The Energy Authority

TECHNICAL ASSESSMENT OF THE NUCLEAR OPTION FOR SASKATCHEWAN

For: Saskatchewan Energy Conservation
and Development Authority

By: Energy Research Group, Inc.
400 Fifth Avenue
Waltham, MA 02154

SECDA Publication No. G800-94-P-006 July 1994

Saskatchewan Energy Conservation and Development Authority

Creating a rational energy future

MANDATE:

(i) to promote research, development and application of new technologies related to energy conservation and alternative energy;

(ii) to promote research, development and application of new technologies related to expanded production or value added processing of conventional energy resources;

(iii) to identify, evaluate and promote the development of business opportunities associated with these new energy technologies;

(iv) to evaluate future electrical generation options for Saskatchewan and make recommendations with respect thereto for the period from 2003 to 2020, including an assessment of socio-economic and environmental considerations;

(v) and to report on the foregoing as may be required by the Minister of Energy and Mines or his or her designate from time to time.

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Preface

This report was prepared by the Energy Research Group, Inc. in the course of performing work contracted by the Saskatchewan Energy Conservation and Development Authority (SECDA).

This document is one of a series of reports prepared for SECDA in support of its evaluation of Saskatchewan's long-term electricity options, renewable energy sources, and energy conservation potential. SECDA is a partner agency in the province's Comprehensive Energy Strategy (CES) and the information contained in this report will contribute to the development of the CES.

The opinions expressed in this report do not necessarily reflect those of SECDA and reference to any specific product, service, process, method, information source, or policy does not necessarily constitute an implied or expressed recommendation of same.

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1. INTRODUCTION

To contribute to long term energy planning in the Province of Saskatchewan, the Saskatchewan Energy Conservation & Development Authority (SEDCA) has a mandate to evaluate future electrical generation options. The nuclear option is based on uranium mined in Saskatchewan, a single CANDU 3 reactor and local waste storage.

SEDCA has retained Energy Research Group, Inc. (ERG) to perform a limited review of CANDU 3 data and information that has been provided by Atomic Energy of Canada Ltd. (AECL). Specifically, ERG was requested to focus on the variability or uncertainty in cost and performance estimates, as well as the fuel cycle environmental impacts of routine operations and accidents associated with a CANDU 3. In addition, ERG was asked to outline a methodology for evaluating externality costs related to this option.

This scope of work is consistent with the screening evaluations that utilities typically perform to evaluate viable technologies and programs as part of the integrated resource planning process. Thus, more detailed analysis might be required before a final selection could be made between a CANDU 3 and other viable technologies. It is also important to emphasize that ERG's evaluation was limited to the CANDU 3 -- so no comparisons with other technologies were made.

Methodology

While broad based, this scope of work did not allow for a detailed engineering evaluation of a CANDU 3 with complete access to AECL design data and information. Rather, the effort involved the review of methodologies, key assumptions and the magnitude of numerical values supplied by AECL to determine consistency with sound engineering practice, the past experience of the Canadian nuclear power industry and ERG's engineering judgment.

ERG based its review on the following information sources to assure as much perspective as possible:

- AECL information and data that SECDA forwarded to ERG. (See Appendix A for a listing.)

- Publicly available data and information on the operation, performance and impacts of other CANDU reactors in Canada. CANDU's that are operating overseas were discounted because of limited data availability and the different regulatory regimes and public oversight that they operate under. Also, the design pedigree of CANDU reactors warranted that the CANDU 6 units (Pt. Lepreau and Gentilly 2) be used for comparative purposes with more weight than the earlier vintage, larger, multi-unit CANDU's operated by Ontario Hydro.

- Conversations with representatives of Ontario Hydro, Pt. Lepreau and Gentilly 2. These conversations were primarily used to gain data, insights and anecdotal information.

- Publicly available information/data on Light Water Reactors (LWR's) operating in the United States. Although there are distinct technological and regulatory differences between LWR's and CANDU's there is some data that provide useful insights and comparisons:

- Engineering judgment by ERG's staff of nuclear engineers and the use of appropriate calculations to establish bounding limits for certain parameters. Such judgments and calculations were often combined with scaling based on the capacity of a CANDU 3 vs. CANDU 6 plants -- which yields a factor of 0.70 (i.e., 450 MWe ÷ 640 MWe). While there are limitations to simple scaling relationships, when combined with other information and insights it is a useful tool for establishing approximations and bounding conditions.

Generic Parameters

Throughout the evaluation, several generic parameters were applied to calculations. These parameters are summarized in Table 1-1 which also shows the conventions and units that were used in reporting results. To aid in the interpretation of this report a glossary of frequently used terms is provided in Appendix B.

Population Density - In order to calculate the impact of a nuclear plant's operation on the general public, the population density within a 100 km radius of the facility must be known. A site for a potential CANDU 3 in Saskatchewan is likely to be located on either the Saskatchewan River or Lake Diefenbaker (for an adequate source of cooling water). ERG therefore assumed that a 100 km radius from the plant would include both Saskatchewan's average population density of people per square kilometer and the entire population of either Saskatoon or Regina (both are approximately 180,000 people) -- yielding a population density of 7.3 people per square kilometer. Although this is conservative, it does assure that any analysis that is proportional to population density will reflect an upper bound.

Radiological Health Effects - The biological damage caused by radiation exposure depends not only on the amount of radiation absorbed by the body, but also on the type of radiation, whether the radiation source is external or internal to the body, which part of the body is exposed, and the time over which the exposure takes place. When radiation interacts with tissue, it deposits energy in the tissue which can cause harm. The radiation dose delivered through this energy absorption by tissue can be measured or calculated and related to the potential biological harm. The unit used to measure this quantity is the sievert (Sv).

The dose-response relationship for radiation exposure has been intensively studied over the last half century on the basis of animal experimentation, human epidemiology and theoretical analyses. Detailed reviews of the biological effects of radiation exposure can be found in recent reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the Committee on the Biological Effects of Ionizing Radiations of the U.S. National Academy of Sciences (BEIR V) and the International Commission on Radiological Protection (ICRP), among others. In Canada, values published by the ICRP have been adopted by federal regulators and they are, therefore, used in this report as well.

The main concerns arising from exposure to low doses of radiation are changes in a living cell that produce gross effects such as cancers and heritable (genetic) damage. The deposition of energy by ionizing radiation is a random (stochastic) process, so that even at very low average doses sufficient energy can be deposited in critical sites within a cell to cause changes in its function. When unrepaired changes remain in the programme structure (the DNA) of even a single cell, gross effects, such as cancer or genetic changes, may result. These effects have therefore been called stochastic, and it has been assumed that when large populations are exposed to low doses, some individuals may develop cancers or genetic damage. It is not possible, however, to distinguish beyond a statistical basis the effects caused by low doses of ionizing radiation from the large number of cancers and genetic changes arising from other causes. In this evaluation, ERG follows the recommendations of the ICRP and when making risk calculations, assumes that the risks of stochastic effects remain to the lowest doses received.

The latest guidelines from the ICRP call for a statistical risk coefficient of 0.05 cancer fatalities per Sv for members of the general public.* Radiation-induced cancer risk depends strongly on age at time of exposure, and is generally higher for younger ages. The risk, however, is not markedly different between males and females. The risk coefficient cited above is based on the summation of the cancer risks to the most sensitive body organs and tissues. Because nuclear plant workers tend to be middle aged and healthier than the average member of the general population, the ICRP statistical risk coefficient is somewhat lower at 0.04 fatalities per Sv.

Genetic changes (heritable gene mutations and gross chromosomal aberrations) have not been demonstrated in epidemiological studies of irradiated human populations. However, extensive studies of large numbers of highly irradiated experimental animals (mainly mice) have demonstrated the possibility of such changes. The estimates of risk derived from these studies are believed to be conservative when applied to man. In order to account for genetic aberrations and non-fatal cancers, ERG elected to conservatively double the risk coefficient cited above (which bounds ICRP guidance). Thus, the total risk of health effects (fatal cancers as well as genetic aberrations and non-fatal cancers) for the general public and nuclear plant workers are 0.1/person-Sv and 0.08/person-Sv respectively.**

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* This means that if 100 members of the public each received a 1 Sv radiation dose then 5 cancer fatalities, would over time, be statistically expected to occur. The "population dose" would be 100 people multiplied by 1 Sv or 100 person-Sv.

** ERG is not aware of any epidemiological study which shows that chronic, low levels of radiation cause the human immunological system to be suppressed.

For perspective ICRP, UNSCEAR and BIER all re-evaluate their guidelines on the order of once a decade. As more information is collected and evaluated, all three committees have increased their risk coefficients with succeeding publications. Whether or not this trend continues cannot be predicted.

Financial - Unless stated otherwise, all costs are in 1994 Canadian dollars. Finally, based on information from SECDA, the fully burdened salary of a construction worker was set at $40,000/year and for a nuclear plant worker at $90,000/year. A plant operating period of 40 years was assumed. (AECL correctly points out that with equipment replacement a CANDU 3 could operate beyond 40 years. On the other hand, no nuclear plant -- CANDU or otherwise -- has yet to reach 40 years of operation.)

Risk/Impact Index - In general, the literature reports the health and environmental impacts of electrical energy systems on the basis of electrical energy generated. Electrical energy generated is typically stated by Canadian utilities in gigawatt-years (GWa) -- which for example would be the production of a power plant rated at 1,000 megawatts (MW) electrical, if operated continuously for one year at rated capacity. (Electrical production at a CANDU 3 was calculated for an 88% capacity factor and would therefore be 0.4 GWa or 3500 GWh/y.) For those impacts that are not directly related to electricity production -- meaning the impact generally occurs whether or not the plant is operating -- reporting is in terms of the plants rated capacity (GW). For a CANDU 3, the rated capacity would be 0.45 GW. The use of these conventions will allow SECDA to more readily and fairly compare the benefits and impacts of a CANDU 3 with other energy technologies.

Report Organization

This report is organized according to the six segments comprising the nuclear fuel and plant cycles. Nuclear fuel requirements and costs are reviewed in Section 2. The schedule and cost of plant construction are evaluated in Section 3. Next, Section 4 presents plant operations which includes topical areas covering design enhancements, capacity factor, radiological emissions, staffing requirements' occupational dose and Operational, Maintenance and Administrative (O,M&A) costs. Sections 5 and 6 review plant decommissioning and radioactive waste; the back ends of the plant and fuel cycles. Finally, Section 7 presents a recommended strategy for evaluation of the environmental externalities for a potential CANDU 3 in Saskatchewan.

Summary of Results

The results of ERG's evaluation are presented in Table 1-2, which present technical parameters and environmental impacts, and Table 1-3 which presents cost estimates. In each table the quantitative estimates of AECL and ERG are presented.

In general, ERG believes that a CANDU 3 will provide adequate protection for both human health and the environment. Indeed, the plant's design should afford an increment of additional protection beyond that provided by the 22 CANDU plants currently operating in eastern Canada. As indicated in Tables 1-2 and 1-3, ERG found -- on the basis of the information made available for this report -- that some of AECL's performance and cost objectives are optimistic in that while theoretically achievable, they allow little or no margin for unforeseen events over a 40-year period of operation.

The plant's construction schedule, capacity factor and plant staff size projections are the most significant examples of values that should be viewed with some skepticism by SECDA. The optimism of these projections tends to minimize plant capital and operations costs below realistic levels. The values that were estimated by ERG were generally intended to establish a realistic upper and lower bound for a given parameter.

Table 1-1
Summary of Generic Parameters

Parameter	Value
Population density within 100 km of a plant in Saskatchewan	7.3 people/sq km
Radiological health effects - general public (fatal and non-fatal cancers and genetic defects)	0.1/person-Sv
Radiological health effects - plant workers (fatal and non-fatal cancers and genetic defects)	0.08/person-Sv
Exchange rate (U.S. to Canadian)[1]	1.36
Real interest rate	5% per annum
Construction worker salary (fully burdened)	$40,000/year
Nuclear plant worker salary (fully burdened)	$90,000/year

Note:
(1) *Wall Street Journal,* Friday, March 18, 1994, p. C6.

Table 1-2
Summary of CANDU 3 Projected Technical & Environmental Parameters & Impacts

Segment/Cost Parameter	Estimates: AECL	Estimates: ERG	
Fuel Consumption			
Uranium requirement	188 Metric Tonnes Uranium (MTU)/GWa	188 MTU/GWa	
Construction			
Permanent site area	20 hectare	20 hectare	nominal
		25 - 30 hectares	upper limit
Project schedule	64 months	71 months	
Construction period	38 months[1]	45 months	
Routine Operations			
Capacity factor	94% target	94%	high case
		88%	nominal case
		81%	low case
Staff size	351 people[1]	368-423 people	
Population dose	not calculated	0.0107 person-Sv/GWa[2]	
Occupational dose (per year)	1.67 person-Sv/GW	4.5 person-Sv/GW[3]	high case
		1.7 person-Sv/GW[4]	expected case
		0.8 person-Sv/GW[5]	low case
Catastrophic Accident	not calculated	<u>Delayed Release</u>	<u>Quick Release</u>
Probability		1×10^{-6}/reactor-yr	6×10^{-8}/reactor-yr
Population dose		87 person-Sv	920 person-Sv
Health effects		8.7 effects	92 effects
Property damage		$100 million	$1 billion
Human risk		2.2×10^{-5} effects/GWa	1.4×10^{-5} effects/GWa
Decommissioning			
I/LLW volume	4,000 cubic meters	4,000 cubic meters	
Occupational dose	not calculated	less than 2.3 person-Sv[6]	
Population dose	not calculated	less than 0.01 person-Sv[6]	
Radioactive Waste[7]			
Used fuel	79.2 metric tonnes (MT)/yr	79.2 MT/yr	
Routine ILW	40 cubic meters/yr	40 to 50 cubic meters/yr	

Notes:
(1) Estimate modified or received after draft ERG report presentation.
(2) Yields 0.04 health effects over a 40-year period.
(3) Yields 6.5 health effects over a 40-year period.
(4) Yields 2.5 health effects over a 40-year period.
(5) Yields 1.2 health effects over a 40-year period.
(6) Health effects would be based on the length of dismantlement.
(7) From routine operations.

Table 1-3
Summary of CANDU 3 Project Cost Estimates

Segment/Cost Parameter	Estimates	
	AECL	ERG
Fuel Consumption Uranium & Fabricated Fuel Bundles	$23M/GWa	$23M/GWa
Plant Construction Capital Costs (without interest during construction)	$1.19 - $1.26B ($2,645/kW-$2,800/kW)	$1.219 to 1.289 billion[1] ($2708 to 2866 $/kW)
Routine Operations O,M&A Capital Improvements Fuel Channel Retubing	$48M/year[2] $10.5M/year[2] $120 to 140M[2]	$46 - $52M/year $9 - $10.5M/year $120-180M
Decommissioning Decommissioning Final I/LLW Cost Site Monitoring	$100 - $140M $7.2M $27.5M[2,3]	$163 - 213M $7-$18M $45M[1,3]
Radioactive Waste[4] Final Used Fuel/Disposal Final I/LLW Disposal	0.35 - 0.7 mills/kWhr Not provided	0.7 - 1.36 mills/kWh $2.9 - 9M

Note:
(1) Estimate reflects adjustment in construction cost only. Not enough information was provided by AECL to judge the capital estimate.
(2) Estimate modified or received after draft ERG report presentation.
(3) Total cost over the 30-year "mothball" period.
(4) From routine operations.

2. FUEL CONSUMPTION/PRODUCTION

The uranium requirements of a CANDU 3 have been estimated by AECL to be 188 MTU/GWa, which is consistent with classic textbook fuel utilization rates.[1] For CANDU reactor technology, uranium requirements are essentially linearly related to the plant's capacity factor because there is no enrichment of U-235.

In recent years, stringent controls have been imposed on uranium mining operations to ensure that radiological and chemical emissions from the mill tailings are mitigated. In Saskatchewan, uranium mines are regularly inspected for environmental compliance by the Saskatchewan Mines Pollution Control Branch, the Saskatchewan Mines Inspectors, the Atomic Energy Control Board (AECB) and Environment Canada.[2] Standards are in place for most of the chemical contaminants released as a result of uranium mining and milling operations. Recent environmental impact assessments of existing and proposed mine sites in Saskatchewan indicate that, as long as recommendations on site clean-up practices are met and regulations enforced, then mining will not pose significant environmental or health impacts.[3] Any incremental impacts from a single CANDU 3 would be relatively small as, even when operating at 100% capacity, it would require only about 0.5% of the existing annual uranium production at mining sites in the Province of Saskatchewan.[4] Thus, any incremental impacts to the environment would be minor.

Uranium for a CANDU 3 is expected to cost approximately $23 million/GWa according to AECL. This estimate appears reasonable given the prevailing spot market prices of yellow cake ($12.92/Lb U_3O_8) and conversion ($7.27/KgU).[5] These spot market prices are at historically low levels and should remain so for the foreseeable future. Even if prices increase, they would have to do so several times over to measurably impact busbar cost because fuel costs are a small part of the total cost of power for a nuclear station.

3. PLANT CONSTRUCTION

Schedule Requirements

Background - The most recent information from AECL[6] identified the total project schedule for the first of a kind CANDU-3 to be 64 months from project inception (contract effective date) to commercial operation. The 64-month schedule proposed by AECL includes the optimum time required in advance of the first concrete pour for procurement activities and completion of site-specific design, and further assumes that items such as procurement of required licenses and preparation of the site for erection of formwork can be accomplished within the same time. The construction portion of this schedule -- defined as time from first concrete pour to commercial operation -- is projected to be 38 months which includes a three-month contingency.

Pre-Construction Activities and Improvements - The preconstruction activities involve such things as procurement of site-related construction licenses, completion of site specific building and system designs, initiation of the procurement process and finally site preparation, erection of construction facilities and excavation for the permanent plant facilities. AECL is planning to complete all up-front licensing in advance of beginning the first project, and one of the primary objectives is to standardize the design to suit a wide variety of site conditions with minimal site-specific design. Assuming that these goals are met and there are no site-specific peculiarities, ERG finds that this portion of the project should achieve significant schedule reductions in comparison to previous CANDU construction.

Construction Improvement - There are several reasons why a CANDU 3 should have a shorter construction sequence and time frame than previous CANDU designs,[7,8] namely:

- simplification of station layout;

- considerable reductions in cabling and wiring as a result of distributed control systems;

- fewer components and commodities because of simplification and scaling factors; (See Appendix C)

- CADD based design which should minimize construction interferences; and

- extensive use of modularization construction techniques.

On the other hand, the passive containment is a more robust structure with a steel liner, features which are new to the CANDU 3 and may offset some of the expected construction sequence and time frame savings.

AECL is planning to use extensive modularization techniques which rely on very heavy lift (VHL) cranes, and open top construction intended to minimize construction by allowing multiple activities to be conducted in parallel. ERG has confirmed that this technique has been used extensively -- with success -- on other non-nuclear construction projects. However, ERG is unaware of widespread use of these techniques in nuclear plant construction either in the US or in Canada. Moreover, there are some significant differences between the modularization projects cited by AECL and a CANDU 3 -- the size and number of components being but one example. It is therefore unclear that dramatic reduction in schedule will be obtained through modularization techniques on a plant the size of a CANDU 3.* Also, first-of-a-kind problems associated with the lead CANDU 3 plant are inevitable and could somewhat offset savings from the design and construction technique enhancements.

Project Schedule - The AECL anticipated project schedule of 64 months[6] from project inception to plant start-up, although based on sound engineering practices, is optimistic, especially for the first CANDU 3 to be built (and possibly the first wide-scale use of modularization in nuclear power plant construction in North America). In

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* As an example, the Zimmer Generating Station conversion project attributed the short construction schedule to extensive use of modularization.[9] However, during discussions with personnel involved with the conversion,[10] ERG learned that much of the gain was in the fabrication of large components at vendor facilities and shipping by barge to the construction site. A CANDU 3 plant does not, because of its size, have as many large components where modularization at Zimmer proved so effective and, even if it did, a site in Saskatchewan will not have access to facilities that can transport such modules. So, AECL may have to fabricate large modules on site in a temporary facility -- which could increase costs.

a stable regulatory environment and with demonstrated construction techniques, later CANDU 3's are more likely to achieve the 64 month schedule. ERG's primary area of concern is the "construction schedule" -- which is only 38 months in length (including a three-month contingency). It is important to note that the actual period of physical construction is only 32 months in length as "plant commissioning" comprises the other six months. ("Plant Commissioning" incorporates among other actions initial critically and low power acceptance testing as shown in the AECL CANDU 3 "Target Schedule" N-PS-566-2-E.)

Clearly, there is substantial worldwide knowledge and experience with the pouring of concrete, welding of pipe, wiring and the like that is involved in building a nuclear power plant. The extensive modularization that AECL plans for a CANDU 3 will make the construction easier and quicker. However, modularization may introduce new potential project delays that could result from improper manufacturing, design flaws, late deliveries, and substandard quality control. Likewise, traditional impediments to achieving a construction schedule such as severe weather, labor strikes and adverse regulatory actions are still possible in spite of modularization. It is not unreasonable to assume that the entire three-month contingency could be absorbed in the 32-month construction phase -- as there will be a learning curve on this first of a kind CANDU modularized construction. In fact, for the first CANDU 3 it would be prudent to triple the construction contingency from three to nine months.

If the existing contingency of just three months is used during physical construction, then plant commissioning would have to be perfect for the overall schedule to be achieved. A review of the time required for the plant commissioning of the CANDU 6 reactors indicates the following:[7]

Pt. Lepreau	7 months
Gentilly 2	13 months
Wolsong 2 (Korea)	3 months
Embalse (Argentina)	10 months

The Canadian average (Pt. Lepreau and Gentilly 2) is 10 months and the overall range shows how unpredictable a plant commissioning process can be -- which is not surprising given that the aim is to test equipment and correct deficiencies.

Accordingly, ERG recommends that an additional one-month of contingency be added to AECL's proposed six-month plant commissioning process to at least make it consistent with the Pt. Lepreau experience.

With the added contingency suggested by ERG, the overall schedule would be 71 months in length -- with the construction phase 45 months in length. This extra time is a prudent hedge for economic planning -- in fact a conservative investor might justifiably include additional contingency time. Once a CANDU 3 has been successfully built this added contingency time could be reconsidered.

Construction Staffing - The construction staffing levels provided by AECL(8) are strongly dependent on construction practices and the duration of the construction activities. AECL's anticipated peak trade workforce of 1,000 to 1,300 people (which ERG could not verify) should in theory result in the efficient use of manpower. Large workforces, especially on small sites, are difficult to manage efficiently and are apt to result in decreased productivity and, in turn, increased costs. AECL did not provide enough information to reach any substantive conclusions relative to the expected total person-years of the trades workforce other than that it is largely dependent on construction practices and duration of construction.

Capital Costs

AECL estimates the capital costs at $1.19 to $1.26 Billion or $2,645/kW to $2,800/kW.(8) (This includes a construction cost of $320 to $350 million.) On the basis of limited information from Pt. Lepreau regarding that facility's overnight construction cost, the estimates for a CANDU 3 appear reasonable. ERG cannot verify a specific range of capital costs given the incomplete information currently available from AECL. Of course, the eventual purchase price for a CANDU 3 is subject to the completion of the design work and commercial negotiation and could differ from the above estimates. (Komanoff's(11) arguments regarding capital cost escalation during construction at Ontario Hydro's units were driven by new regulatory initiatives. Such regulatory requirements have been incorporated in the CANDU 3 design.)

For planning purposes, however, the effect of ERG's proposed seven-month construction contingency should be added to the AECL estimate. Assuming that the construction extension (of six months) occurs during the peak work force period of 1,300 people with a fully-burdened cost per person-year of $40,000 the effect on the capital budget would be $26 million. The additional one-month contingency on the plant commissioning process -- assuming an average of 390 plant workers at $90,000/year and 300 construction workers at $40,000/year would add another $3.9 million to the capital cost. So the capital cost could be $1.219 to 1.289 billion or $2,708 to $2,866/kW. (Interest during construction is not included in this estimate. At a 6% rate, however, interest costs would increase at least $44 million with a seven-month construction delay.)

4. PLANT OPERATIONS

Design Enhancements

It is important to note that the CANDU 3 is intended by AECL to satisfy an expected demand in many countries for a smaller version of the existing CANDU 6 which has so far achieved superior levels of performance. Thus, AECL's focus was, understandably, to achieve "capital and operating cost which are not substantially greater per unit of generating capacity ($/kW) than those achievable with larger nuclear units (>600 MW) which have demonstrated attractive economics in utility operation."[12]

The CANDU 3 design is evolutionary[13,14] in that it incorporates both: the "lessons learned" from its pedigree of CANDU 6 and Ontario Hydro multiple unit sites; and more advanced materials and instrumentation/control technologies. In a review of the CANDU 3's design features,[14] ERG identified several that should simplify operation and potentially make it an incrementally better performer than the CANDU 6 plants currently in operation. Some of the more significant are:

- fewer components as a result of simplified design;
- reductions in the amount of equipment requiring seismic/environmental qualification;
- control feature enhancements;
- fewer fuel channels (232 vs. 380 for the CANDU 6);
- simplified primary system (two steam generators vs. four for the CANDU 6); and
- modifications of human-machine functions to incorporate feedback from operating CANDU stations.

On the other hand, some design concerns remain. It cannot be stated definitively that the issue of pressure tube degradation has been resolved, although it is clear that the phenomena is understood and that better materials and designs (annular spacers) are being used. In fact for a CANDU 3, pressure tube replacement sometime after 25 to 30 years of operation is likely[13] -- albeit a process that design improvements will make easier and faster relative to the experience at other CANDU plants. Steam generator tube fretting is not unique to CANDU technology. The type of change made for Ontario Hydro's Darlington facility appears to be a good solution that will be proven by the time a CANDU 3 is built.[15] For added reliability, the CANDU 6 design includes installed spares for most rotating equipment and power transformers required for 100% power operation. It was unclear from the available literature whether this same philosophy was used for the CANDU 3. The single-ended refueling machine is intended by AECL to improve refueling tasks. However, since it is a new design, unanticipated problems could be experienced early in plant life.

The degree to which a simplified design and the use of fewer components will improve a CANDU 3's reliability in comparison to previous designs cannot be quantified without detailed engineering studies and some actual plant performance. Nevertheless, the CANDU 3 design enhancements are consistent with those being incorporated in advanced LWR designs in the United States and Europe and should result in an incremental improvement in plant reliability.

Capacity Factor

The recovery of capital and O,M&A costs for a facility are closely related to a plant's capacity factor -- accordingly a realistic one should be used to account for both planned and unanticipated events over a plant's operating life.

AECL's assignment of a "target" lifetime capacity factor of 94% for a CANDU 3,[6] is optimistic and is not recommended for use in SECDA's economic planning. Table 4-1 shows the basis of AECL's CANDU 3 capacity factor estimate. The combination of the planned and maintenance outages are in agreement with the experience of Pt. Lepreau over its first eleven years of operation. The major outage of 180 days is interpreted by ERG to be for retubing which is anticipated for the CANDU 3 at about year 30. Derating and spurious trips total 98 hours per year which ERG believes is not realistic over a 40-year period. As an example, if a CANDU cannot start up within 30 minutes of a trip it must wait 36 hours because there is insufficient reactivity to overcome the xenon "poison" (meaning neutron absorption) which builds up immediately after shutdown and then decays.

Overall, AECL's capacity factor estimate provides almost no margin for unanticipated events and new AECB requirements. It should be viewed as a "high case."

Table 4-1
AECL Estimated Impact of Outages on a CANDU 3's Capacity Factor[6]

Anticipated Outage Activity		Effect On Lifetime Capacity (%)
Planned outages	(10 days/odd years)	1.37
Maintenance outages	(18 days/even years)	2.47
Major outage	(180 days in 40 years)	1.14
Derating	(2 days at 60% annually)	0.22
Spurious trips	(70 hour outage annually)	0.80
	TOTAL	6.00

The operation of Pt. Lepreau, Gentilly 2 and the Ontario Hydro units plus the CANDU 3's design data provide some guidance in selecting expected and low-case capacity factors for economic analysis.

Pt. Lepreau has achieved a 93.4% cumulative capacity factor over its first 11 years of operation.[16] This is a strong indicator that a CANDU 3 could operate for substantial stretches of time at the "target" capacity. Conversely, such a high capacity factor is unlikely to be maintained for a 40-year period. For instance, Pt. Lepreau will enter a six-month outage in 1995 for electric generator repairs and fuel channel spacer adjustment.[14] At that time, the plant's cumulative capacity factor will be reduced to around 90%, or even less if there are delays or unanticipated events. In future years, an additional outage period of 12-18 months (as currently planned) for fuel channel replacement will be necessary for the station to run to the end of its 40-year design life.[16]

Gentilly 2 has also performed well over its lifetime with a 70.7% capacity factor.[17] ERG's analysis shows that about 10 percentage points of capacity factor loss may have been from load reductions due to excess hydro capacity. Problems with the turbine pedestal during the first 10 years of operation has caused long outages for re-alignment that account for about 12 percentage points of the capacity factor loss. (This is a good example of an unanticipated technical issue that is clearly not considered in AECL's capacity factor target.) Labor issues, which can happen anywhere, accounted for another five percentage points of capacity factor. (There have also been some persistent fuel handling machine problems that caused Gentilly 2 to run in a coast-down mode.)*

Ontario Hydro's multi-unit CANDU's represent the other end of the performance spectrum with a weighted cumulative capacity factor of 73.5% (which by U.S. LWR standards would be quite high). These units have faced the learning problems associated with new technologies such as material behavior (pressure tube hydriding), design flaws (steam generators) and the need to accommodate more demanding regulatory requirements (environmental qualification programs).[15] If the "learning curve" of retubing is taken into account, the Ontario Hydro weighted cumulative capacity factor would increase to 81%.[18]

Komanoff[15] has suggested that plant aging phenomena will cause capacity factors at Ontario Hydro's nuclear plants to drop off significantly after the first 11 years of operation. His regression analysis, however, assumed that current plant problems would continue and combine on a statistical basis with tenuous aging trends into an almost exponential decline in plant performance. Moreover, the regression also fails to account for the capacity improvement from management initiatives, increased O&M spending and design improvement. Over the course of a 40-year operating life, nuclear power plants undergo rigorous maintenance, upgrading and refurbishment/replacement under a comprehensive regulatory regime. These actions mitigate age-related degradation of components and systems. In short, a plant's advancing age should not mean a decline in performance or reliability -- although economic factors could change, and in some circumstances cause a premature shutdown, as demonstrated by several plants in the United States. Such economic factors can be beyond the control of plant owners -- programmatic regulatory

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* For perspective, Wolsong 1 in Korea and Embalse in Argentina have cumulative capacity factors of 85.2 and 80.2 respectively.

requirements (stemming from technical considerations or political/public pressure) that increase cost but not performance is but one example.

In summation, the CANDU 6 design appears to have mitigated many of the problems encountered in the Ontario Hydro multi unit plants. Still, the design life of the reactor pressure tubes remains 30 years and will require replacement before the end of both a CANDU 6 and 3's operating life.[13,16] And, new materials or technological problems can always arise once contemporary issues are solved. Accordingly, ERG recommends a nominal CANDU 3 lifetime planning capacity factor of about 88%. Table 4-2 summarizes the components of this estimate which is based on our engineering judgment and the performance of Pt. Lepreau and Gentilly 2. It is important to note this table represents typical outages that are both planned and unanticipated. A brief discussion of the basis of ERG's capacity factor estimate is provided below.

The 30-day equivalent maintenance outage every two years was based on Pt. Lepreau's experience and is quite close to the AECL estimate. The six-month outage to replace fuel channels is the same as the AECL estimate for this activity and includes the planned maintenance cited above. The 60-day outage every 10 years (which would also include planned maintenance) for major turbine generator work is included to account for maintenance problems that are more extensive than those scheduled for the routine annual maintenance. This was not included in AECL's estimate.

Over a 40-year period, some unanticipated problems that cause the plant to be shutdown for an extended period of time are inevitable -- based on the experience of over 400 LWR and CANDU reactors operating worldwide. For example, there are numerous cases of turbine generator problems occurring that could not be quickly repaired by the station staff with available material. Excess reactor coolant pump seal leakage and condenser tube leaks are examples of problems that any plant can experience. ERG believes that the six months included in the unavailability calculation is reasonable and assumes the utility will have access to an extensive parts inventory for use in case of equipment failures.

Table 4-2
Estimated Impact of Outages on a CANDU 3's Capacity Factor[1]

Anticipated Outage Activity	Effect on Lifetime Capacity (%)
30 day equivalent maintenance outage every two years (shutdown to return to 100% power operation).	3.5
6 month fuel channel replacement at year 30.	1.25
60 day outage every 10 years for planned turbine generator and secondary side repairs. (3 Total)	1.25
The equivalent of an unanticipated six-month outage before year 40.	1.25
The equivalent of two weeks per year for unanticipated operational occurrences such as spurious trips, deratings, instrumentation problems, etc.[2]	3.85
The equivalent of five months over a 40 year period for regulatory or labor related issues.[2]	1.00
TOTAL	12.1

Notes:

(1) The potential for the occurrence of two outage activities at the same time (i.e., routine maintenance) and the six-month fuel channel replacement have been accounted for to eliminate double counting.

(2) These two activities are separated and distinct and by definition do not occur at the same time. For example, if a plant is shut down for a regulatory issue it cannot have a spurious trip.

The equivalent of two weeks of down time per year for unanticipated operational occurrences such as spurious trips, deratings and instrument problems is not unreasonable given the performance histories of other CANDU reactor designs. Finally, the equivalent of five months of lost operating time over a 40-year operating period for regulatory and labor issues is conservatively low given the experience of other nuclear plants in Canada.

Finally, it should be noted that some site-specific conditions can influence capacity factors. In Saskatchewan, conditions such as the variation of cooling water temperature (between summer and winter) as well as the size of a plant relative to the capacity of the electric grid might influence the capacity factor. The quantifications of such possible influences on a CANDU 3's capacity factor were beyond the scope of this effort.

The achievement of high capacity factors, which ERG believes the 88% represents, requires a strong commitment from the operating utility to staff, train and provide the incentive to run efficiently as well as plan and execute short outages. As an example, there are many instances of identical, single-unit nuclear plants in the U.S. with substantially different capacity factors -- apparently because of different staff expertise and management philosophy. A worst case capacity factor would be about 81% based on the Ontario Hydro CANDU performance.[18,19] The best case would approach the 94% that AECL targeted.

Staffing Requirements

The staff size and make-up to support the operation of a CANDU 3 will be based upon three factors; manufacturers estimates, AECB regulations and the philosophy of the operating utility. It is important to note that nuclear power plants are dependent on a high quality and sufficient level of staffing to assure safe and reliable operations.

For a new plant, the manufacturer typically recommends a staffing plan that is consistent with the design and existing regulatory requirements. In turn, it has been historically typical for these recommended levels to be exceeded once the plant starts operation. (ERG is not aware of any nuclear plant that has an operating staff that is less than manufacturer recommendations.) New regulations and initiatives by the

AECB can lead to additional staffing requirements. As an example, AECB actions recently required Pt. Lepreau to increase its security staff by four individuals.[18] Often times the operating utility finds it desirable to add staff so that other important goals can be achieved. For instance, additional health physics technicians might reduce occupational exposure or more maintenance workers may increase plant performance. In other cases, the operating utility simply finds that more staff is needed just to meet nominal performance targets.

Staffing levels can also vary significantly from plant to plant based on utility management practices. Gentilly 2 and Pt. Lepreau, which are essentially identical plants, have on-site staffs of 600 and 453 respectively -- a difference of over 30 percent. In the Unites States, staffing levels at identical nuclear plants that are operated by different utilities can vary by up to 15% when statistical outliers are discounted.[20] The difference can be attributed almost exclusively to management practices.

AECL has estimated a 320 to 360 person staff for a CANDU 3's operation, based on a "balance of the variables of operational philosophy" and scaling.[8] In their most recent communication with SECDA, AECL provided an analysis showing a CANDU 3 staff of 351 individuals based on a bottoms-up comparison with Pt. Lepreau's 1989 staff level of 436.[8] (Recall that Pt. Lepreau staff is currently 453.) ERG found that approach logical, but somewhat optimistic when a long-term view is considered. That is because some of the largest reductions in staffing between a CANDU 6 and 3 were made in areas like maintenance, technical support, training and health physics, which are central to a plant's overall performance and often subject to adjustment by management.

Based on the AECL estimate and the current staff level at Pt. Lepreau, ERG believes that a lower bound for CANDU 3 staffing is 368 individuals (351 from AECL estimate plus 17 additional production related employees at Pt. Lepreau since 1989). As an upper limit, ERG used the 15 percentage point staff difference between some U.S. plants of identical design and vintage as an adder to the lower limit -- thus yielding a projected staff of 423 individuals.

Radiological Emissions

The operation of any nuclear power reactor results in the formation of radioactive materials. Almost all of this radioactive material remains contained within the used uranium fuel under normal operating conditions. During the course of operations, however, there is activation of material exposed to neutrons from the process of nuclear fission and there may also be isolated instances of leakage from the fuel bundles. For instance, impurities in the heavy water coolant may become activated and some heavy water can be converted to tritium (which is a radioactive isotope of hydrogen). Although filtration systems are utilized to minimize the concentration of these radioactive materials within the power plant, small -- often trace -- quantities are released to the environment.

The emissions of radioactive substances occur thru both airborne and waterborne pathways as summarized below:

Airborne

- Tritium - a radioactive isotope of hydrogen formed by neutron irradiation of heavy water; exists mainly as tritiated heavy water.
- Noble Gases - chemically inert gases which are by-products of the nuclear reaction within the reactor.
- Iodine - a vapour which is a by-product of the nuclear fission reaction.
- Particulate - minute solid particles which contain some radioactivity (e.g., radioactive iodine or cesium on dust particles).
- Carbon 14 - a radioisotope of carbon which is released primarily as carbon dioxide.

Waterborne

- Tritium - as above

- Gross beta and gamma - an all-encompassing category, which covers quantities of dissolved or suspended radionuclides in water.

- Carbon 14 - a radioisotope of carbon which is released as a carbonate or bicarbonate.

Atmospheric Emissions - These emissions are continuously monitored and must remain below regulatory limits set forth by the AECB. Specifically, the dose for a person living at the site boundary must be less than 5 mSv/a (the AECB is currently deliberating on a lower limit of 1 mSv/a).

ERG concurs with AECL's assertion that the design of a CANDU 3 should result in doses to a person living on the station boundary that are lower than the 0.008 mSv/a doses resulting from the Pt. Lepreau and Gentilly 2 facilities (which are only about 0.2% of the AECB limit).[8] However, it must be remembered that plant management and staff expertise can significantly impact radiological emissions. Typically smaller plants have smaller emissions than larger ones. Also, outage periods can cause emissions to "spike" in comparison to those during power operations because of the need to vent systems and buildings to perform maintenance. Ultimately, emissions are capped by AECB regulations and a plant would have to shut down if they were exceeded. To the best of ERG's knowledge, in over 300 reactor years of operation no Canadian plant has exceeded regulatory emissions limits.[6]

The impact of airborne emissions beyond the site boundary are a function of the level of radioactivity released and the total human population exposed (termed "integrated population dose").* Historical integrated population doses from Ontario Hydro's Bruce B units provide some insights that can be interpolated for a rough approximation of the impact of a CANDU 3 operating in Saskatchewan.[21] Using the Bruce B facilities' average (as measured) nominal total population dose of 0.01 person-Sv/GWa and ratioing respective population densities, a CANDU 3 might cause a population dose of 0.0107 person-Sv/GWa (or less) which would in turn yield less than 0.04 health effects over a 40-year operating period. (To account for the buildup -- albeit, a trivial

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* It is important to note that population density is a driving factor in the integrated population dose.

one -- of radioisotopes in the biosphere surrounding the plant, emissions were assumed to occur for 50 years after cessation of plant operations. This allows for the decay period for dominant isotopes such as Co-60, Ce-137, I-131 and Sr-90.) This value is both minor and consistent with the results from the U.S. National Institutes of Health (NIH) study on the health impacts due to nuclear power plant operations.[22] The NIH study, which was completed in 1990 examined the counties surrounding U.S. nuclear power plants for increased incidence of cancers -- none were found.

Waterborne Emissions - Ontario Hydro recently sponsored extensive studies on water quality impact (based on end-uses such as swimming, shoreline recreation, irrigation, drinking water and fish habitat) as a result of thermal and radiological emissions from its Darlington and Pickering A&B nuclear stations.[23] In all cases, the concentrations of radionuclides emitted into receiving waters were estimated to be less than the criteria levels adopted by various domestic and foreign regulatory agencies. In addition, the lifetime risks to the members of the most exposed group were estimated to be less than the de-minimis risk criteria for each of the identified water uses.

Thermal Emissions - For a CANDU 3 in Saskatchewan, AECL has estimated that the cooling effluent will be returned to the originating water body about 13°C above that of the intake.[8] That is not an unusual temperature increase -- however, the ability of the water body to assimilate such substantial thermal emissions even when diffuser systems are used is highly site-specific and remains an open issue.

The warm discharge water from a CANDU 3 can be used for other programs such as fish farming or agriculture greenhouses. Indeed, a tomato greenhouse is in operation at Ontario Hydro's Bruce facility along with some internal steam heating. In addition, secondary side condenser water is successfully being used from the Pickering A station to supply an aquaculture farm nearby.[24] (This concept would not be new to Saskatchewan as a tree farm is operated from the thermal discharge of an existing Sask Power plant.)

Occupational Dose

In the operation of nuclear power plants, workers can be exposed to small amounts of radiation in the performance of their work within limits that have been established by the AECB. A key principle of operating a nuclear power plant is to keep worker doses "as low as reasonably achievable" through good housekeeping at the plant, sound radiological protection procedures, worker training, comprehensive planning, and the use of robotics. The layout, testing, inspection, maintenance and equipment replacement requirements of a plant can also have a significant impact on occupational exposure. Typically, workers receive their lowest doses when performing routine functions during full power operations. The highest doses can be received in an outage period -- especially when a special project such as retubing or steam generator tube plugging is being performed.

The best way to compare occupational doses is on a net GW per year basis -- because occupational exposure occurs even when a plant is in a shutdown mode. Based on available data, ERG has calculated the range of doses that can be expected at CANDU's and LWRs. These calculations are summarized in Table 4-3. (Health effects were previously defined on page 3.)

Table 4-3
Comparison of Occupational Exposure Calculations

Facility		Annual Dose (person-Sv/GW)	Health Effects (40 yr. period)
Ontario Hydro Units (1988-1990)[1]		1.4	--
Ontario Hydro Units (1983)[1]		4.8	--
Gentilly 2	(1987-1993 average)[2]	1.5	3.2
	(High - 1993)	3.9	--
	(Low - 1987)	0.2	--
U.S. BWR	(1993 INPO Goal)[3]	2.9	8.0
U.S. PWR	(1993 INPO Goal)[3]	2.0	6.0

Notes:
(1) Derived from unit capacity factors[19] and reported occupational exposures[24] for all units.
(2) Source: conversations with Gentilly staff.[16]
(3) Derived from INPO performance indicators and average unit size of a U.S. BWR (866 MW) and PWR (948 MW).

The AECL occupational annual dose target for a CANDU 3 is 1.67 person-Sv/GW which, because of better plant layout, is 50% lower than the CANDU 6 design objective.[8] There is no doubt that an optimum plant layout can reduce occupational dose. AECL's estimate, however, will always be subject to the uncertainties of a plant staff's expertise and performance. Based on the values outlined above, ERG recommends the range of occupational doses shown in Table 4-4 for SECDA's planning purposes.

Table 4-4
ERG's Recommended CANDU 3 Occupational Dose Ranges

Case	Dose (person-Sv/GWe-a)	Health Effects (40 yr. period)	Source
Worst	4.5	6.5	ERG estimate based on Gentilly and Ontario Hydro high years
Expected	1.7	2.5	AECL CANDU 3 target projection
Low	0.8	1.2	ERG estimate, 50% of the Gentilly average occupational dose

Regulatory oversight, comprehensive procedures, worker training and plant design all combine to prevent a worker error or equipment failure from causing an excessive exposure to radiation. In fact, the "Nuclear Power Hazard Report"[25] prepared for the Coalition of Environmental Groups showed that only 1.5% of the significant events in the review period examined were classified as employee radiation exposure. In general, exposure from such "incidents" does not measurably increase the occupational exposure at a facility.

Operation, Maintenance & Administration (O,M&A) Costs

For a CANDU 3, AECL has estimated annual O,M&A costs of $39 to $52 million per year. In their most recent communication with SECDA, however, AECL states that they currently calculate an O,M&A cost for a CANDU 3 in Saskatchewan to be $48 million/year. ERG finds AECL's most recent estimate to be reasonable. This conclusion is based on the approximation -- from Pt. Lepreau data -- shown below.

The annual O,M&A budget (excluding fuel) at Pt. Lepreau is about $60 million.[16] If staffing and heavy water requirements are considered to be linear with plant size, then a CANDU 3 annual O,M&A cost would be 70% of $60 million or about $42 million. Because staffing is not linear, a further refinement to this approximation is to add in the cost associated with the difference between the linearized staff (70% of 453 or 317) and ERG's recommended staff size (368 to 423), which is 51 to 106 people. Assuming a fully burdened average budget of $90,000 per person, the resultant CANDU 3 O,M&A budget would range from $46 to $52 million/year.

Finally, in a properly run plant operating within a stable regulatory environment, O,M&A costs should increase at the nominal rate of inflation. Poor management and/or increased programmatic requirements by AECB can lead to sustained increases in O,M&A costs that are above the inflation rate.

Capital Improvement Costs

Capital improvements are required over the entire operating life of a nuclear plant and typically reflect routine equipment replacement and plant upgrades and improvements. In general, capital improvement costs at U.S. nuclear plants have ranged from less than 1% to over 7% per year of initial capital costs.[26] Because of the advanced design of a CANDU 3 and the historical performance of Pt. Lepreau and Gentilly 2, ERG has assumed that nuclear capital improvements will be equal or less than those incurred at other nuclear plants with superior performance -- that is, about 1% of initial capital costs. This annual capital cost (subject to nominal inflation) for a CANDU 3, assuming an original equipment capital cost of $910 million ($1.26 billion total capital cost minus $350 million construction cost) should be about $9 million. At Pt. Lepreau and Gentilly annual costs have been about $11 million and $15 million respectively (and holding steady).[16,17] On a linear scale, that translates into $7.7 to $10.5 million for a CANDU 3 which is a good check on the above estimate. Additionally, AECL has found annual capital improvement costs of $10.5 million to be reasonable.[6]

It has been reported that the pressure tubes of a CANDU 3 will probably have to be replaced at about year 30 of operation.[13] This would constitute an extraordinary capital improvement that was not considered in the above estimate. AECL estimates that retubing a CANDU 3 will cost between $120 and $140 million which appears reasonable given the goals of the plant's design.[6] If the design improvements of a CANDU 3 fall short then the retubing cost could approach that which is projected for Pt. Lepreau. More specifically, Pt. Lepreau reports that retubing could cost from $400-800 million. Using the $400 million cost* and scaling by both plant size (0.7) and the absolute number of fuel channels (0.64) an upper cost limit for a CANDU 3 could be $180 million.

Safety

Design Improvements - The design of a CANDU 3 contains numerous features which should add an additional margin of safety relative to the CANDU 6:[27,14]

- improved shut-down system due to faster response times from lighter shut-off (control) rods, fast-trip logic and an increased number of trip parameters;

- better Emergency Core Cooling System (ECCS) instrumentation layout with increased computerization. And, the reliability of the ECCS should be increased through added redundancy and more amenable access for testing and inspection;

- enhanced heat transport system through a simplified one-loop arrangement and larger pressurizer which allows for a larger coolant inventory;

- higher moderator heat sink margins which provide better heat transport under accident conditions;

- seismically and environmentally qualified shutdown cooling system designed to operate at full heat transport pressure and temperature;

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* There is some indication that the $800 million value may be an unrealistic upper limit for Pt. Lepreau so it has not been used in this analysis.

- a passive containment system designed for higher accident pressures; and

- increased seismic stability.

ERG is confident that a CANDU 3's smaller core, improved in-core neutron monitoring system and optimized reactor physics design should ameliorate the impact of core flux tilting because of xenon build-up and subsequent oscillation. This phenomena is well understood and can theoretically occur in any type of nuclear reactor although it is exacerbated with larger reactor cores typical of CANDU technology. It should not be considered as a significant safety issue by SECDA.

All of these features can be viewed as positive safety enhancements. However, the only way that their impact can be quantified is through a comprehensive probablistic risk assessment (PRA). The magnitude of improvement could then be ascertained through a comparison with the PRA performed for the CANDU 6. AECL reports that a "mini" PRA -- to provide reliability targets in the early design phase of safety related equipment -- has been completed for a CANDU 3. The results, however, are considered proprietary and were not available for this evaluation.[8] The CANDU 3 is an evolutionary design that incorporates both the "lessons learned" from the operation of the CANDU 6 reactors and technological advancements. Therefore, there are unlikely to be substantially different PRA results between a CANDU 3 and CANDU 6 -- in fact the results should be within the same order of magnitude.

Almost all postulated accidents at nuclear power plants are mitigated by safety systems and do not result in radiation releases to the environment. Recall that the Three Mile Island accident which involved a core meltdown released only small quantities of radioisotopes. This occurred because the containment system performed as designed and isolated the radioisotopes from the environment. It is also completely inappropriate to relate the Chernobyl accident to CANDU (or LWR) reactors because they have completely different designs and massive containment structures.

For this review, some simple calculations were performed to approximate the upper limit of public health impacts and property damage from a catastrophic accident at a CANDU 3 operating in Saskatchewan. (A more precise calculation would result from a "level 3" PRA, which to the best of ERG's knowledge has not been performed on a CANDU.) By definition, a catastrophic accident involves an extensive core meltdown, the joint or sequential failure of all plant safety features and a bypass or rupture of the plant's containment. For perspective, this is an accident orders of magnitude worse than the one which occurred in 1979 at Three Mile Island.

The approximate upper limit was based on the CANDU 6 PRA results (CANDU 3's should be incrementally safer) and published data from Ontario Hydro and U.S. facilities.[24,28,29] Data was linearly scaled on the basis of plant size and population densities. Because the CANDU 6 PRA accounts for only the internal initiators of a catastrophic accident, ERG increased the probability of occurrence by a factor of 2 to account for external events such as earthquakes, tornados and aircraft crashes (into the facility). Property damage was based on a semi-rural and agricultural economy.

As shown in Table 4-5, ERG's approximation covers both a delayed and quick release scenario (hence the range of values). This approximation should be used with caution given that such calculations are highly plant-specific and should be based on comprehensive PRA's.

The primary reason why the consequences of a catastrophic accident are relatively small is the low population density that would surround a CANDU 3 in Saskatchewan. For perspective, in an estimate made by the U.S. General Accounting Office (GAO) about 25% of the nuclear power plants in the U.S. would have less than 100 health effects and less than $1.3 billion (U.S.) in property damage as the result of a catastrophic accident.[29] On the other hand, the same GAO report indicates that such an accident at the Indian Point 3 plant, located near New York City would cause 1,700 health effects and $17 billion (U.S.) in property damage.

Table 4-5
Approximation of Public Health and Economic Consequences of a CANDU 3 Severe Accident in Saskatchewan

Parameter	Value		Source
	Delayed Release	Quick Release	
Accident Probability of Occurrence[1]	$1x10^{-6}$/reactor-year	$6x10^{-8}$/reactor-year	CANDU 6 PRA results
Population Dose per Accident	87 person-Sv	920 person-Sv	Linearly scaled from Ontario Hydro data
Health Effects per Accident	8.7 effects	92 effects	See note 2
Overall Health Risk	$2.2x10^{-5}$ effects/GWa	1.4 $x10^{-6}$ effects/GWa	See note 3
Property Damage per Accident	$100 million	$1 billion	ERG estimate based on Bruce data

Note:

(1) Probability of Occurrence includes both internal and external accident initiators.

(2) 87 person-Sv • 0.1 effects/person-Sv = 8.7

(3) 8.7 eff./accident • $1x10^{-6}$ accident/reactor-year • $\frac{\text{1 reactor-yr}}{\text{0.4 GWa}}$ = $2.2x10^{-5}$ affects/GWa

92 eff./accident • $6x10^{-8}$ accident/reactor-year • $\frac{\text{1 reactor-yr}}{\text{0.4 GWa}}$ = $1.4x10^{-5}$

5. DECOMMISSIONING

Background

Decommissioning a nuclear plant involves: shutting the station down; removing radioactive materials; recycling/reusing useful, non-radioactive material and equipment; and finally dismantling the plant so that the site is available for other uses. Conceptual planning in Canada calls for decommissioning to occur over a 40-year period.[30]

Basically, following the shutdown of a nuclear station, materials such as used fuel would be removed and stored on site in existing facilities or transported to a storage site if one is available. Heavy water would either be sold or treated as a liquid waste depending on the demand for heavy water at the time of station shutdown. Other structures and equipment contaminated with radioactivity would be left in place -- subject to monitoring and security -- for about 30 years to allow radioactivity levels to decay. Subsequently, dismantlement would take place with resulting low and intermediate radioactive wastes. Dismantlement would also generate a large volume of non-radioactive waste which could be landfilled or sold as scrap.

Decommissioning Cost

Plant Dismantlement - AECL provided little data relative to the decommissioning of a CANDU 3 reactor, especially in the areas of cost, waste volumes, and occupational and public radiological doses. It is also important to note that the Canadian nuclear industry has no experience in the full-scale dismantling a commercial nuclear power plant as the currently retired plants, Douglas Pt. and Gentilly 1, are in a so-called "storage and surveillance" state.

The decommissioning cost of $100 to $140 million that AECL estimated for a CANDU 3 are low in light of recent estimates from U.S. plants. For the Yankee Rowe reactor (185 MWe, LWR), dismantlement was recently projected on the basis of a detailed engineering evaluation to cost $141 million.[31] The dismantlement of a plant is actually a straightforward process from an engineering perspective and fairly accurate budget estimates should be possible. Based on the Yankee estimate, ERG believes that the cost of a CANDU 3's decommissioning could be as much as $213 million (exclusive of waste disposal costs and any necessary caretaking while the facility is in a storage and surveillance type state). *

In their decommissioning cost estimate, AECL takes into account the salvage value of heavy water. ERG believes that this may be somewhat optimistic because the long term market for heavy water that is contaminated with tritium is uncertain. And, even if new CANDU plants are constructed it would seem that the inclination of the owners would be to purchase the contaminated heavy water at a discount -- probably equal to the cost of removing the tritium. (Simply, the value of pure heavy water cannot be the same as heavy water contaminated with tritium.) Accordingly, ERG assigned a heavy water salvage value of $50 million (which reflects the cost of tritium removal) and used it to estimate a low end dismantlement cost of $163 million. A high end dismantlement cost of $213 million assumed no net salvage value for heavy water. Based on a 5% real interest rate and an 88% capacity factor, this would require a decommissioning fee of between 0.39 and 0.51 mills/kWhr to be recovered during plant operations over a 40-year period.

I/LLW Disposal - It is not clear if AECL included the cost of I/LLW disposal in their decommissioning cost estimates. Based on the information that AECL provided and data available on other CANDU's[24], ERG estimates that up to 4,000 cubic meters of I/LLW could be generated with the dismantlement of a CANDU 3 -- a value that AECL concurs with. The sources of such waste would be component parts of the reactor assembly, reactor vault concrete, steel liner and steam generators, as well as pumps, heat exchangers and some surfaces of concrete structures. The cost of the disposal is hard to quantify, but as will be discussed in the next section could be as much as $1,785 to $4,500/cubic meter. (In fact, much of the recent escalation in the estimates for U.S. nuclear plant decommissioning have been because of LLW disposal

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* The basis for this estimate is as follows. First, the Yankee cost was scaled upward to reflect the larger size of a CANDU 3 (450 MWe + 185 MWe * $141 million = $342 million). Of that total cost, about 75% is for labor, with the remainder for fuel, machinery and transportation. To reflect the fully burdened salary of a construction worker in Saskatchewan (see Table 1-1) the labor cost ($342 million * 0.75 = $256 million) was halved -- as the Yankee estimate used Massachusetts labor costs. Thus the estimated CANDU 3 dismantlement cost is: $128 million + ($342 million * 0.25) = $213 million.

costs.) This potentially means another $7 to $18 million would have to be available in decommissioning funding. Using a 5% real interest rate and an 88% capacity factor, this yields an additional decommissioning fee of .017 to .042 mills/kWhr.

Long Term Monitoring - For a single unit site, the costs of monitoring and guarding a retired nuclear power plant -- with spent fuel and other wastes still on the property -- can accumulate over a 30-year period. AECL estimated this cost at $915 thousand per year which is not unreasonable. An upper limit cost might average around $1.5 million per year over the 30-year mothball period (or $45 million total). Thus a fee of 0.06 mills/kWhr may also have to be collected for this. Obviously, if the site is immediately used for other purposes (e.g., new adjacent power plant) this cost estimate could be substantially reduced.

Occupational Exposure

Even after a 30-year cooldown period, a nuclear power plant still contains substantial quantities of radioactive materials. As a result, workers and the general public will receive small radiological doses. In the absence of detailed decommissioning plans, it is difficult to make estimates of the potential radiological doses. However, if properly performed, radiological doses to both the public and workers from dismantlement should not exceed those from normal, full power operations. In other words, if dismantlement took 3 years, worker doses should be less than 2.3 person-Sv. (From Table 4-4, 1.7 person-Sv/GWe-a * 0.45 GWe * 3 years = 2.3 person-Sv.)

6. RADIOACTIVE WASTE

Used Fuel

Estimated Quantity - Under normal operations, ERG agrees with AECL that a CANDU 3 would produce approximately 200,000 kg of used fuel per GWa.[8] At an 88% capacity factor, approximately 3,199 metric tons of used fuel would be produced by a CANDU 3 over a 40-year period (or 79.2 MT/yr).

Storage/Disposal Cost - Used fuel must be stored for at least several years under water to allow for radiation (and residual heat) to decay to lower levels. Subsequently, dry storage in concrete or steel casks outside of the reactor building is a viable long-term strategy if the capacity of the used fuel pool is exceeded - an increasingly common occurrence in the U.S. -- or after plant dismantlement if a permanent disposal site is not yet available.* AECL has included the costs of constructing and operating a dry storage facility in their capital and O,M&A estimates for a CANDU 3. ERG could not confirm the AECL estimates because they were not defined.

The safe disposal of used fuel is an issue of national responsibility in every nation that operates a nuclear reactor. The disposal concept under consideration by the Canadian government -- which is being coordinated by AECL -- involves encapsulating used fuel in long-lasting containers. These containers would be placed in engineered vaults some 500 to 1,000 meters deep in the stable, granitic rock of the Canadian shield.[32] (The governments of Japan, France, Sweden, the United States and others have performed studies that show this is currently the safest storage concept available.) A Canadian disposal facility of this type would take about 40 years to be filled and would then be backfilled and sealed, once general confidence in disposal had been

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* Dry storage is being proposed for use at Ontario Hydro's Pickering facility. Dry storage involves monitored storage of used fuel above ground in concrete containers. Since 1988, Ontario Hydro has operated two demonstration dry storage containers at Pickering under the approval of the AECB. Results to date show this technology has a capability for safe and long-term storage of used fuel similar to water-filled pools. Studies by AECL and Ontario Hydro indicate that dry storage technology could be used to store used fuel for at least 100 years.[31]

established. Initial schedules call for the site to be available in 2025. Studies by Ontario Hydro and others[33,24] have estimated that a Canadian disposal site would cost between $9 and $15 billion.

AECL stated that the cost for final disposal at a federal facility would be in the range of 1 to 2% of the "unit energy cost" or about 0.35 to 0.7 mills/kWhr which appears low in comparison to the spent fuel fee of 1.36 mill/kWhr (in Canadian dollars) U.S. utilities are assessed. ERG finds a used fuel disposal fee between 0.7 (the high end of the AECL estimate range) and 1.36 mills/kWhr (which is the U.S. fee) to be a reasonable range. Over a 40 year period, with a 5% real interest rate, a CANDU 3 operating at an 88% capacity factor would accrue between $210 and $571 million for used fuel disposal. A rough approximation shows that in addition to a CANDU 3 in Saskatchewan the remaining Canadian nuclear plants (Ontario Hydro units, Pt. Lepreau and Gentilly 2) would accrue about $6.5 to $17.7 billion.

The used fuel disposal fee range proposed by ERG (0.7 to 1.36 mills/kWhe) appears adequate to cover the range of contingencies associated with the $9 billion dollar estimate for constructing and operating a disposal facility operated by the federal government. The lower value reflects a disposal facility costing 30% less (possibly due to the lessons learned from the U.S. experience), while the upper value is consistent with a doubling of the current $9 billion cost estimate -- which would mean that the U.S. experience is more the rule than the exception.

I/LLW

Description and Estimated Quantity - Solid intermediate and low level wastes (I/LLW) are produced during a nuclear power plant's routine operations, outages and decommissioning. The amount of waste produced is related to plant size, layout, activity type and staff practices and can vary significantly from year to year. For perspective, this class of waste is also produced in uranium mining and refining, several industries such as nuclear fuel fabrication and those dealing with naturally occurring radioactive materials, and by various licensed users of radioisotopes such as hospitals and universities.

Canadian utilities divide I/LLW into three categories that are based on overall level of radioactivity. A typical breakout of the three classifications would be:[32]

- Type 1 waste consists mainly of common industrial items which have become contaminated with low levels of radioactivity during routine clean-up and maintenance at the nuclear facilities. Items used in the radioactive areas of the station include mops, rags, paper towels, temporary floor coverings, floor sweepings, protective clothing, and hardware items such as tools. Some of this waste has very low levels of radioactivity, and is of insignificant radiological hazard and is referred to as *"de minimis"* waste.

- Type 2 waste generally consists of spent ion-exchange resins and filters used in water purification systems in nuclear reactors.

- Type 3 waste includes the more radioactive ion-exchange resins and filters, as well as reactor components which have been removed from a reactor.

Much of the radioactivity in the waste decreases to background levels (i.e., levels normally present in the environment) in several hundred years. Some waste may however contain significant amounts of carbon-14 and remain radioactive for several thousands of years.

AECL estimates that a CANDU 3 will produce I/LLW at a rate of 40 m^3/year. This appears to be a reasonable estimate given good housekeeping and work practices by the plant staff and state-of-the-art compaction equipment (which can reduce the wastes' original volume by over 90%). The absence of any one of these key factors, however, could lead to higher waste volumes. A reasonable upper limit can be inferred from Pt. Lepreau data. Since it commenced operation in February 1983, Pt. Lepreau has averaged about 73 m^3/year of I/LLW, which when scaled to a CANDU 3 yields 51 m^3/year. Similarly, if Ontario Hydro's I/LLW is subjected to state-of-the-art compaction and scaled to a CANDU 3, the annual production would be 49 m^3/year. Accordingly, 50 m^3/year appears to be a reasonable upper limit for I/LLW production at a CANDU 3.

Disposal Cost - For a single-unit CANDU 3 plant in Saskatchewan, this type of waste would typically be stored in "in-ground containers" prior to shipment to a permanent disposal facility. Such a facility would probably be operated by the Province of Saskatchewan or the waste might be disposed of (for a fee) at another facility in Canada if circumstances permit. Based on discussions with Pt. Lepreau and Gentilly,[16,17] ERG assumes that the capital and O,M&A costs for a CANDU 3 (as discussed earlier in Section 4) include the cost of on-site storage for I/LLW. It should not be assumed that the cost of final, off-site disposal has been included.

In the United States the cost to site, build, operate and close an I/LLW storage facility can vary significantly and is subject to much politicking and negotiation. Based on several sources of information[31,34] ERG estimated -- in a very approximate manner -- the cost of I/LLW disposal in Saskatchewan to be from $1,785 to $4,500/m^3. The lower value (which AECL found to be reasonable) reflects the cost of disposal at the existing Barnwell, South Carolina facility -- which employs shallow burial in unlined, earthen trenches. The higher value would be for a site utilizing modular concrete canisters below ground, which is similar to the type of facility that Ontario Hydro may use for the final disposal of its I/LLW. A breakout of the estimated costs, based on a conceptual facility in the State of Massachusetts, are:

Construction	278 $/m^3
Operation	3,391 $/m^3
Closure	146 $/m^3
Post closure	685 $/m^3
Total	4,500 $/m^3

Accordingly, if a CANDU 3 produced 1,600 to 2,000 m^3 I/LLW over 40 years of operation, the cost of final disposal would likely approach the mid-point of the range from $2.9 million to $9 million. The large, relatively unpopulated land area of Saskatchewan will tend to reduce the cost from the upper limit -- with the construction of an Ontario Hydro type facility increasing costs from the lower limit.

7. RECOMMENDED ENVIRONMENTAL EXTERNALITY METHODOLOGY

Approach

SECDA is using a cradle-to-grave, or full plant and fuel-cycle, approach to externality cost evaluation for all electricity demand- and supply-side sources under consideration as it is the only way to establish a level playing field for objective comparisons. Nuclear power technology fits well into such a framework because substantial data are available upon which to calculate the full extent of associated environmental impacts -- especially those resulting from radiological emissions.

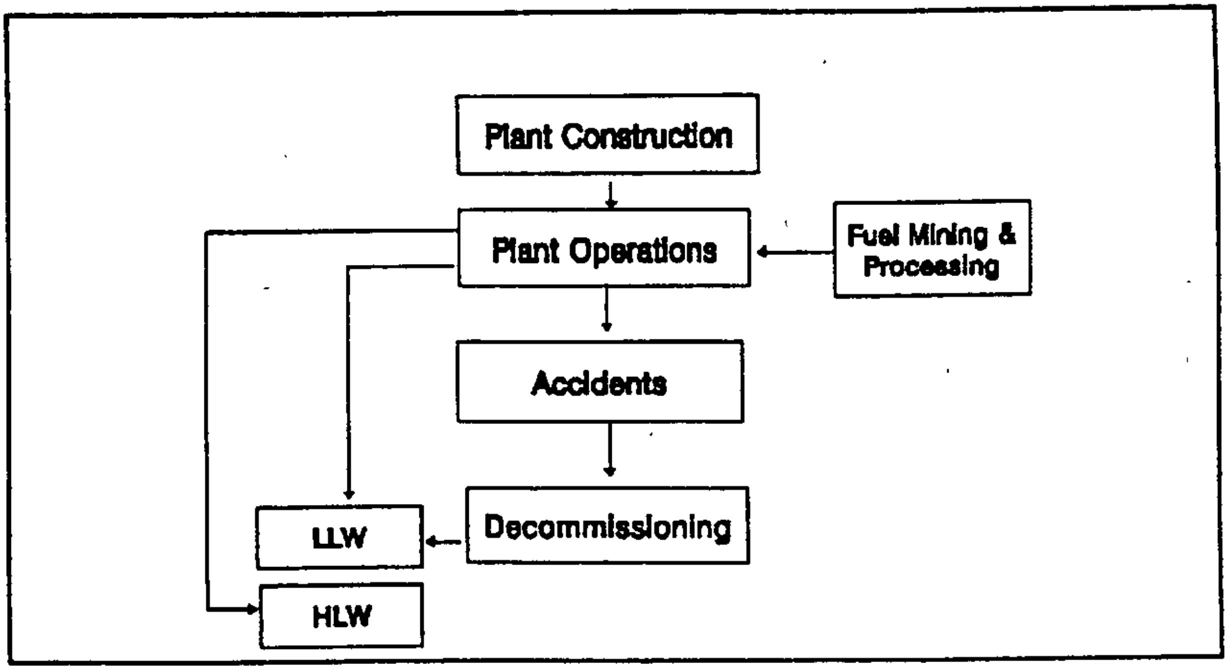
Demand- and supply-side sources of energy can be divided into discrete life-cycle processes, or events. The interrelationship among the seven segments that comprise the nuclear fuel/plant cycle, shown in Figure 7-1, is generally representative of other supply- and demand-side sources as well. The variances found within this framework are attributable to the unique characteristics of each source. In evaluating the environmental impacts of nuclear power generation, pollutant emissions from the combustion of fossil fuels (SO_x, CO_2, NO_x, CO, CH_4, VOC and PM_{10}) and radioactive isotopes releases must be considered. While uranium is the fuel source for nuclear power generation (and the cause of radiological releases to the biosphere), significant amounts of fossil fuels are combusted in each segment of the nuclear fuel/plant cycle -- from the machinery used to mine uranium through the periodic testing of emergency equipment at the plant site.

Cost Treatment

Monetization - The pollutants considered in externality cost calculations for each segment of the nuclear fuel/plant cycle are listed in Table 7-1 which also shows whether the emission of a listed pollutant is dependent upon plant operation. This is an important consideration, one which determines how the environmental cost is recovered.

Figure 7-1

Nuclear Plant/Fuel Cycle Segments for Externality Calculations



For instance, if a pollutant is released as a function of electricity generation, it can be accounted for as an "expense" that is fully recovered as the plant operates. On the other hand, pollutants released as a result of plant construction and decommissioning are independent of electricity generation and occur over fairly discrete time periods -- both before and after the plant is in operation. These pollutants can be viewed as "capital costs" and amortized over the plant's operating life. Therefore, if a plant operates for its planned 40-year economic life, the externality costs -- whether expensed or amortized -- can be fully captured. However, if a plant is prematurely shut down the externality costs from a segment such as construction or decommissioning would not be fully amortized and would have to be considered in the price of the replacement power source. This approach of amortizing and expensing ensures that resource planning is truly integrated.

Table 7-1
Nuclear Plant/Fuel Cycle Externality Assignments

Segment	Externalities		
	Radiological	Fossil Energy Use	Collateral Damage
Construction (site only)		✔	
Fuel mining/processing	X	X	
Operations	X	X	
Accidents	X		X(1)
LLW	✔	✔	
HLW	X	X	
Decommissioning	✔	✔	

Notes:

X Externality computed as a function of electric generation.
✔ Externality computed as a function of operating life.
(1) Includes crop and property damages.

Monetizing Pollutant Values

In valuing externalities, the societal costs of pollutant impacts or the costs of controlling pollution can be used. Establishing fossil pollutant damage costs can be difficult because impacts are region-specific and frequently must be evaluated within complex scenarios such as global warming. ERG has assessed a comprehensive data base of fossil pollutant damage costs and has developed damage cost correlations that are a function of population densities and land-use. By comparison, control costs are much easier to calculate, but they can bear little or no relationship to the actual environmental damage caused by the pollutants.

Human health effects from radiation exposure are determined by converting the predicted dose to a specified population into statistical fatal and non-fatal cancers (see Table 1-1 for an example). There is a range of published factors that can be used to estimate statistical health effects from population doses. Monetizing these statistical human health impacts can be done on either a cost of control or direct damage basis. The cost of control can be inferred from U.S. Nuclear Regulatory Commission (NRC)* regulations in 10CFR50, Appendix I. The cost of a non-fatal impact is not defined in the NRC value, so some reduction factor must be assumed. Direct damage costs are reported in the literature based on lost wages and other societal impacts.

In ERG's opinion, the health impacts of nuclear plant workers are not an externality cost, as workers assume certain risks upon employment and are duly compensated through salary as well as health and life insurance. At nuclear power plants, workers have a thorough understanding of potential risks because the AECB requires them to receive comprehensive training before and throughout their employment. Moreover, ERG believes that employment compensation, health insurance, life insurance and the judicial system effectively internalize any worker impacts. On the other hand, some researchers such as Pace[35] have argued that worker health impacts are an externality cost.

ERG recommends that the same monetizing approach -- preferably one that's damage based -- should be used for both fossil and nuclear power plants. This keeps the playing field level.

Discount Rate - For a cradle-to-grave calculation of nuclear power externality costs, the use of discount rates is a necessity for two reasons. First, to properly account for some externality costs -- such as those associated with plant construction, LLW and decommissioning -- they must be amortized. Second, as the externality costs for low- and high-level waste involve long time horizons of thousands of years, the associated impacts must be discounted. The exact discount rate will likely vary from utility to utility. It is clear, however, that a zero discount rate is inappropriate simply because it overestimates the present value of future environmental costs.

Each segment of the nuclear plant/fuel cycle has unique features that must be addressed when calculating environmental externality costs. Each of the seven segments are reviewed here to provide SECDA with additional insights.

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* Actually, this regulation reflects NRC's estimate of value/impact which is used to define a value or maximum cost of control for radiation protection.

Plant/Fuel Cycle Segments

Plant Construction - The robust design of nuclear plants requires significant quantities of fossil fuels to be consumed by construction machinery and for site steam heating. In addition, significant amounts of pollution can be emitted during the fabrication of steel and the manufacture of cement used for plant construction. (In its full cost accounting program, Ontario Hydro excluded the externalities associated with steel and cement manufacture.)

Fuel Mining and Processing - The principle form of radiation release is the emanation of gaseous radon from mill tailings piles during active mining and milling operations. In addition, mining operations can consume large quantities of fossil fuels whose pollutant emissions must be accounted for. (ERG has previously estimated that 1.9 liters of diesel fuel is required to mine one cubic meter of ore.)

Plant Operations - All nuclear power plants routinely emit small quantities of radiation to the biosphere -- subject to comprehensive monitoring and sampling programs. Fossil fuels are used to periodically test emergency diesel generators, fire pumps and other backup equipment. The externality costs from fossil fuel emissions can be substantial because of operation of such equipment. SECDA must also consider the fossil pollutants emitted in the production of heavy water if Ontario Hydro does not account for externalities incurred in outside sales.

Plant Accidents - Although the probability of occurrence is exceedingly low, the radiological impacts and property damage that could result from a catastrophic accident are externality costs in Canada if they exceed the insurance pool limit of $75 million. (The calculations shown earlier in Section 4, indicate that the consequences of a CANDU 3 catastrophic accident would exceed $75 million.) While the Canadian government would presumably provide relief funding to make up for any insurance shortfall, its source of money is the taxpayer who is a third party. The taxpayer burden would then be an externality cost.

Low-level Waste - Fossil fuel is consumed to transport low-level radioactive waste (LLW) and to construct state or regional waste disposal facilities. The calculation of associated externality costs from radiation releases is somewhat speculative, as they could occur at any time -- up to hundreds of years after the disposal facility closes. LLW is generated as a function not only of electricity production, but also plant maintenance -- even in periods of extended shutdown or decommissioning. Thus, the associated externality costs of LLW should be amortized. Assumptions must be made to establish radiological release and human exposure scenarios. ERG suggests scenarios identified in the U.S. NRC Final Environmental Impact Statement on 10CFR61.

High-level Waste (Used Fuel) - The calculation of externality costs associated with high-level waste (HLW) is very similar to that for LLW. The major difference is the time horizon. HLW may need to be isolated from the biosphere for up to 10,000 years under federal regulations. In addition, unlike LLW, high-level waste is generated strictly as a function of plant operation and its long-term isolation in a national repository is the responsibility of the federal government. Again, assumptions must be made regarding radiological release and human exposure scenarios. The most plausible scenario involves human exposure from ground water contamination.

Decommissioning - Just like plant construction, large quantities of fossil fuel will be used for the operation of demolition machinery and the shipment of material off-site. There will also be some release of radioactive material to the biosphere which will yield statistical health effects.

Expected Externality Costs

Finally, based on ERG's previous work with CANDU reactor technology, SECDA should expect very low environmental externality costs for a CANDU 3 -- on the order of .001 to 0.1 ¢/kWhr (as shown in Table 7-2). That is because the environmental impacts of nuclear power plants have been largely internalized. Robust plant design, redundant safety systems, stringent operating criteria and constant regulatory oversight minimize environmental impacts. The cost of these actions and requirements are reflected in the relatively high busbar cost of nuclear power plants.

Table 7-2
Summary of Typical Externality Costs for CANDU Nuclear Plants

Plant/Fuel Cycle Segment	Typical Externality Cost[1] (¢/kWhr)
Construction	.00003 to .00085
Fuel Production	.00044 to .00114
Routine Operations	.00019 to .01652
Accidents	.00001 to .09591
I/LLW	.00031 to .00078
High Level Waste	.00001 to .00007
Decommissioning	.00001 to .00631

Note:
(1) Includes both fossil fuel pollutants and radiological emissions.

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APPENDIX: B
GLOSSARY

ACTIVATION
Activation refers to the process where certain materials become radioactive when exposed to neutrons.

ACTIVITY
The rate at which a radioactive substance is decaying or the number of nuclear disintegrations occurring in a given quantity of material per unit time. The Systeme International (SI) unit of activity is the Becquerel (Bq); 1 Bq = 1 disintegration per second.

AECB
Atomic Energy Control Board, a federal authority which sets regulations and requirements, and issues licenses for all the life-cycle activities of nuclear power generation.

ALARA
An acronym for "as low as reasonably achievable." A basic principle of dose limitation in radiation protection, taken from recommendations of the ICRP. It means that the design and use of radioactive sources, and the associated practices, should be such as to ensure that exposures are kept as low as reasonably feasible.

BECQUEREL (Bq)
The International System of Units (SI) unit of radioactivity, equivalent to the disintegration of one radioactive atom per second.

BOILING WATER REACTOR (BWR)
Light water reactor designed to allow boiling in the upper part of the core.

CADD
Computer aided drafting and design relates to the process of developing design and construction drawings on a computer system.

CANDU
'CANada Deuterium Uranium': A Canadian-designed reactor which uses natural uranium fuel and is moderated and cooled by heavy water (D_2O).

CAPACITY FACTOR
A term used to compare the actual electrical energy produced by a generating station with the maximum that it could produce at 100% rated output, 24 hours per day over a period of time. The figure is expressed as a percentage.

COAST DOWN
Coast down refers to the gradual reduction in reactor power that occurs when there is insufficient fuel (reactivity) in the reactor core to maintain 100% power. Normally in a CANDU reactor used fuel is continually replaced with new fuel during plant operation, precluding coast down.

COLLECTIVE EFFECTIVE DOSE
The product of the number of individuals in the population and the individual effective dose equivalent. It is measured in terms of person-Sv.

CONTAINMENT
A structure or envelope that ensures the retention of radioactive material in such a way that is effectively prevented from being dispersed into the environment.

CURIE (Ci)
A pre-SI unit of radioactivity, equivalent to 3.7×10^{10} disintegrations per second. This unit has been superseded by the SI unit, Becquerel (Bq) (1 Ci = 3.7×10^{10} Bq).

DECAY
In the context of radioactivity, the spontaneous transformation of a radioactive material from one nuclide to another or into a different energy state of the same nuclide.

DECOMMISSIONING
The work required to retire a facility from active service, ensuring public health and safety and environmental protection.

DE MINIMIS
A term, derived from a Latin expression, which is used to describe materials with such low radioactivity that AECB licensing is not necessary for their disposal.

DERIVED EMISSION LIMITS (DEL)
Regulatory limits which specify the maximum quantity of a radionuclide group which can be emitted over a specified period of time. For each nuclear facility, these are defined in a specific DEL document.

DISPOSAL
Ultimate emplacement of nuclear materials in some engineered facility, with no intention of retrieval; the objective is permanent isolation.

DOSE
A term used in radiation protection as a measure of the radiation 'received' or 'absorbed' by a target.

DOSE EQUIVALENT
The product of the absorbed dose and all other modifying factors as specified by the ICRP.

EFFECTIVE DOSE EQUIVALENT
Sum of the products of the mean dose equivalent in each organ or tissue and its weighting factor specified by the ICRP.

EMERGENCY CORE COOLING SYSTEM (ECCS)
Injection of cold water in the heat transport circuit to provide fuel cooling under accident conditions.

EMISSION MONITORING
Measurement of the amount of radionuclides that are discharged into the surrounding air or water.

ENVIRONMENTAL EXTERNALITIES
As defined, an externality is a societal cost or benefit of production or consumption which is not borne or received through the price system by the firm or household which produces or consumes it. Environmental externalities are a subset of the externalities universe, a broad complex sphere extending well beyond the physical environment.

ENVIRONMENTAL MONITORING
A measurement of the concentration of radionuclides in milk, vegetation, vegetables, etc., surrounding a station.

ENVIRONMENTAL QUALIFICATION
Environmental qualification is a rigorous analytical/testing process that must be followed to prove that critical components will perform as required when subjected to the harsh environmental conditions (temperatures, pressures and radiation) which might be encountered under certain postulated accident conditions.

EPIDEMIOLOGY
Study of the elements contributing or not contributing to the occurrence of a disease in a population.

EXPOSURE
A general term relating to the incidence of ionizing radiation on living or inanimate material, by accident or intent. A measure of the 'quantity of radiation' present in, or 'given' by, a radiation field.

FISSION
The splitting of a heavy nucleus into two parts accompanied by the release of energy and two or more neutrons.

FISSION PRODUCTS
Nuclides created in nuclear fuel by the breakup of uranium atoms during the operation of a reactor.

FREQUENCY
The number of times an event occurs in a unit time. For nuclear power risk assessment, the unit for frequency is the number of occurrences per GWa.

FULLY BURDENED
A term used to account for all direct and indirect costs associated with workers.

GIGAWATT (GW)
Measure of electrical output at any one point in time of a generating facility; 10^9 watts. (GWa is electrical output per annum and GWE-a is a plants rated capacity per annum.)

GROSS BETA/GAMMA
An overall measure of the amount of beta particles and gamma rays emitted from a radioactive material.

HALF-LIFE
Unit of time used to measure radioactive decay. It is the time required for half of the quantity of atoms of an element to decay into another element or isotope.

HEAVY WATER (D_2O)
Water in which the hydrogen atoms have been replace by heavy hydrogen atoms (deuterium, D_2); used as a moderator (slows down neutrons effectively) and coolant in CANDU-type reactors.

ICRP
International Commission on Radiological Protection. Founded in 1928, it is an independent non-government body that establishes radiation protection standards followed by most countries in the world.

I/LLW
The term intermediate/low level waste refers to such things as clothing, used filters, tools and other materials which have become contaminated with radioactive material.

INPO
Institute of Nuclear Power Operation, a private organization supported by U.S. utilities to increase safety and performance at nuclear power plants.

IONIZING RADIATION
Radiation that causes atoms to gain or lose electrons and so develop a net electrical charge. Ionization occurring in tissue can alter the molecular structure of the tissue and lead to cancer and congenital malformation, and possibly to genetic damage.

ISOTOPES
Atoms of the same element, having the same number of protons but different number of neutrons in their nuclei.

LIGHT WATER REACTOR (LWR)
Nuclear reactor with light water (H_2O) as the coolant and moderator.

LINEAR SCALING
Linear scaling refers to the process whereby quantities are changed in direct proportion to the difference in plant output capacity. For example, a linear multiplier of 70% would be used when going for the CANDU 6 (640MW) to the CANDU 3 (450MW).

MEGAWATT (MW)
Measure of the electrical output at any one point in time of a generating facility; 10^6 Watts.

MTU
Metric tons of uranium.

NATURAL BACKGROUND RADIATION
The net unavoidable, low-level radiation from a number of natural sources around us, the earth's crust, the sun, building materials, etc.

NEUTRON ACTIVATION PRODUCTS
Radionuclides formed when nuclides adsorb neutrons. For example, used fuel bundles contain activation products of uranium (i.e., actinides) and of zircaloy cladding.

NEUTRON ACTIVATION (neutron capture)
The process of an atomic nucleus absorbing an impinging neutron.

NOBLE GASES
Xenon, argon, krypton, neon, radon, and helium. They are chemically inert gases. Radioisotopes of these gases are created during the operation of a nuclear reactor.

OCCUPATIONAL EXPOSURE
Exposure of a worker received or committed during a period of work.

PATHWAYS
The routes by which radioactive material can reach and migrate through the environment to eventually reach humans.

PRA
Probabilistic risk assessment is a process which attempts to develop a complete listing and quantification of accident scenarios and consequences. The overall risk model can be thought of as three linked models: the plant model (Level I), the containment model (Level II) and the site model (Level III).

PRESSURE TUBE
In the CANDU reactor, the pressure tubes contain the fuel assemblies and coolant (heavy water) and are comparable to the reactor vessels in light water reactors.

PRESSURE TUBE HYDRIDING
Pressure tube hydriding refers to blistering of the pressure tubes caused by hydrogen build-up.

PRESSURIZED WATER REACTOR (PWR)
Light water reactor designed to achieve high water temperature without boiling by pressurizing the primary system.

PROBABILITY
A measure of the likelihood of an event. The probability of the outcome of an event is a number between 0 and 1; zero probability indicates an impossible event, a probability of 1 indicates a certain event.

RADIATION
The emission and propagation of energy through space or matter by means of electromagnetic waves or fast moving particles. Three common types of ionizing radiation are those associated with gamma rays and alpha and beta particles.

RADIOACTIVE DECAY
The change of an atom of an element to an atom of another element or isotope by releasing an alpha or beta particle or other forms of radiation.

RADIOACTIVITY
Spontaneous disintegration of the nucleus of an atom by expulsion of particles, alpha or beta. It can be accompanied by electromagnetic radiation (gamma rays).

RADIOACTIVE MATERIAL
A material that exhibits radioactivity; it contains elements (radionuclides) which emit radiation.

RADIOISOTOPE
Species of an atom with the same number of protons in their nuclei but different number of neutrons that is radioactive. The chemical characteristics are practically the same but the nuclear characteristics may be very different.

RADIONUCLIDE
A radioactive isotope of a chemical element.

REM
Acronym for Roentgen Equivalent Man. The unit of dose of ionizing radiation which produces the same biological effect as a unit of absorbed dose of ordinary X-rays. This unit has been superseded by the SI unit, Sievert (Sv) (1 rem = 0.01 Sv).

RETUBING
Refers to replacing the pressure tubes in a CANDU nuclear reactor.

RISK
Chance of injury, damage or loss resulting from occurrence or potential occurrence of some event or a sequence of events. Risk is measured by product of the frequency of an event and the consequence, measured in the number of lives lost.

SHIELDING
A barrier of material which reduces radiation intensity, primarily to protect human health.

SHUTDOWN SYSTEMS
Two independent, redundant and diverse (different shutdown methods) systems whose functions are to shut down the reactor in the event of an accident.

SIEVERT (Sv)
The SI unit of dose of any ionizing radiation which produces a certain biological effect. (1 Sv = 100 REM)

STEAM GENERATORS
Steam generators are used to transfer the heat produced in the primary system to steam used in the secondary side of the plant to power the turbine generator.

STEAM GENERATOR TUBE FRETTING
Damage to steam generator tubes caused by wear at the support plates or anti-vibration supports.

STORAGE
The emplacement of waste in a facility in such a way that (a) isolation, monitoring, environmental protection and human control are provided; and (b) subsequent action involving treatment, transport and disposal or reprocessing is expected. Compare with 'disposal'.

TRITIUM
A radioactive isotope of hydrogen which is an inherent by-product of the operation of a CANDU reactor; it builds up in heavy water due to neutron capture on deuterium.

VHL
Very heavy lift cranes which typically have the capacity to lift and move loads up to 1500 tons.

YELLOW CAKE
Yellow cake refers to uranium oxide, U_3O_8, that is processed into fuel for nuclear reactors.

APPENDIX C
COMMODITY COMPARISON[8]
(CANDU 6/CANDU 3)

Item/Unit	CANDU 6	CANDU 3	% Difference
Concrete (cubic meters)	120,000	100,000	17
Formwork (square meters)	140,000	90,000	36
Structural Steel (tonnes)	10,000	6,000	40
Piping (1/2-24") (meters)	120,000	70,000	42
Tubing (meters)	40,000	20,000	50
Power Cable (meters)	210,000	150,000	29
Instrument Cable (meters)	980,000	600,000	39
Instrument Terminations	60,000	35,000	42