A Submission to the Ontario Power Authority (OPA) Concerning the Selection of New Electricity Generation Capacity for Ontario

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Introduction

I am a retired nuclear scientist with 23 years experience working for OPG's Research Division in Toronto. I have spent most of my professional career dealing with technical problems with OPG's fleet of CANDU reactors at Pickering, Bruce and Darlington. I am writing to the OPA to urge our electricity supply planners *not* to recommend the refurbishment or construction of any more CANDU reactors to supplement or replace the Province's existing electrical generating capacity. I base this view largely on the poor performance of certain critical systems inherent to the CANDU reactor design

The innovative features of the CANDU design, namely the use of D_2O as coolant and moderator, natural uranium fuel and the capability to refuel the reactor while operating under power, are implemented through systems involving great engineering complexity. For example, a Pickering 'A' reactor has over 2 km of specialized zirconium pressure tubing and over 7 km of feeder piping. Each reactor has 1,560 water and gas connections to the reactor core. Every one of these 1,560 connections has to be leak tight. If D_2O leaks from the reactor core it must be recovered and upgraded because it is very expensive to manufacture and contains radioactive tritium as a hazardous contaminant.

These features of the CANDU reactor design - that is the need for hundreds of fuel channels, end fittings, feeder pipes, annulus gas supply and return lines; as well as elaborate D_2O recovery and tritium control systems - have proven to be the source of unreliability and poor performance of aging CANDU reactors, especially compared to reactors of similar age incorporating less complex designs operating around the world. Unfortunately, the most significant of CANDU's deficiencies are long-standing problems caused by technical (design) issues that remain largely unresolved to this day.

Over the past 35 years CANDU reactors have been subject to their fair share of the same problems that have commonly been encountered in other reactors designs such as the BWR and PWR. These common problems include fuel failures, activity transport and steam generator corrosion. However, the history of CANDU reactor operations shows that our homegrown system derives most of its unreliability and high costs from:

(i) The use of D_2O and the associated production of tritium
(ii) The use of pressure tubes, feeder pipes and annulus gas systems.

These systems and components, *which are completely absent from other reactor designs*, are considered in detail below.

D_2O and Tritium

A typical CANDU reactor requires about 450 tonnes of heavy water (D_2O), valued at about $250 million. Nearly all of the tritium present in a CANDU reactor is produced by neutron activation of D_2O and is chemically bound as tritiated heavy water, DTO. A typical OPG reactor produces about 1.5 million Curies of tritium per year. In spite of every effort to prevent it, heavy water and tritium leak from an operating CANDU reactor. Most of the heavy water that leaks, or is spilt from a CANDU heat transport or moderator system, is recovered. However, a significant amount of D_2O escapes from containment and enters the environment through the so-called contaminated stack. The Pickering “A”, Pickering “B”, Bruce “A”, Bruce “B” and Darlington contaminated stacks each exhaust the equivalent of about 0.5 kg of D_2O vapor per hour. Because the effective specific activity of tritiated water released to the environment from a mature CANDU reactor is ≈ 1 Ci/kg, each of the five CANDU stacks noted above release an average of about 5,000 Curies of tritium per year.

Tritium emission control is accomplished by liquid collection systems and by water vapor recovery through containment air drying. The moderator vapor recovery enclosure is the most important primary barrier for tritium control and the drying requirements for this enclosure are the most stringent of any in the station. Moderator room dewpoints are typically specified to be –40° C or lower at D_2O collection rates of up to 1 kg/hr. In most cases several 6800 m^3/hr capacity single-bed dryer units are used at OPG stations with 13X or 4A molecular sieve as the desiccant.

Areas such as moderator purification rooms and heavy water management areas in service buildings used for drumming operations involving high isotopic moderator D_2O also require effective vapor recovery dryers, as well as proper ventilation to reduce occupational dose. The reactor building itself offers a secondary, and final, barrier to tritium emissions to the environment. Reactor building air is passed through an exhaust dryer typically operated at an outlet dewpoint of –18° C thereby setting an upper control limit to the heavy water vapor losses through the contaminated stack.

The need to maintain and monitor expensive and labor intensive systems related to heavy water management and tritium emission control add substantially to the cost of operating a CANDU reactor.

Pressure Tubes

Pressure tube problems have plagued CANDU reactors since the early days of Pickering NGS in the mid 1970s. OPG, NBP, AECL and other members of COG, the CANDU Owners Group, have collectively spent over $100 million on pressure tube research and development in the past 20 years but achieved only marginal improvements in pressure tube performance. There have been problems with leakage at the pressure tube rolled joints, neutron induced creep of in-core pressure tube sections (leading to sagging), pressure tube embrittlement and hydride blister formation caused by excessive hydrogen pickup, and localized fretting corrosion.

Starting in 1974 many individual pressure tubes were replaced in Pickering and Bruce Units, typically involving outages of several months and a dose commitment of about 10 man-rem per tube. In August 1983 pressure tube G16 in Pickering Unit 2 suffered a catastrophic rupture and the decision was made to replace all 390 pressure tubes in all four Pickering “A” Units.

One would expect that after OPG and AECL fixed all these early problems, CANDU pressure tubes would now be able to deliver many years of trouble free service. Indeed, the CNSC stipulates that nuclear pressure boundary materials meet stringent inspection codes as a licensing requirement. Unfortunately, the complexity and inconsistent results of pressure tube inspections over the past 25 years leave the question of future CANDU pressure tube performance still very much in doubt. For example, in the CNSC’s 2004 *Reason for Decision* on Bruce ‘A’ there is a section, albeit a very short one, that discusses the issue of pressure tube integrity. The perfunctory discussion offered by the CNSC fails to deal with, or even mention, some very important observations concerning Bruce ‘A’ pressure tubes. Just a small sampling of these observations is given below:

- Anomalous eddy current (EC) scans for a number of Unit 4 pressure tubes during SLAR inspections carried out in 1993.

- Some EC scans near the center of channel B4O13 that were so noisy it was impossible to reliably locate the spacers. The noisy EC signal was attributed to *either* very thick oxides *or* magnetite deposits.

- SLAR UT blister detection inspections, also carried out in 1994, produced highly variable signals that were later shown to be caused by interferences from lubricant and/or adhesive contaminants.

- Metallographic sectioning of removed tubes carried out in 1993 - ’94 showed *some* very thick patches of oxide on ID surfaces close to mid-bundle positions. Other sections that were predicted to have thick patchy oxides on the basis of EC inspections, were found to have thin uniform oxides.

- Data on deuterium uptake by Bruce pressure tubes are largely derived from scrape samples taken from “scrape campaigns” first undertaken on Unit 3 in October 1988. By 1993 it was realized that all previous scrape data were essentially worthless because of oxide contamination of the samples.

- Scrapes taken from pressure tube outlet regions of Unit 3 in 1994 were higher than predicted by the current AECL/OPG deuterium uptake model. The model was therefore revised to accommodate the new data.

- Re-scraping of Bruce 3 tubes in 1996 showed a *decline* in deuterium levels. AECL/OPG declared that the 1994 data were obviously in error and should not be included in deuterium uptake prediction calculations.

These observations raise serious concerns about the reliability of the inspection procedures used for pressure tubes at Bruce, and undermine any belief in the long-term integrity of pressure tubes in all CANDU reactors. Certainly, as a veteran of many years of research into pressure tube corrosion and hydrogen pickup, I can attest to the poor level of mechanistic understanding of pressure tube behavior inside a CANDU fuel channel in spite of the efforts of literally hundreds of scientists and engineers worldwide.

A good example of an observation lacking a cogent explanation is the remarkable variability, frequently by more than a factor of two, in the rate of corrosion and deuterium uptake by nominally identical pressure tubes sitting side by side in a reactor. The through-wall distribution of deuterium is another mystery. Some researchers have observed a deuterium concentration peak just below the oxide-metal interface in laboratory specimens of Zr-2.5%Nb. This would give *elevated* deuterium values compared to the bulk average value sought by scrape measurements. However, other studies indicate a possible *depleted* zone in the near-surface region of a pressure tube caused by migration of deuterium away from the oxide-metal interface during reactor cooling. In this case, all scrape data currently accepted by the CNSC are biased low.

The CANDU research community is also unable to account for another unexpected problem observed in a number of Bruce "A' fuel channels: namely, thick oxide patches in high flux regions of the core. Unfortunately, the true extent of this problem is largely unknown and this ignorance is compounded by the phenomenon of oxide spalling, which is known to have occurred in Bruce 'A' Units. Measurements on heat transport system particulate from Bruce Unit 3 indicate that several *kilograms* of pressure tube oxide have been released to the coolant over 15 years of operation.

An additional observation that should give added cause for concern to the operators and regulators of CANDU reactors is the detection of lithium-6 enrichment and beryllium braze bearing-pad corrosion product in oxide patches formed in high-flux areas of some tubes removed from Bruce reactors.

<u>Feeder Pipes</u>

Feeder pipe cracking and wall thinning was first discovered in CANDU reactors in the 600 MW(e) Unit at Point Lepreau in 1997. Subsequent studies have shown that wall thinning is widespread in CANDU outlet feeders and has become a very serious issue for OPG's aging fleet of reactors. The wall thinning observed in CANDU reactors has been attributed to flow accelerated corrosion (FAC). Studies have show that FAC is most likely to occur at tight bends in carbon steel piping carrying high temperature water at high flow velocities; a condition present at the first elbow of every outlet feeder pipe in CANDU reactors. FAC in Pickering "A" Units has been very severe for a number of reasons, but in particular:

(i) The use of carbon steel containing less than optimum chromium.
(ii) The use of aggressive decontamination reagents in the mid 1980's

FAC is a very complex phenomenon that is poorly understood in spite of considerable research by AECL and OPG. Some important facts to consider are:

• The initial wall thickness of feeder pipes varies between 7 mm and 3.5 mm.

• 40 % of the original wall thickness is the maximum acceptable thinning.

• The wall thickness at a feeder pipe bend is subject to considerable variability making it difficult to determine feeder thinning *rates* at this critical location without a number of repeat measurements.

• Up to February 2005, ultrasonic measurements at the extrados of the first elbow of Pickering 'A' feeders found a minimum wall thickness greater than 3 mm. At this time the extrados of the first elbow was considered to be the location most susceptible to wall thinning and it was therefore concluded that the Pickering feeders were within the fitness-for-service guideline.

• In April 2005 *direct* micrometer measurements were made at the extrados *and intrados* of two removed feeders from P1. These measurements gave the unexpected result that *the elbow intrados was thinner than the associated extrados, and well below the fitness-for-service guideline*.

To conduct a full outlet feeder inspection on a large CANDU reactor costs about $10 million and involves a radiation dose to the inspection crew of about 27 man-rem. To remove and replace *one* feeder pipe from a CANDU reactor costs about $1 million. To remove and replace the full complement of feeders in a Pickering 'A' Unit (390 pipes in total), costs about $300 million. Worse yet, a full feeder pipe replacement would take at least a year to complete and allow millions of dollars of interest charges and replacement fuel (coal?) costs to accrue on the refurbishment debt.

The Annulus Gas System

The annulus gas system is a specialized gas circulating system unique to the CANDU reactor design. It is used to provide thermal insulation between the high temperature heat transport system and the moderator, which must be kept cool for efficient reactor operation. CANDU reactor operators also rely on the measurement of water vapor in the annulus gas system (AGS) for the detection of small pressure tube leaks. Nitrogen gas was originally used in CANDU annulus gas systems but was found to produce Curie quantities of carbon-14 in gaseous and solid forms. After the completion of the Pickering Large Scale Fuel Channel Replacement (LSFCR) project in the early 1990's, all domestic CANDU Units switched from N_2 to CO_2-filled annulus gas systems. This switch created a new set of problems due to the unexpected formation of radiolytically-produced intractable polymeric deposits that plugged the annulus gas lines and flow rotameters. More recently, batch additions of O_2 have been made to the AGS of operating CANDU Units in an attempt to prevent annulus gas system plugging.

In 1991, as part of the re-commissioning of Pickering 'A', it was deemed necessary to test the pressure tube leak detection capability of a refurbished Unit to verify that the AGS exhibited the predicted response to a controlled injection of moisture. A series of leak detection tests was therefore carried out on Pickering Unit 3 (P3). A typical test involved the injection of D_2O into the external AGS circuit to simulate a pressure tube leak in the range of 20 g/hour. Previous tests of this type had been successfully carried out on a newly commissioned Darlington Unit in the late 1980's. It therefore came as a complete surprise when the P3 AGS response to moisture injection fell well below expectations. After 5 hours of continuous D_2O injection, a dew-point meter response equivalent to only 25 % of the expected water vapor concentration was measured.

Additional tests of the P3 AGS response to helium injections suggested that the injected water vapor was being held up within the AGS pipe-work by some type of adsorption phenomenon. Confirmation of this hypothesis was provided by subsequent tests of the purge dry-down response of the P3 AGS. Sluggish system response was observed and attributed to the slow *de-sorption* of water from sites that had previously adsorbed water vapor from the moisture laden gas stream.

It is now believed that the sluggish response of the P3 AGS during the July 1991 moisture injection tests was caused by corrosion product that had become dispersed throughout the pipe work of this system since the early 1970's. The source of the P3 AGS corrosion product is the carbon steel shielding sleeves and bearing journals located between the stainless steel lattice tubes and end fittings in each fuel channel. It is well documented that in the period 1973 -'75 the P3 AGS was subject to significant D_2O in-leakage and concerns over delayed hydride cracking lead to the replacement of 17 pressure tubes in 1975. Station records show that the D_2O in-leakage problem in P3 was so severe that the entire AGS was flooded a number of times and the carbon steel components in many lattice tubes were subjected to long periods of severe corrosive attack. Regrettably, this unanticipated corrosion has generated substantial quantities of poorly adherent hydrated iron oxide (rust) in the affected fuel channels.

Because of the inaccessibility of much of the pipe work, the full extent of the cumulative corrosion damage to the P3 AGS remains uncertain. However, it is probable that, by the time of the start of the P3 LSFCR in the fall of 1989, kilogram quantities of non-adherent rust particulate had accumulated in the P3 AGS. Furthermore, it has been reported that: "*vacuuming the material was not very successful*". Thus, even *after* the P3 reactor was returned to service in the fall of 1991, the majority of the pre-LSFCR corrosion debris remained in the AGS. It is also quite probable that other CANDU reactors besides Pickering Unit 3 have annulus gas systems with restricted flow from corrosion deposit and/or radiolytic polymer formation. Oxygen addition *may* inhibit polymer formation, but recent research has implicated nitrogen from air ingress as a new and troublesome polymer precursor.

Discussion

As noted previously, the CANDU reactor design incorporates a number of intricately engineered and highly complex systems that require an inordinate amount of skilled manpower to operate, inspect and repair. Many components are difficult to access, or are located in areas of high radiation fields, adding to the problems of CANDU reactor operation and maintenance. This situation is reflected in the exorbitant OM&A costs routinely reported for domestic CANDU reactors which, as we shall show, are largely attributable to the high staffing levels required to safely operate CANDU reactors.

To quantify CANDU operating costs we quote from OPG's latest financial results that cover the period for the first half of 2005. For its nuclear operations, OPG report $1,120 million in revenues from the sale of 21.4 TWh of electricity. OPG's OM&A costs for this electricity are stated to be $859 million, equivalent to $40/MWh, *or 79.5 % of revenues*.

It might be argued that OPG, as a government enterprise, is notoriously inefficient in how it runs its business. However, a comparison of OPG's nuclear operations to Bruce Power's privately run, for profit, nuclear operations shows otherwise. Thus Bruce Power's operating expenses, excluding fuel, for the six months ended June 30, 2005 were $39/MWh, or only marginally below OPG's $40/MWh for the same time period.

And to support the claim that the staffing levels at CANDU stations are excessive in comparison to other non-nuclear stations, we present some representative data for the number of employees at some well-known power stations in Canada.
(N.B. Nanticoke and Lambton are coal-fired, Darlington, etc, are nuclear):

Facility	**Available Capacity(MW)**	**Number of Employees**	**Employees/ MW**
Nanticoke	3938	600	0.15
Lambton	1975	300	0.15
Darlington	3524	3000	0.85
Bruce A & B	4680	3700	0.79
Pickering A & B	3090	5400	1.75
Point Lepreau	600	530	0.88

As a further comparison, it should be noted that the average staffing level for U.S. nuclear power plants is about 0.5 employees/MW, *or about half the number required to run a typical CANDU plant*.

Fuel costs per MW of electricity generated are, of course, much lower for CANDU than for any conceivable fossil fuelled station - a fact much emphasized by proponents of nuclear power. However, when capital costs are added to fuel *and OM&A costs*, CANDU-generated electricity must be priced at about $75/MWh just to break even. Thus, far from being "too cheap to meter", CANDU power is at least 25 % more expensive than any fossil fuelled electricity currently available in Ontario.

Summary and Conclusions

When the CANDU reactor was first introduced in the 1960s, particularly in the demonstration Units at Rolphton and Douglas Point, it was proclaimed by AECL to be a reliable and economic means of producing electricity. Eight larger and even more ambitious versions of the basic CANDU design soon followed at the Pickering and Bruce sites. Initial performance of these Units was promising. Indeed, some early CANDU Units led the world in annual average capacity factor, an accepted measure of reactor reliability.

Unfortunately, as Ontario's CANDU reactors approached 20 years of operation, serious problems with critical components started to emerge. Pressure tube integrity became a major issue in the 1980s, while steam generator corrosion and annulus gas problems dominated the 1990s. Outlet feeder pipes are the latest CANDU components to suffer from premature failures. Thus, looking at the status of CANDU in the year 2005, we see many of the 22 domestic Units in need of major refurbishments or already abandoned as beyond repair. This situation has arisen within 30 years of the commissioning of most of these Units; worse yet, some Units were shut down for long periods during their lifetime.

The hard pill for AECL to swallow is that CANDU's innovative engineering, seen as leading edge in the 1960s, has become its Achilles' heel by the year 2000. This is perhaps not so surprising for 50 year-old technology. After all, many engineering marvels from the 1960s, such as the Space Shuttle and Concorde, have now outlived their usefulness as recent events have so dramatically shown. But, to return to the main thesis of this submission, CANDU was destined to run into difficulties due to the complexity of its design. Corrosion is a well-known concern for all nuclear plant, but when it occurs in essentially inaccessible pipe work, such as the annulus gas system, it presents a problem that is next to impossible to fix.

As we have shown, each new problem that developed in CANDU reactors - whether it was leaking pressure tube rolled joints, annulus gas system flow blockages or feeder pipe thinning – has required more inspections leading to more outages and higher OM&A costs. The CANDU reactor was always an experimental venture; it has had its successes and was probably a worthwhile undertaking because it added to our understanding of nuclear science and engineering. However, it is time to declare the CANDU experiment over, and move on to something simpler, something proven, something better.

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Hamilton, Ont
August, 2005

To:
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August 28, 2005

Dear Mr. Carr,

It is my understanding that the Ontario Ministry of Energy has issued a directive to the Ontario Power Authority to develop an integrated plan to ensure a reliable long-term electricity supply for Ontario. To this end, I believe the OPA will be seeking input on supply options from the general public during the period September to December of this year.

Based on recent statements from Energy Minister Dwight Duncan, new nuclear generation capacity is being considered as a major component of Ontario's future electricity supply, and various "improved" CANDU reactor designs are already being actively promoted by AECL.

I am writing as a former OPG research scientist, with 23 years experience in nuclear operations, to suggest that any further investment in generating capacity based on the CANDU design would be a serious mistake. I have put together a summary of my reasons for rejecting CANDU technology in an attachment to this letter and would ask that this material be considered by the OPA.

Sincerely,

Dr. F. R. Greening

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