“NEW NUCLEAR POWER PLANTS FOR ONTARIO - THE CONTENDERS” - 2008 October

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Early in 2009 the Ontario government will select the technology for its future nuclear power plants. The following overview provides some background and clarifies some of the differences between the contending reactors.

Ontario's requirement is for a stand-alone two-unit nuclear power plant to provide around 2,000 to 3,500 MWe of baseload generating capacity with an option for one or two additional units. The first units will be located at the Darlington site near Bowmanville. All nuclear-electric generation in Ontario comes from CANDU reactors designed by Atomic Energy of Canada Limited (AECL) at Pickering, Darlington and Bruce.

THE VENDORS
The Request for Proposals issued by Infrastructure Ontario on 2008 March 7th was for, AECL's 1,085 MWe (net) ACR-1000 (Advanced CANDU Reactor); Westinghouse Electric Company's 1,117 MWe (net) AP1000 (Advanced Passive); AREVA NP's 1,600 MWe (net) U.S. EPR (United States Evolutionary Pressurized Reactor or Evolutionary Power Reactor), and the 1,550 MWe (net) GE - Hitachi Nuclear Energy's ESBWR (Economic and Simplified Boiling Water Reactor). None of these reactors are in service but four AP1000 units are being built in China and single units of the European version of the U.S. EPR are being built in Finland and in France. In early April GE-Hitachi Nuclear Energy, the designer of the ESBWR, decided not to submit a proposal. However the ESBWR is included in the following discussion to show how it compares to the other technologies because it may be considered by Bruce Power Alberta for new build in Alberta, together with the other contenders.

Westinghouse has Toshiba as a majority shareholder. Siemens has a minority stake in AREVA NP with the government of France a majority shareholder, and GE -Hitachi has GE as the major shareholder. AECL is a federal crown corporation and is part of Team CANDU consisting of Babcock and Wilcox Canada, GE- Hitachi Nuclear Energy Canada Inc., Hitachi Canada Limited and SNC-Lavalin Nuclear Inc.

Typically the scope of work split in Team CANDU could be, AECL, Mississauga, Ontario, responsible for the design and supply of the nuclear steam plant inside the reactor building; Babcock and Wilcox Canada, Cambridge, Ontario, responsible for manufacture of the steam generators and other heat exchangers and pressure retaining components; GE- Hitachi Nuclear Energy Canada Inc., Peterborough, Ontario for manufacture of the fuel and fuel handling equipment; Hitachi Canada Limited, Mississauga, for the supply of conventional balance of plant steam to electricity conversion equipment; and SNC-Lavalin Nuclear Inc. in Mississauga, Ontario, for project management skills, some balance of plant, and the balance of the nuclear steam plant.

ACR-1000 DESCRIPTION
The ACR-1000 uses heavy water as a moderator and light (ordinary) water as a coolant. The circulating light water is heated to 319 degrees Celsius under a pressure of 11.1 MPa(g) in the reactor and the heat is transferred to boilers, called steam generators, where steam is produced and piped to the turbine-generator system outside the reactor building where the electricity is generated. The coolant conditions allow some small amount of boiling of coolant in the reactor core. The reactor itself consists of a horizontal steel cylinder (calandria) 7.6 metres diameter and about 6.0 metres long filled with heavy water at near atmospheric pressure and temperature which acts as a moderator to slow down the neutrons and enable the nuclear reaction to take place. Tubes, or channels, that contain the uranium fuel pass through the calandria in the axial direction and connections are made at both ends so that the light water at high pressure can pass through and take away the heat from the nuclear reaction. Fuelling

machines at each end of the reactor can select any of the channels and replace used, or damaged, fuel with fresh fuel while at full power. The ACR-1000 uses fuel that is low enriched to around 2 percent uranium - 235. Previous CANDU reactors in Canada and around the world used natural uranium fuel (0.7 percent uranium - 235) and thus required heavy water to be used as the coolant.

AP1000, U.S. EPR and ESBWR DESCRIPTION

The AP1000, the U.S. EPR and the ESBWR are light water reactors (LWRs). The AP1000 and U.S. EPR are pressurized water reactors (PWRs). The nuclear reaction takes place in a thick walled vertical steel vessel that contains fuel strings that are left inside until they need to be replaced, usually every 12 to 24 months. The reactor has to be shutdown for up to three weeks for this to take place. Light water coolant, as in the ACR-1000, is pumped through the vessel at high pressure to remove the heat and transfer it to boilers that produce steam for the turbine- generator. The conventional part of the PWR power plant, that is, the electricity generating part outside the reactor building, is generally the same as the ACR. The PWR fuel needs enrichment to around 5 percent uranium - 235. Typical coolant conditions for a PWR would be 15.0 MPa(g) at 320 degrees Celsius with no boiling of coolant. The U.S. EPR reactor pressure vessel is 12.7 metres high with an inside diameter of around 4.9 metres and walls 0.25 metres thick, weighing about 520 tonnes.

The ESBWR is a boiling water reactor (BWR). The ESBWR does not have boilers like the ACR and PWRs, the steam is produced directly in the reactor vessel itself. This means that the steam in the turbine outside the reactor building is radioactive so shielding will be required around the turbine during operation and radiological protection will be necessary during maintenance. The ESBWR reactor pressure vessel is large, 27.7 metres high and 7.1 metres diameter. Unlike other reactors the ESBWR relies on natural circulation instead of pumps to remove the heat from the reactor core. It requires a shutdown to replace used or damaged fuel just like the PWR and uses fuel enriched to 4.2 percent uranium - 235. Typical coolant conditions for a BWR would be 7.0 MPa(g) at 285 degrees Celsius.

REFERENCE PLANTS

The ACR-1000 is based on AECL's CANDU 6 pressurized heavy water reactors (PHWRs) operating in New Brunswick (Point Lepreau), Quebec (Gentilly Unit 2), South Korea (Wolsong Units 1 to 4), Argentina (Embalse), China (Qinshan Units 4 and 5) and Romania (Cernavoda Units 1 and 2) which in turn evolved from power reactor designs for the old Ontario Hydro that go all the way back to the Nuclear Power Demonstration reactor that started up in 1962 near Rolphton, Ontario. These units have an output of around 680 MWe (net). Note that there are no CANDU 6 units operating in Ontario. India's indigenously well designed and well operated nuclear plants are based on CANDU PHWR technology. The ACR-1000 has light water coolant not the heavy water coolant of the CANDU 6, together with other evolutionary changes.

The AP1000 was developed from the Westinghouse reactors now operating in the U.S. These in turn were developed from submarine reactors that Westinghouse built for the U.S. navy, starting with the USS Nautilus, launched in 1954. The last order, in 1979, was the 1,188 MWe (net) Sizewell B unit in the UK which was based on the generic Standardized Nuclear Power Plant System (SNUPPS) design used for the Wolf Creek and Callaway plants in the U.S. The AP1000 makes more use of passive safety features than Westinghouse's previous plants which depended on engineered safety systems.

The U.S. EPR is based on the four Framatome (subsequently AREVA) 1,475 MWe (net) N4 series reactors, a completely French design, that was the latest reactor series to be put into service in France between 1996 and 2000, and on the three Siemens 1,400 MWe (net) Konvoi series units in Germany. The earlier French reactors of the 900 and 1,300 MW(e) series that started up in the late 1970s and after were based on a Westinghouse design supplied under the "atoms for peace" initiative of President Eisenhower.

The ESBWR is based on the 1,350 MWe (net) ABWR (Advanced Boiling Water Reactor) developed by General Electric, Hitachi and Toshiba, the only operating Generation 3 reactor, four of which were built in Japan between 1996 and 2006 and two are being built in Taiwan. The distinction between Generation 2 and Generation 3 reactors is imprecise but generally Generation 3 units could be said to, have fewer systems, have a 60 year design life, generate less waste, have a standardized design, be easier to build, and have lower core damage frequencies than the earlier Generation 2 reactors in service today. In turn the ABWR is based on the older BWR many of which are operating in Japan and the U.S. While the ABWRs used pumps to circulate the coolant through the reactor the ESBWR relies on natural circulation.

EXPECTED CAPACITY FACTORS

Capacity factor is an indication of plant performance and is the ratio of actual energy produced over a period of time to the amount produced if the plant were running at its maximum continuous rating over the same time period. The ACR-1000 is expected to operate with an annual capacity factor of 95 percent and the LWRs at around 93 percent. The ACR-1000 does not have to shut down for refuelling although it will be necessary to shut down every three years, for three weeks, to do routine maintenance that cannot be done when the unit is operating.

The ACR-1000 and the LWRs are designed for a life of 60 years but the ACR-1000 will require a shutdown of less than a year, after 30 years service, to replace the pressure tubes that pass through the calandria because of dimensional and material property changes due to radiation. This will also provide an opportunity to replace obsolete equipment and do other refurbishment to meet contemporary standards. Such refurbishment is taking place on the CANDU 6 reactor in New Brunswick that started up in 1983 and had a lifetime capacity factor of 82.1 percent up to the end of 2007 and will also be done soon on the reactors in Korea (Wolsong Unit 1) and Argentina that started up in 1983 and 1984 respectively and had lifetime capacity factors of 85.7 and 84.9 percent respectively at end of 2007.

LWRs need to shutdown for refuelling and maintenance every one to two years so, all in all, lifetime capacity factors of the new reactors after 60 years could be expected to be similar at around 93 percent.

ACTUAL CAPACITY FACTORS OF THE REFERENCE PLANTS

Up to end of 2007 the average lifetime capacity factor for the 11 operating CANDU 6 reactors was 88.8 percent with an annual average capacity factor also of 88.8 percent in 2007, down from 90.8 percent for 10 reactors in 2006. The four CANDU 6 units in South Korea had an average lifetime capacity factor of 93 percent up to the end of 2007. In countries that have both CANDU 6 reactors and PWRs, like South Korea and China, the CANDU 6 has out performed the American and French reactors in Korea and the French reactors in China. Capacity factor depends on the way the plant is managed as well as on its inherent design.

Although not CANDU 6 units, the four unit Darlington station in Ontario had a lifetime capacity factor of 82.5 percent up to the end of 2007 and 88.7 percent for the 2007 year. The four unit Bruce B station in Ontario, also not CANDU 6 units, had a lifetime capacity factor of 82.2 percent up to the end of 2007 and 89.7 percent for the 2007 year. India has operated its 15 PHWRs at around 90 percent capacity factor but shortages of natural uranium fuel has affected current performance.

The International Atomic Energy Agency publication, "Nuclear Power Reactors in the World", shows that for reactors over 600 MWe the lifetime capacity factor up to 2004 for 20 PHWRs was 80.7 percent, for 192 PWRs (excluding 23 former Soviet Union designed WWERs) it was 76.1 percent and for 78 BWRs it was 72.8 percent. In the U.S. the average annual capacity factor from 2000 to 2007 was over 89 percent for all 104 operating reactors, not just the 52 Westinghouse PWR and 35 GE BWR reactors. Previous to year 2000 average annual capacity factors in the U.S. were low, in 1990 it was 66 percent and in 1980 it was 56.3 percent but today annual average capacity factors are around 90 percent, for example 91.8 percent for 2007. Sizewell B in the UK, a standard 1188 MWe Westinghouse plant that went into service in 1995 had a lifetime capacity factor of 83.5 percent at end of 2006.

In France the 58 PWR reactors, including the four of the N4 type on which the U.S. EPR is based, had an annual utilization factor (allows for unit being available but output restricted due, say, to load following) of 80.2 percent in 2007, down from 83.6 percent in 2006. The N4 type has been around 75 percent, and the Konvoi type at over 90 percent. The capacity factor of the French nuclear fleet is low, at around 77 percent, due to load following.

The four ABWRs (reference plant for the ESBWR) in Japan had a lifetime capacity factor of 64.2 percent up to end of 2006 with an annual capacity factor of 57.2 for that year. The 32 BWRS and 23 PWRs in Japan had an annual capacity factor of 63.9 percent and 79.2 percent respectively in 2006.

UNIT SIZE

There are economies of scale with larger unit size but the larger the unit, the larger must be the operating reserve on the grid in case that unit is lost. Typically, today, the operating reserve on the Ontario grid is around 1,400 MW with the largest single unit being a Darlington size unit of around 878 MWe (net). Reactors of the size of the U.S. EPR or the ESBWR would require an additional 1,000 MW of operating reserve. Coal-fired generation is a significant part of the operating reserve but this is to be phased out in Ontario by 2014.

SUPPLY CHAIN

Future nuclear build will depend on a reliable supply chain. While both the ACR-1000 and the LWRs use enriched uranium the enrichment levels are much lower for the ACR-1000. The LWRs need large reactor pressure vessels. With the resurgence in demand for nuclear power plants world wide a lot will depend on the limited availability of uranium enrichment facilities and on the very few suppliers of nuclear grade heavy forgings for fabricating the reactor pressure vessels and other very large pressure retaining components. Ontario would have to take it's place in the global queue for these services and components. The lead time for delivery of LWR reactor pressure vessels and other very large components is about eight years which could make a 2018 in-service date difficult to meet for a LWR. Some generation companies in the U.S. have ordered long lead items even before committing to plant build. The ACR-1000, with an in-service date of 2016, does not use a reactor pressure vessel and has much more local content, including the reactor vessel (calandria) itself, than the other types of reactor. This means more jobs in Canada. Some equipment, for example the turbo-generators and standby diesel generators, would not be manufactured in Canada irrespective of the technology selected.

ACCIDENTS

Both CANDU and PWRs have suffered accidents. The small loss of cooling event at the Three Mile Island Unit 2 PWR in 1979 escalated to a partial meltdown of the core and a permanent reactor shutdown. CANDUs have had several small loss of coolant events but with no fuel damage.

SAFETY

There has been over 13,000 reactor-years of civil nuclear power plant operation world wide with only two major accidents, Chernobyl and Three Mile Island. All contending plants are "safe" and all are said to be Generation 3 +. The difference between Generation 3 and Generation 3+ is not clear. One definition is that Generation 3+ units have passive safety features not available on Generation 3 units. However, the U.S. EPR relies more on engineered safety systems and less on passive safety systems than the AP1000, the ACR-1000 or the ESBWR and would not be a Generation 3+ by this definition. The safety of the ACR-1000 in severe accidents is enhanced by the cool heavy water moderator that surrounds the fuel channels and by the cool shielding water that surrounds the calandria in the reactor vault, which act as emergency passive heat sinks.

The large steel reactor pressure vessel of a PWR, pressurized to over 15 MPa(g) (2,175 psig) at around 320 degrees Celsius, gets irradiated over time and becomes brittle, making it less able to withstand flaws that may be present. The addition of cold water to an embrittled reactor pressure vessel results in what is called pressurized thermal shock and could lead to cracking and even failure of the vessel. This affects PWRs more than it does BWRs. In LWR design the catastrophic failure of a reactor pressure vessel is regarded as an incredible event. In the ACR-1000 failure of a pressure tube is a design basis event. The U.S. Nuclear Regulatory Commission expects all plants in the U.S. to maintain adequate toughness of their pressure vessels throughout their operating lives. Embrittlement was an issue in the closure of the Yankee Rowe plant in the U.S. in 1992 after 32 years of operation.

Another concern with PWR reactor pressure vessels is primary water stress corrosion cracking of control rod drive vessel head penetration nozzles, and other nozzles, which could result in a loss of coolant accident and possible ejection of a control rod. The most extreme example of this occurred at the Davis-Besse plant in Ohio in 2002. Leaking borated water from cracked nozzles resulted in a cavity being formed in a part of the reactor pressure vessel head that extended all the way through the 0.168 metre (6.63 inches) thick carbon steel wall to the thin internal stainless steel liner. In the ACR-1000, control rods that penetrate the reactor calandria wall operate in near atmospheric conditions of pressure and temperature since the high pressure and temperature coolant is flowing in the pressure tubes.

The LWR vendors in Ontario are having problems meeting the requirements of Regulatory Document RD-337, Design of New Nuclear Plants, that was issued for comment by the Canadian Nuclear Safety Commission (CNSC) in 2007 October. According to Linda Keen, ex President of the CNSC, this was a technology neutral document. The LWR proponents have raised many major technical objections, for example, the requirement to have two fast acting independent reactor shutdown systems in addition to normal shutdown by the reactor regulating system, like AECL's ACR-1000, and that Canadian safety standards are higher than accepted international standards.

COST

New reactors will be based on standard designs to reduce construction times, and total costs, by extensive modularization and advanced construction techniques. Except for those in France, and AECL's CANDU 6s, the earlier Generation 2 reactors were not based on standardized designs. Follow-on units will be cheaper and quicker to build than the first-of-a-kind unit. Reliable cost figures are hard to find. The overnight costs, which exclude interest over the construction period, could be, according to Nucleonics Week for 2006 July 6, $1500 to $1800/kWe for the AP1000, $1800 to $2000/kWe for the U.S. EPR and $1600/kWe for the ESBWR. These numbers are probably for first-of-a-kind units and will vary widely depending on the source. AECL gives $1000/kWe for the ACR-1000, which could be for the nth unit. The cost of steel, concrete, copper and other construction materials has significantly increased since these estimates were made.

The actual real construction cost will depend on construction time and interest rate. The two unit CANDU 6 station in China, built 1997 - 2003, came in at an actual cost of $2850/kWe based on a cost of $4 billion for 1,400 MW. The first two ABWRs in Japan reportedly had an actual cost of $2000/kWe but the later two cost more. Electricite de France (EdF) claims an actual cost of $1349/kWe for the last two of the N4 series at Civaux. The Westinghouse Sizewell B station cost about $5400/kWe (including first-of-a-kind costs for UK construction) but Callaway and Wolf Creek, similar plants in the U.S., cost around $2500/kWe. Present installed costs in the US vary from $3000 to $7000/kWe depending on what is included. Costs are in $US.

Total generating cost (Levelized Unit Energy Cost - LUEC) for the AP1000 is said to be less than 3.5 cents/kWh and 3 cents/kWh for the ACR-1000. These costs are sensitive to the assumptions applied and would be based on estimates of operations and maintenance cost, fuel cost, waste management and decommissioning costs, capacity factor, design life, capital cost and discount rate over the construction period. For comparison the Electric Power Research Institute (EPRI) estimates a general levelized cost of around 4.7 cents/kWh for new nuclear and the Organization for Economic Co-operation and Development (OECD) report, Projected Costs of Generating Electricity - 2005 update, gives 2.1 to 5.0 cents/kWh. These LUEC figures will increase with the latest increase in capital costs.

Production cost of nuclear generated electricity can be low. In 2007 the average production cost (includes operations and maintenance cost and fuel cost but excludes capital and interest cost) of nuclear in the U.S. was 1.68 cents/kWh from its 104 operating Generation 2 PWRs and BWRs. Darlington production cost is reported at 1.3 cents/kWh. For the customer the total (LUEC) generating cost is the most important consideration. The retail cost will be higher than the total generating cost due to other charges, like transmission and distribution costs, and the law of supply and demand.

OTHER CONSIDERATIONS

The AP1000 had design certification in the U.S. in 2006 but Westinghouse submitted an application in 2007 May to amend the certified design. The regulator is currently reviewing this application. The ESBWR and the U.S. EPR are in the design certification process. The ACR-1000 is presently not in the design certification process. Design certification in the U.S. does not mean automatic, or even easier, licensing in Canada. The Canadian nuclear regulator does not have much experience with LWR technology so licensing would take longer than licensing an ACR-1000. The ACR-1000 has a planned in-service date of 2016 which is ahead of the Ontario government's 2018 in-service date for the new reactors.

Prior to China ordering four AP1000 reactors, Westinghouse had no reactor orders since Sizewell B, in the UK, was ordered in 1979. The AP1000 has new passive safety features that are a major departure from the earlier proven designs of the 1970s. Westinghouse claim a 36 month construction schedule from first concrete pour to fuel load but this is based on computer simulation not on recent build experience. Engineering, procurement and construction contracts for two plants, each with two AP1000 units, have been signed in the U.S., but no commitment to build.

One EPR is under construction at the Olkiluoto site in Finland, one at Flamanville in France and another in France at a site to be decided in 2009. Two are to be built in China. However China is more interested in AP1000 technology than the EPR which it regards as more expensive and complex with engineered rather than passive safety systems. The four French N4 series reactors, on which the U.S. EPR is based, suffered serious safety related design problems and delays in commissioning that extended over several years, and AREVA's EPR in Finland is nearly three years behind schedule and between 25 and 50 percent over budget since start of construction in 2005. The French nuclear regulator has identified quality control problems in the early construction phase of the EPR at Flamanville and has asked AREVA to fix them. According to UniStar Nuclear (combination of AREVA and Constellation Energy with Bechtel as subcontractor) in the U.S. a U.S. EPR could be expected to be online in the U.S. less than 48 months after receipt of the Combined Operating Licence from the nuclear regulator.

The two ABWRs in Taiwan are suffering construction delays and are around six years late based on the original schedule, the ABWR is the reference design for the ESBWR. For an ESBWR in the U.S.a time of 45 months from first concrete (after receipt of Combined Operating Licence) to commercial operation is anticipated.

The latest CANDU 6 reactors, on which the ACR-1000 is based, in Korea and Romania were built on time and on budget and came into service between 1997 and 2007 and the two in China that came into service in 2002 and 2003 were ahead of schedule and below budget. Based on this, the ACR-1000 is expected to have a 42 month construction schedule (first concrete to fuel loading) for plants following the first, that is, the nth plant. The CANDU 6 project in China holds the record for the shortest construction time for a nuclear plant in China. Romania is planning for two new CANDU 6s in addition to the two that are operating and Argentina is ready for new build. India is building more CANDU type reactors as part of its three stage plan to use its thorium deposits as reactor fuel. There is the potential for increased trade in CANDU technology with India. Ukraine, Lithuania, Jordan and Turkey are also interested in CANDU technology using natural uranium. Since 1991 South Korea, Canada and the U.S. have been working to perfect a proliferation resistant process whereby spent fuel from LWRs can be mechanically recycled into fuel and used directly in CANDU reactors without re-enrichment. This process is at an advanced stage in South Korea where both PWRs and CANDU 6s are in operation.

Periods of low demand on the Ontario grid combined with generation from intermittent self-scheduling wind turbines will require some load following from the nuclear units. Since nuclear provides nearly 80 percent of France's electricity its PWR fleet has employed load following for many years but this has not avoided the need to shutdown some units on week-ends. Early CANDU reactors in Ontario and off-shore have also shown their load following capabilities. The use of low enriched uranium fuel and light water coolant in the ACR-1000 reduces the xenon load after power reductions, compared to CANDUs, and makes it inherently more responsive. The ACR-1000 can provide a degree of regulation service (frequency control of grid) as well as rapid load reductions down to 75 percent of full power on a daily basis, and periodically down to 60 percent, with a reduction to 50 percent of full power on week-ends.

Over the last 40 years Canada has developed a lot of skills and knowledge based on its own CANDU technology and would have to start from scratch if any of the foreign technologies were selected. With CANDU Canada is the design authority, with any other technology it is merely the customer. Hopefully this overview has provided some background and clarified some of the differences between the competing technologies.

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