrication without compromising the wear rate of the spacers.

- The endcap design conforms with compatibility with fuel handling systems similar to CANDU 6. This minimizes the need for changes to the fuel handling system concept.

The following sections describe the expected performance of the HAC fuel bundle.

WATER-SIDE CORROSION

The nominal residence time of the HAC fuel bundle in the reactor is about 5 years at full power. Zircaloy fuel components oxidize and develop a layer of ZrO_2 when exposed to the coolant for a prolonged period. Excessive water-side corrosion could lead to fuel failures via a number of mechanisms, e.g. (1) a through-wall defect in the sheath, (2) reduction of load-bearing capability due to wall thinning, and (3) hydriding. Hence, an assessment of water-side corrosion of the sheath has been done.

To estimate the extent of anticipated corrosion, we reviewed the available sheath corrosion data from CANDUs and from Pressurized Water Reactors (PWRs). Figure 2a shows the peak oxide thickness in PWR sheaths for burnups up to 60 GW.d/tU. Based on the trends noted in the PWR data, the CANDU oxidation data was extrapolated to the high burnups of the HAC CANDU reactor. Figure 2b shows the average oxide thickness in CANDU sheaths. From this, it was estimated that at 55 GW.d/tU, corrosion will reduce the wall thickness of a HAC sheath by a nominal of about 10%. However, over the same period, irradiation hardening will increase the yield strength of the sheath by 80-90%. This compensates for the effect of corrosion on the load-carrying capacity of the sheath.

The following factors tend to reduce the corrosion rates in CANDU sheaths compared to PWRs: i) the coolant temperature is lower in CANDUs, which reduces sheath temperature; ii) the coolant chemistry (pH) is less oxidizing in CANDUs; and iii) the element ratings are higher in the current commercial CANDUs, so for a given burnup the time in the reactor is lower.

At the operating temperature of the HAC sheath, hydrogen has a high degree of solubility in Zircaloy. Hence, hydriding is not expected to cause embrittlement of the HAC sheath.

VIBRATION

Excessive flow-induced vibrations of the fuel elements and the bundle can cause fretting damage to pressure tubes and to bundle components. Excessive vibrations can also threaten bundle integrity via fatigue of the assembly welds or of the endplate. For these reasons, the vibration amplitudes of the HAC bundle were assessed.

The transverse vibrations of the HAC fuel elements were compared to the CANDU 6 vibrations using four vibration calculation methods : a correlation developed by Paidoussis [2]; a correlation based on data obtained by Quinn [3]; and the theory of random vibration [4] with the turbulent pressure spatial correlations obtained by Chen [5] and Gorman [6]. All led to qualitatively similar conclusions, as described below.

The smaller diameters of the HAC fuel elements tend to increase the vibration amplitudes in HAC fuel. On the other hand, the HAC bundle contains comparatively more open subchannels. This leads to lower coolant velocities in the HAC subchannels, which in turn tend to decrease the vibration amplitudes.

The overall result is that the net transverse vibrations of HAC elements are expected to be similar to those of the CANDU 6 fuel.

FRETTING

One possible consequence of excessive vibrations is fretting of the pressure tube and/or of the fuel bundle. Fretting occurs due to repeated relative motion between the fuel bundle and the pressure tube, or between different parts of the fuel bundle. Fretting is not a problem in the CANDU 6 reactor. Nevertheless, it is prudent to ensure that HAC reactors will also exhibit satisfactory fretting behaviour.

The VIBIC computer code [7] was used to study the relationship between fuel element vibration (i.e., no bundle motion) and the volume wear rate of the pressure tubes by the bearing pads. The forces exciting a fuel element are due to unsteady turbulent pressures acting over its surface. The studies showed that the most significant factor was the smaller diameter of the HAC element which resulted in lower forces and less power available to cause fretting. Because of this, the maximum wear rate of the pressure tube by the HAC bundle was predicted to be lower than that by a CANDU 6 bundle.

Transverse bundle motion, excited by flow turbulence, is another potential cause of pressure tube fretting. A simplified computer model was used to calculate the motion of the 61-element bundle. The preliminary calculations indicate that as long as the inlet turbulence is kept low, the HAC bundle's motion is expected to be less than about 5 μm rms. Design of the channel can minimize inlet turbulence and reduce fretting tendencies. Thus, the fretting wear due to bundle motion is not expected to be a concern.

FATIGUE

Another possible consequence of excessive vibrations is fatigue of the endplate and/or of the assembly weld. We used the BEAM computer code [8] to estimate the resulting alternating stresses at these locations.

The BEAM code shows that lateral vibrations of the fuel elements lead to nominal zero-to-peak alternating stresses of 2.5 MPa in the endplate, and 1.9 MPa in the assembly weld. The corresponding fatigue strength is 28 MPa for the endplate, and 22 MPa for the assembly weld [9]. The preceding fatigue strengths account for the local stress concentrations by including appropriate strength-reduction factors based on Peterson's delta concept [10]. Considering the substantial margins between the alternating stresses and the fatigue strengths, it was concluded that the HAC endplates and assembly welds will not fail by fatigue due to flow-induced lateral vibrations of the fuel elements.

BUCKLING

Since the element diameters of the HAC bundle are smaller than those of the CANDU 6 bundle, it was necessary to confirm that the HAC bundle has adequate strength against possible buckling due to normal axial loads during refuelling. If a fuel bundle does buckle in the reactor, there could be concerns with the bundle jamming against surrounding components like pressure tube, fuelling machine, endfitting, etc. This may lead to difficulties in subsequent removal of the fuel bundle. To confirm that this would not occur in the HAC reactor, the buckling strength of the HAC bundle was evaluated.

The axial load most likely to cause buckling occurs during refuelling, when the fuel bundle is supported by side-stops. The expected in-reactor load is 7.5 kN.

The following factors were considered in estimating the corresponding buckling strength of the HAC bundle : strength of the sheaths; effect of appendages; effect of endplates; effect of contact with neighbouring fuel elements through inter-element spacers; and effect of eccentricity in the support provided by side-stops. The BOW code [11] was used for this assessment.

In the HAC reactor, the reference separator configuration is designed to provide support for a minimum of 14 fuel elements. With this configuration, the HAC bundle is estimated to have a buckling strength of 16 kN at the operating temperature. This estimate does not account for the effects of load shedding and of irradiation strengthening of the sheath. Thus, the actual buckling strength is expected to be higher than 16 kN. Hence, refuelling loads are not expected to be a concern with respect to buckling.

SUMMARY AND CONCLUSIONS

i) After assessing fourteen different bundle designs, the HAC 61 MK3 fuel design has been chosen as the reference fuel design for the 640-channel HAC reactor. Further development and assessment will focus on this fuel design.

ii) The 61 MK3 bundle has 61 fuel elements arranged in five rings. The three outer rings contain slightly enriched fuel. The two inner rings contain depleted uranium and a burnable poison. The bundle contains fuel elements of two different diameters, which are both smaller than the elements of the 37-element CANDU 6 fuel bundle.

iii) Nominal sheath oxidation is expected to be about 10% of the wall thickness. However, the corresponding loss of strength will be compensated by a 80-90% increase in the sheath yield strength due to irradiation.

iv) The vibration amplitudes are expected to be acceptably small. The corresponding alternating stresses in the assembly weld as well as in the endplate are well below their respective fatigue strengths.

v) Preliminary assessments suggest that the fretting of the HAC bundle will likely be similar to that of the CANDU 6 bundles. This rate of fretting is acceptably low.

vi) The in-reactor buckling strength of the HAC bundle is expected to be significantly higher than the normal axial loads during refuelling.

vii) Overall, the HAC 61-element fuel bundle design appears promising, and no serious feasibility issue has been uncovered.

ACKNOWLEDGEMENTS

The authors thank A. Dastur, P. Chan, K. Hau, M. Lim, I.E. Oldaker, T.J. Carter, A. Manzer, and J. Lau of AECL; Mr. T. Tanaka of EPDC; and M. Hoare and A.E. McCorry of ZPI; for their inputs and technical discussions.

The financial support of Electric Power Development Company Limited, Japan, is also gratefully acknowledged.

REFERENCES

1. Dastur, A.R., Chan, P.S.W., Bowslaugh, D., "The Use of Depleted Uranium for the Reduction of Void Reactivity in CANDU Reactors", 13th Annual Conference of the Canadian Nuclear Society, Saint John, New Brunswick, 1992 June 7-10.

2. Paidoussis, M.P., "The Dynamical Behaviour of Cylindrical Structures in Axial Flow", Annals of Nuclear Science and Engineering, Vol. 1, pp 83-106, 1974.

3. Quinn, E.P., "Vibration of Fuel Rods in Parallel Flow", GEAP-4059, AEC Research and Development Report, 1962 July.

4. Meirovitch, L., "Analytical Methods in Vibrations", MacMillan, 1967.

5. Chen, S.S., "Flow-Induced Vibration of Circular Cylindrical Structures", Hemisphere Publishing Corporation, 1987.

6. Gorman, D.J. "The Role of Turbulence in the Vibration of Reactor Fuel Elements in Liquid Flow", Atomic Energy of Canada Limited, Report AECL-3371, 1969.

7. Fisher, N.J., Ing, J.G., Pettigrew, M.J., and Rogers, R.J., "Tube-to-Support Dynamic Interaction for a Multispan Steam Generator Tube", from PVP-Vol. 242, Cross-Flow Induced Vibration of Cylinder Arrays, M.P. Paidoussis and D.A. Steininger (editors), 1992.

8. Tayal, M., Wong, B.J., Lau, J.H.K., Nicholson, A.M., "Assessing the Mechanical Performance of a Fuel Bundle: BEAM Code Description", Atomic Energy of Canada Limited, Report AECL-10643, 1992.

9. Tayal, M., Choo, C.K., "Fatigue Analysis of CANDU Nuclear Fuel Subjected to Flow-Induced Vibrations", Atomic Energy of Canada Limited, Report AECL-8331, 1984.

10. Peterson, R.E., "Application of Stress Concentration Factors in Design", Journal of the Society for Experimental Stress Analysis, Vol. 1, 1943, pp 118-127.

11. Tayal, M., "Modelling the Bending/Bowing of Composite Beams such as Nuclear Fuel: The BOW Code", Nuclear Engineering and Design, Vol. 116, 1989, pp 149-159.

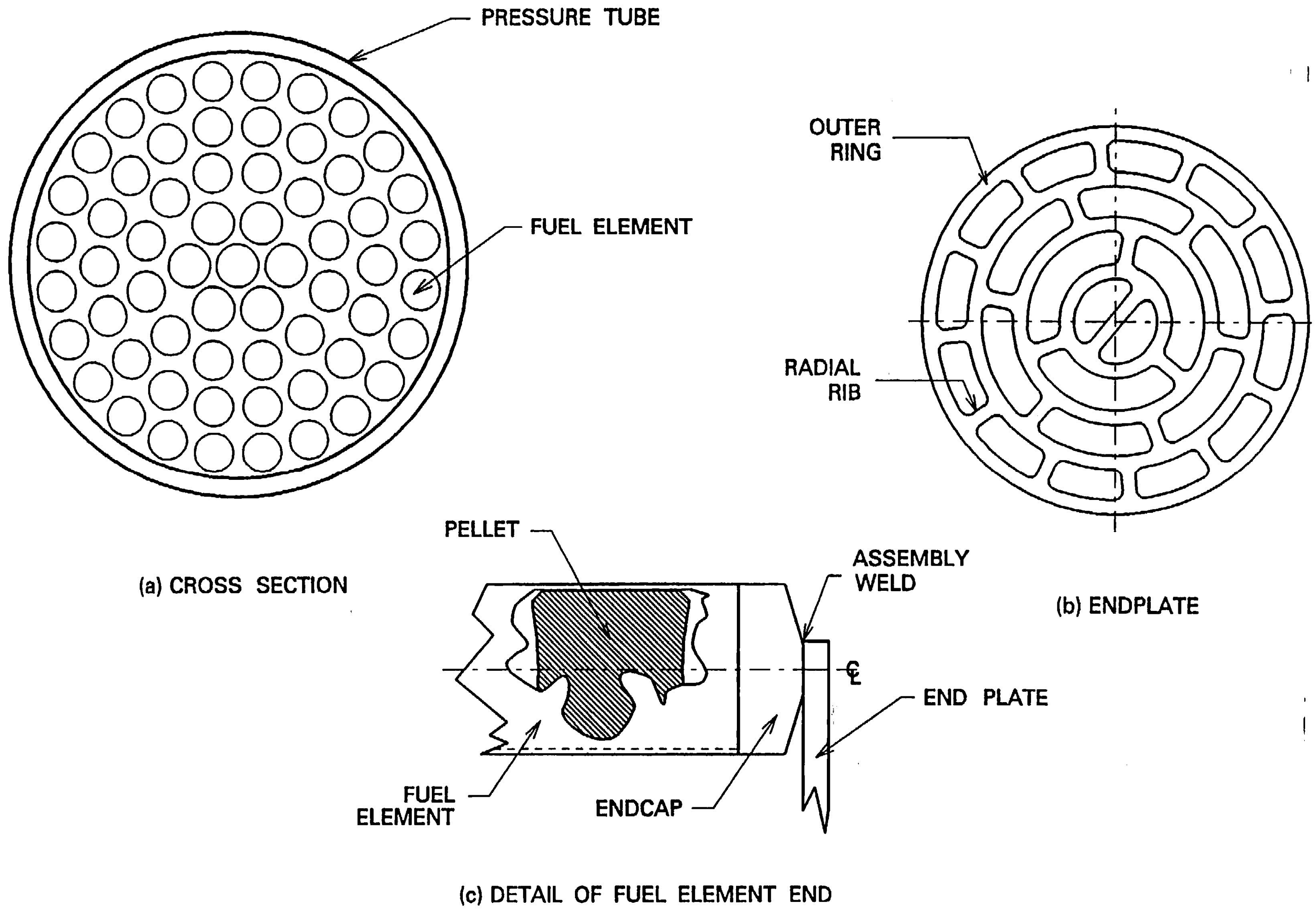
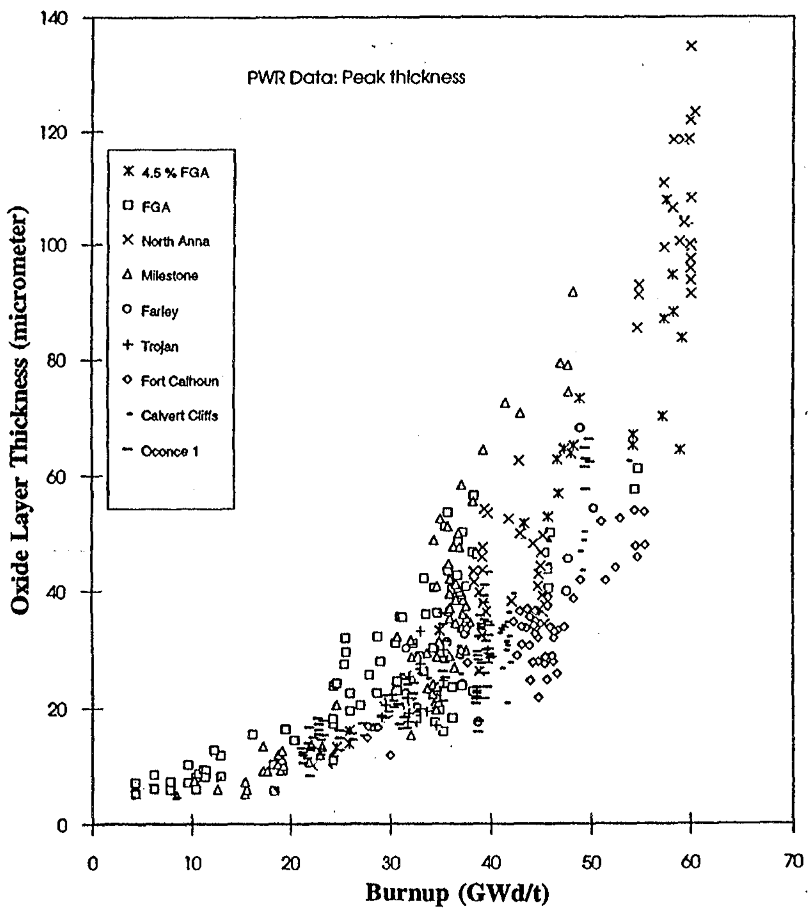
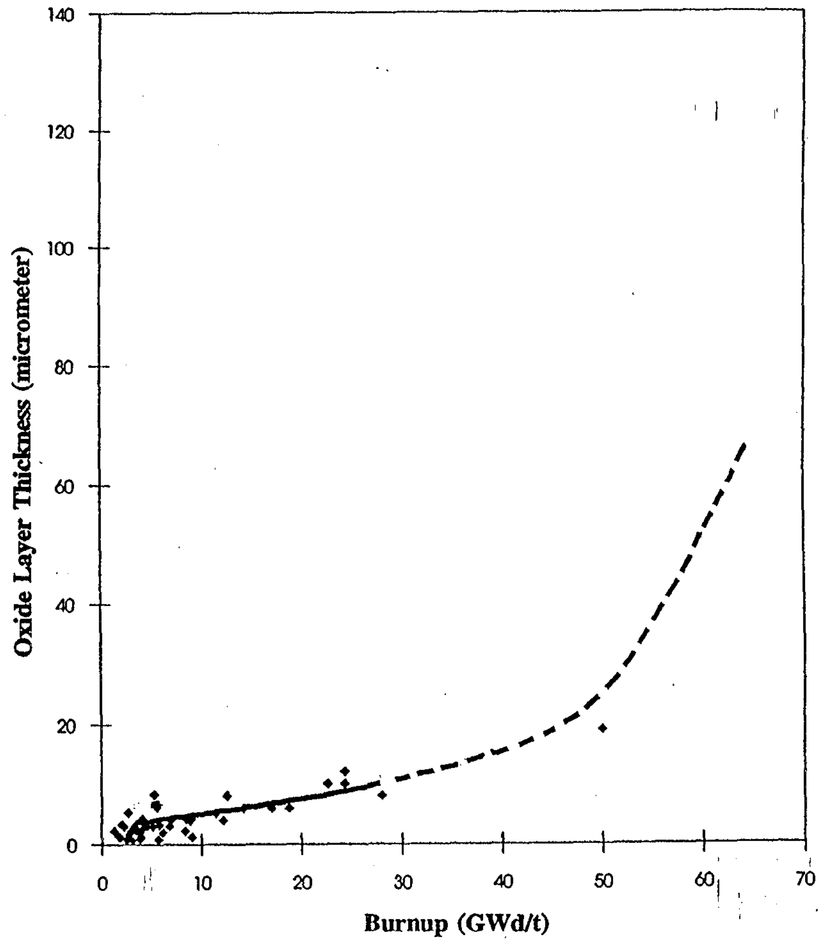


Figure 1 : HAC 61 MK3 BUNDLE



(a) Peak Corrosion in PWR Sheaths



(b) Average Corrosion in CANDU Sheaths

Figure 2 : Corrosion Rates