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THE ECONOMICS OF COAL VERSUS NUCLEAR POWER GENERATION IN ALBERTA WHEN SOCIAL COSTS ARE INCLUDED

by

NG, WING-KWONG BENSON

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Abstract

Coal and nuclear are among the major energy alternatives for meeting the base load demand for electricity. Many cost studies have been done to compare the economics of nuclear and coal-fired power plants. These studies have concentrated mainly on the traditional costs, that is capital costs, operation and maintenance costs and fuel costs, of plant operation.

Similar to other industrial activities, there are social costs attached to electricity generation; for example, health costs due to air pollution generated by coal-fired power plants and due to radiation during the operation nuclear power plants. Studies on such social costs have been done to develop methods of estimating these costs.

Relatively few cost studies include social costs in the economic analysis because: a.) the estimates of social costs are not available; b.) the available estimates are not accurate enough to reflect the social impacts; c.) social costs are too small to have any significant effect on the choice of electricity generation methods when compared to traditional costs. However, those studies that did include the social costs concluded that social costs had some effect on the choice of energy sources for electricity generation.

In this thesis, social costs due to the possibility of using CANDU nuclear and coal-fired power plants in Alberta were included in the traditional costs analysis. The traditional costs were adopted from an Alberta study of the

economics of these two power plants. The social costs were estimated by transporting estimates obtained in a literature survey to the Alberta situation. The variations of these social costs were described by a log-normal distribution and were also included into the cost analysis.

In this thesis, two methods of analysis were established and used: total cost analysis and unit cost analysis. By comparing the levelized unit costs of nuclear and coal-fired power plants, and similarly the total costs of different schedules of implementing nuclear power plant, the importance of social costs, the uncertainty of the estimates, and other factors on the choice and time of adopting nuclear power for electricity generation in Alberta were found.

In the initial case study, where the real escalation rates for both coal and nuclear were the same, nuclear power for electricity generation in Alberta was not justifiable even though social costs were included. In the base case study, however, where the real escalation rate of nuclear fuel was assumed to be lower than that of coal, nuclear power was shown to become more economical in the year 2032. The inclusion of the expected social costs in the base case study caused the nuclear power plant to become economical 12 years earlier in the planning horizon, even though the expected social costs were less than 5% of the total traditional costs. When the rate of increase in traditional costs of both electricity generation methods were very close, the uncertainty of the social cost estimates had a profound effect on the time at which nuclear power became economical.

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List of Symbols

A...... annual cost, in million dollars, all in January 1982 Canadian dollars, except as specified.

AFUDC.. allowance for funds used during construction

a...... factor for levelizing the tradition costs over the service life of power unit

C...... capital cost for a power unit

CPI.... consumer price index

D...... electricity demand, in GweY

d...... interest rate in real terms(inflation free)

ΔE..... annual electricity generation, in GweY

F...... fuel cost, in million dollars per year

f...... cash flow for each year during construction, in percentage of the total capital cost.

G...... annual electricity generated by existing plants, in GweY

H...... material cost in the operation and maintenance cost in million dollars per year

I...... annual insurance, interim replacements and property taxes

K...... real escalation rate for capital construction cost

k...... nominal (current dollars) escalation rate for capital cost during construction

L...... labour cost in operation and maintenance cost, in million dollars per year

l...... real escalation rate for labour cost

M...... operation and maintenance cost in million dollars

N...... total number of operating power units

p,Q.... total cost, in million dollars

q...... electricity generated by one unit in a year, Gwe

R...... research cost, in million dollars

S...... social costs, in million dollars

s...... social costs constant, in million dollars per GweY

T...... traditional costs, in million dollars

t...... construction year

U...... capital cost of a power station, commissioned in 1982, in million dollars

u...... number of units in a power station

v...... social costs estimated from the literature

w...... number of estimates for one particular social cost

y...... number of construction years required to build a unit

Subscripts

k...... coal-fired power plant

i...... plant type/unit

j...... year during the service life of an unit

m...... year during the study period

t...... year in construction year of a unit

n...... nuclear power plant

z...... year at which the power unit is commissioned

x...... literature from which social costs are derived

y...... number of years required to construction a unit

Arithmetic Operators

Σ...... summation

Units

Gwe.... gigawatt electricity power generated 1Gwe=10^3 Mwe

GweY... electricity generated by one Gwe for 1 Year

kwh.... electricity generated by one kilowatt for an hour

Mw..... megawatt thermal power generated

Mwe.... megawatt electricity power generated

M/GweY. million dollars/GweY

man-rem.. a measure of radiation dosage of one man being exposed to one rem of radiation: the rem is defined in terms of biological significance such that one rem from any radiation source should have the same effect on a man.

mill... 1/1000 of a dollar

(net).. after deducted by the usage of the power plant itself

ppm ... parts per million

$\mu g/m^3$.. 10^{-6} grams per cubic meter

Greek letters

β...... escalation rate for fuel

μ...... mean

σ...... standard deviation

Ψ...... fuel cost per unit electricity in million dollars per GweY

1. Introduction

Since the mid seventies, coal-fired power plants have been used in Alberta to supply the base load demand for electricity, leaving natural gas, oil, and hydro to meet net fluctuating demand. Hart[1977, p.10] predicted that western Canada had coal reserves that would last about 300 years and coal would continue to be the future major energy source for electricity generation in Alberta. In all energy associated activities, there are social costs attached to these activities, for example health cost due to ambient air pollution. This loss, when expressed in monetary form, is called social cost (Justus, Williams, Clement, 1973, p.19). Many researchers contend that the social costs due to coal plants are greater than those due to nuclear plants. For example, Gaines, Berry, and Long [1979, p.100] estimated that social cost due to coal plants in the United States is about 16 times higher than that due to nuclear plants. Kim[1981, p.115, 116] and Hill[1977, p.iii] calculated the above social cost ratio for Ontario to be approximately 5.6 and 10 respectively.

If social costs are included in the traditional cost analysis the high capital cost of a nuclear power plant may be offset by its lower social costs. Coal-fired plants may be less economical and nuclear power plants may become more economical for Alberta's future energy planning. The CANDU reactor which is a pressurized heavy water reactor is seen to be the challenger to the coal-fired power plants in

Alberta. In this thesis, social costs are included in the base case of traditonal cost analysis. By introducing the social costs into the cost analysis, one can evaluate their importance in the determination of the energy source(s) for the generation of electricity in Alberta.

Two methods of analysis are used: total cost analysis and unit cost analysis. In total cost analysis, the total cost is defined as the present equivalent value of the traditional costs and social costs over a study period of 30 years (1983 to 2012 inclusive for the base case). The traditional costs refer to capital, operating and maintenance, fuel and research costs using traditional economic analysis. Costs that are used to set the electricity charge rate are grouped into this category. The social costs refer to costs due to the undesirable side effects which are not paid for directly by the electricity users. For example, the health cost due to air-pollution generated from coal-fired power plants is one of the social costs. Gaines, Berry, and Long[1979] have developed a computer program called TOSCA, which has the ability to calculate the present equivalent value of social and traditional costs required to meet a pre-determined demand for electricity in a year, and to accumulate this present equivalent value over a selected study period to give a total cost. The total cost is equivalent to, from the investment point of view, the amount of money to be invested at the beginning of the study period in order to provide the electricity for each study year. Using the TOSCA computer program, total costs of various scenarios in regard to implementing nuclear power and the plant mix between coal and nuclear power plants are obtained. These total costs are the criteria for comparing alternative energy sources. The scenario with the lowest total cost is the preferred choice of electricity generation. In TOSCA, assumptions are made based on the high demand and supply situation of the United States. Since the electricity demand and supply in Alberta are much smaller, the TOSCA program was modified based on the assumptions applicable to Alberta. The effect of demand changes and surplus capacity on the total costs for each electricity generation method can also be studied using this method.

In the unit cost analysis, the levelized cost (over the service life of the power units) for a unit of electricity generated by a new power plant is calculated. This levelized unit cost is, also from the investment point of view, the annual equivalent investment required for each unit of electricity generated during the life time of a power plant. In this analysis a new power plant is assumed to be commissioned every year regardless of the demand for electricity. A series of unit costs, each of which corresponds to each new power plant, is calculated. The unit costs for different generation methods are then compared year by year. The year, or the break-even point, at which the unit cost of one electricity generation method becomes lower than the others is the point where that generation method starts to be economical. The shift in the break-even point, when social costs are included in the analysis, is used as an indicator of the impact of social costs.

The expected social cost due to the coal-fired power plants in Alberta is estimated to be 13.049 M/GweY or about 12 times higher than that due to nuclear power plants. For coal-fired power plants, only about 5 percent of the total traditional cost is social cost. As for nuclear power plants, less than 1 percent of the total traditional cost is social cost. Human health costs for coal-fired power plants are dominant among all the social costs studied, but the property damage is the dominant factor for nuclear.

From the initial case study of unit cost analysis, nuclear power for electricity generation in Alberta is found not to be as economical as coal even though its advantages of lower fuel and expected social costs are taken into consideration. From the base case study of the unit cost analysis, the break-even point is sensitive to social costs and they cause the break-even point to occur twelve years earlier; that is from the year 2032 back to 2020. Giving nine years for construction of a nuclear power plant and ten years for introducing the nuclear technology into Alberta, the development of a nuclear power industry is estimated to begin around the year 2000.

1.1 Including the social costs in economic analysis

Barrager, Judd and North [May 1975, p.549] stressed, "Cost/benefit analysis is intended to provide a quantitative basis for decision-making .... it must treat all factors that influence a decision - not only the traditional economic considerations but also environmental, health and safety impacts." When determining the best energy sources for electricity generation, social costs should be included and considered as one of the influencing factors in the cost analysis.

When comparing the unit electricity costs of all the provinces in Canada, coal as an energy source for electricity generation in Alberta is relatively inexpensive (Rahnama, 1982, p.32; Foulkes, 1982, p.1-1). Inhaber [1978, p.46, p.47] has estimated, however, that coal-fired power plants have the highest risk to the public because of pollution to the ambient air and environment. The combination of Alberta coal, which has a low sulphur content of about 0.3% (Foulkes, 1982, p.II-5), and the use of pollution control devices reduces the risk. The Federal-Provincial Committee on Air Pollution has determined that those harmful particulates of size less than 0.5 μ in diameter can pass deeply into the lung. The present pollution control devices may not reduce the level of the pollutants of this size to an acceptable level. The present pollutant levels due to coal-fired power plants may still be so high that when social costs are included in the economic analysis nuclear power plants may become economical earlier in the planning horizon.

1.2 The scope of the thesis

In this thesis, the objectives are:

1. to estimate the social costs due to CANDU and coal-fired power plants in Alberta,
2. to establish methods of analysis for studying the economics of coal and nuclear electricity generation,
3. to include the social cost estimates in the established methods of cost analysis and investigate the effects of social costs and the uncertainty of their estimates on the choice of and the timing of adopting CANDU for electricity generation in Alberta,
4. to study the sensitivity of the choice of energy source(s) to other factors, which gives perspective on the importance of social costs for decisions about electricity generation methods.

The results of a literature survey are used to estimate the social costs due to coal-fired and CANDU pressurized heavy water reactor power plants. When the original estimation method proposed by each study is not available or is difficult to apply to the Alberta situation, a damage potential function is used to convert cost estimates to Alberta estimates.

As for total cost analysis, a computer model is developed to find the total cost for predetermined scenarios. It is based on the computer program developed by Gaines, Berry, and Long[1979] with several significant changes. First, the mathematical models, especially those for social costs, have been simplified. Second, because real (inflation free) rates of change are included in the total cost analysis, all the traditional costs are levelized into annual equivalent costs in constant 1982 Canadian dollars. This also has the effect of minimizing the influence of initial and final conditions during the planning period. Third, the demand for electricity is met by a stepwise increase equal to the capacity of the power unit. Checks are made to ensure that two stations would not be built at the same time unless required to meet demand and idle capacity is kept to a minimum. In total cost analysis, five scenarios of various plant mixes are implemented (please refer to Chapter 5, 5.3). By comparing their total costs, the optimum plant mix can be determined as well.

The unit cost analysis is based on Foulkes's[1982] ecohomic analysis of coal-fired and nuclear power generation in Alberta. His approach and estimates on traditional costs are adopted, but are modified to include social costs.

Once these models are well established, the best estimates of parameters selected, for example, interest rate, fuel escalation rate, and social costs, can be varied and the most sensitive parameter(s) can be determined. The impact of each parameter on the choice of energy sources for electricity generation can be studied. The effects of surplus capacity, demand for electricity and it's growth rate on total costs can also be studied.

1.3 Over-view of analysis

The present Alberta electric industry is briefly reviewed and the future base load demand for electricity is estimated in Chapter 2. The traditional cost functions and the coefficients of these functions are established and estimated in Chapter 3. The social cost functions are established and their cost estimates are compared and summarized in Chapter 4, but detailed estimation of the social costs is provided in Appendix 5, A.5.2. In Chapter 5, the experimental design on the use of total cost analysis and unit cost analysis for carrying out the base studies and sensitivity tests are discussed. Finally the results and discussion are given in Chapter 6. Chapter 7 concludes the analysis and gives recommendations for further study.

2. The Alberta Electric Industry

There are four major energy sources used for electricity generation in Alberta: hydro, coal, natural gas, and oil (Foulkes, 1982, p.3-2). In the early sixties, hydro was the main energy source for electricity generation. The capacity of hydro power has remained at 800 Mwe(net) since the early seventies. From the early sixties, coal-fired capacity increased rapidly from 283 Mwe(net) to the present level of 3,400 Mwe(net)(ERCB, 1982,p.11). Since the mid seventies, the capacity of coal-fired plants has been able to meet the base load demand, Figure 2.1.

Presently natural gas takes a share second to coal in electricity generation, but its generation has remained at 1,100 Mwe(net) since the last decade (ERCB, 1982, p.11).

2.1 Future electricity generation in Alberta

Inhaber[1978, p.38] stressed eight viable energy sources in Canada. They are coal, oil, nuclear, natural gas, hydro, wind, methanol and solar energy. With the high latitude and unsteady supply of renewable energy (with the exception of hydro), only the first five are viable in Alberta. Foulkes[1982, p.3-2] reported that hydro power contributed only 8.9% of the total electricity generation in Alberta for 1981. As predicted by ERCB[Sept., 1982, p.76] the present electricity production level by hydro would remain the same for the next 25 years. Hart[1977, p.10] indicated that coal will continue to be the future energy

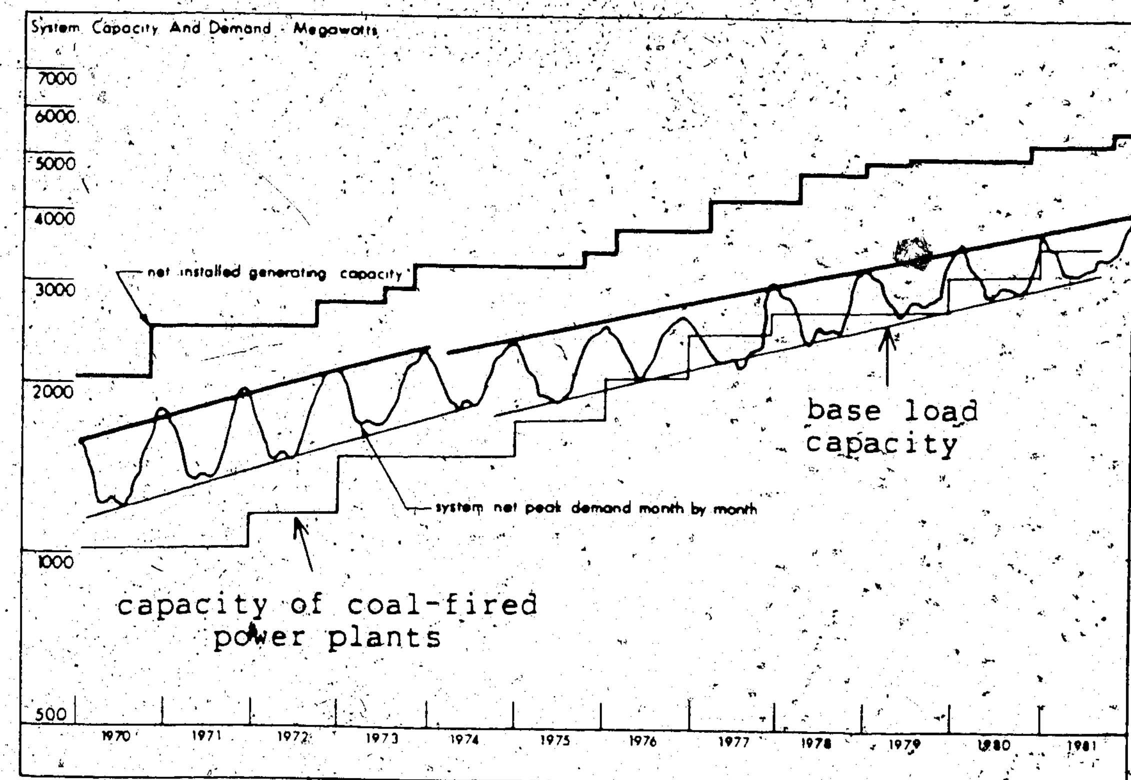


Figure 2.1 Demand and supply for electricity in Alberta

source for electricity generation because the present reserves of coal are sufficient to last for 300 years.

In Ontario, CANDU pressurized heavy water reactors have been proven to be an economical means of electricity generation (Rahnama, 1982, p.28,30). CANDU's large capacity per unit is suitable for meeting the base load demand for electricity. The CANDU reactor is considered in this thesis to be a challenger to coal-fired power plants as a future energy source for electricity generation in Alberta.

2.2 Future demand for electricity

ERCB[Sept., 1982, p.63] has estimated the future demand for electricity in Alberta. This estimated demand is expressed in terms of total elec ricity required for each year during the next 25 years (1981-2005 inclusive). The electricity demand, as shown in Figure 2.1, fluctuates monthly, being highest in December and lowest in June. The annual demand predicted by ERCB includes the base and fluctuating demands as shown in Figure 2.2. The base load demand, which is the subject of interest, would then be obtained by subtracting the total monthly fluctuating demand over a year from the ERCB predicted annual demand. In this thesis, the monthly fluctuating demand is assumed to be met by electricity supplied from natural gas, oil and hydro whose total production levels are assumed to be the same as that of 1982 and constant through out the study period. This expected base load demand (+ marks in Figure 2.3) is further refined by linear regression and is treated as the base case demand for electricity in Alberta (line b in Figure 2.3).

In order to facilitate the sensitivity tests for total costs as a function of demand, two additional electricity demands are defined. They are shown by line a and c in Figure 2.3. One is 4% annual growth (line c in Figure 2.4), as predicted by the Electric Utility Planning Council (EUPC) in 1983, (Ovenden, 1983). The other is 3% annual log growth (line a in Figure 2.3) which is established by projecting from the historical base load demand, i.e. it is obtained by extending the base load capacity line in Figure 2.1. This 3% annual log growth is considered to be the upper bound because it is projected from the time when the economy was relatively active and the energy conservation era had just begun. These two growths in demand for electricity are projected from 2.353 Gwe (ERCB, 1982, p.7) which was the annual electricity production by coal-fired power plants in 1982.

The electricity base load demands in ascending order of growth rates are:

1. 4% annual growth,

   based on EUPC, line c in Figure 2.3.

$$D = 2.353 \times 1.04^{(m-1982)} \qquad \text{.......... 2.1}$$

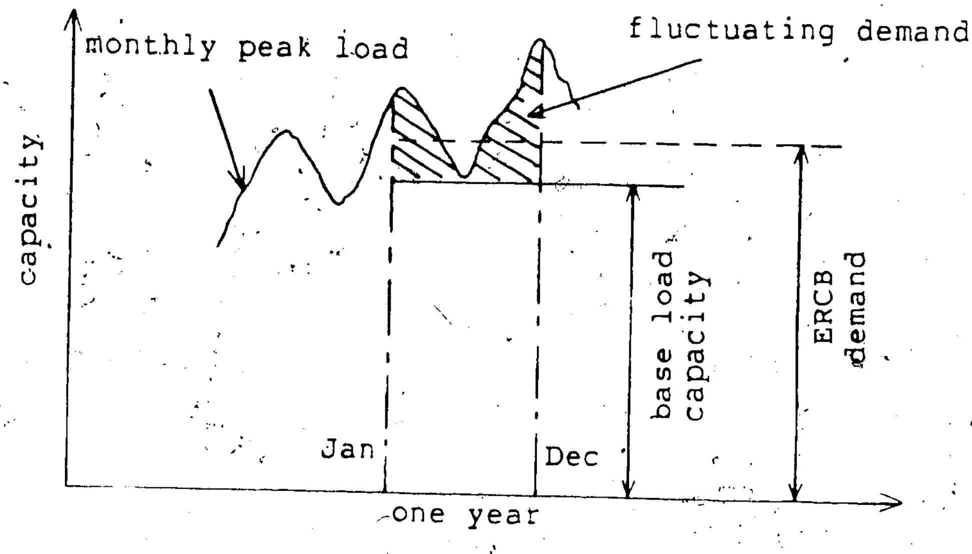


Figure 2.2 A schematic diagram showing the relationship of base load, peak load, and monthly fluctuating demand for electricity

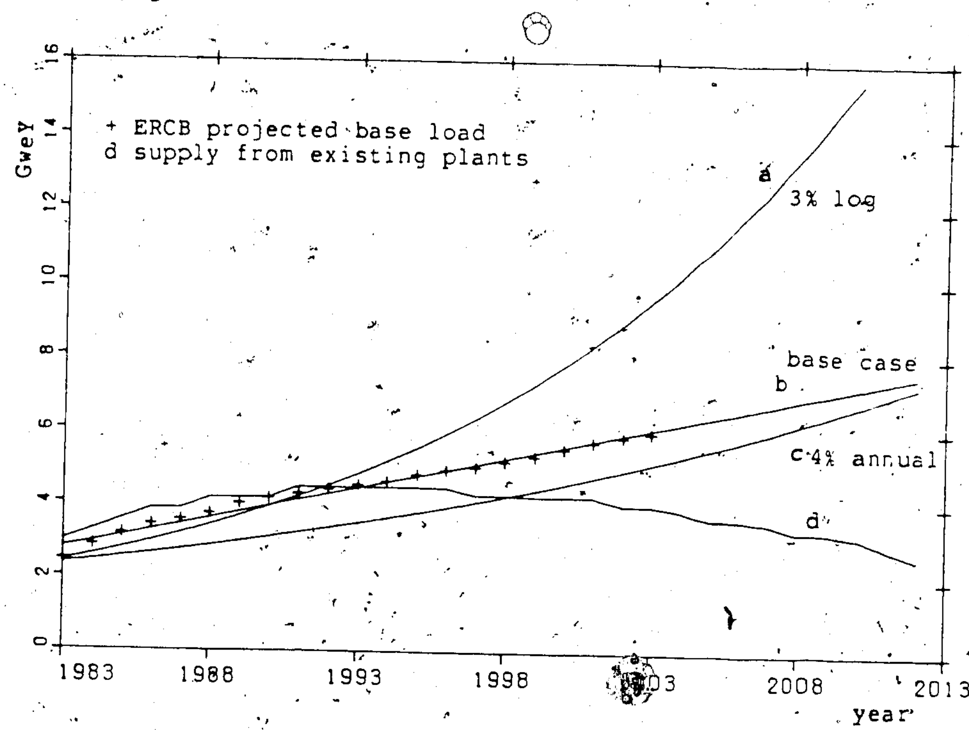


Figure 2.3 The electricity demands in base load during the study year

2. base case growth,

based on ERCB demand, line b in Figure 2.3.

$$D = 2.605 + 0.16448 \times (m-1982) \quad \text{.......} 2.2$$

3. 3% log growth(based on a scale of 10),

based on historical growth, line a in Figure 2.3.

$$D = 2.353 \times 10^{0.03(m-1982)} \quad \text{.......} 2.3$$

note:

a. all in GweY

b. all demand and supply are measured just before the electricity distribution network

c. m is the study year during the study period

For comparison and illustration purposes, line d in Figure 2.3 is drawn. This line shows the supply of electricity from those power plants which have been operating and have been committed in 1981. No other new power plant is commissioned during this study period.

2.3 Capacity of power unit

A plot of the total capacity of coal power plants in Alberta starting from 1970 up to those plants committed in 1981 is shown in Figure 2.4. Multi-unit systems (usually pairwise) are common in Alberta. For example, the newly commissioned Keephill and Sheerness power stations have two

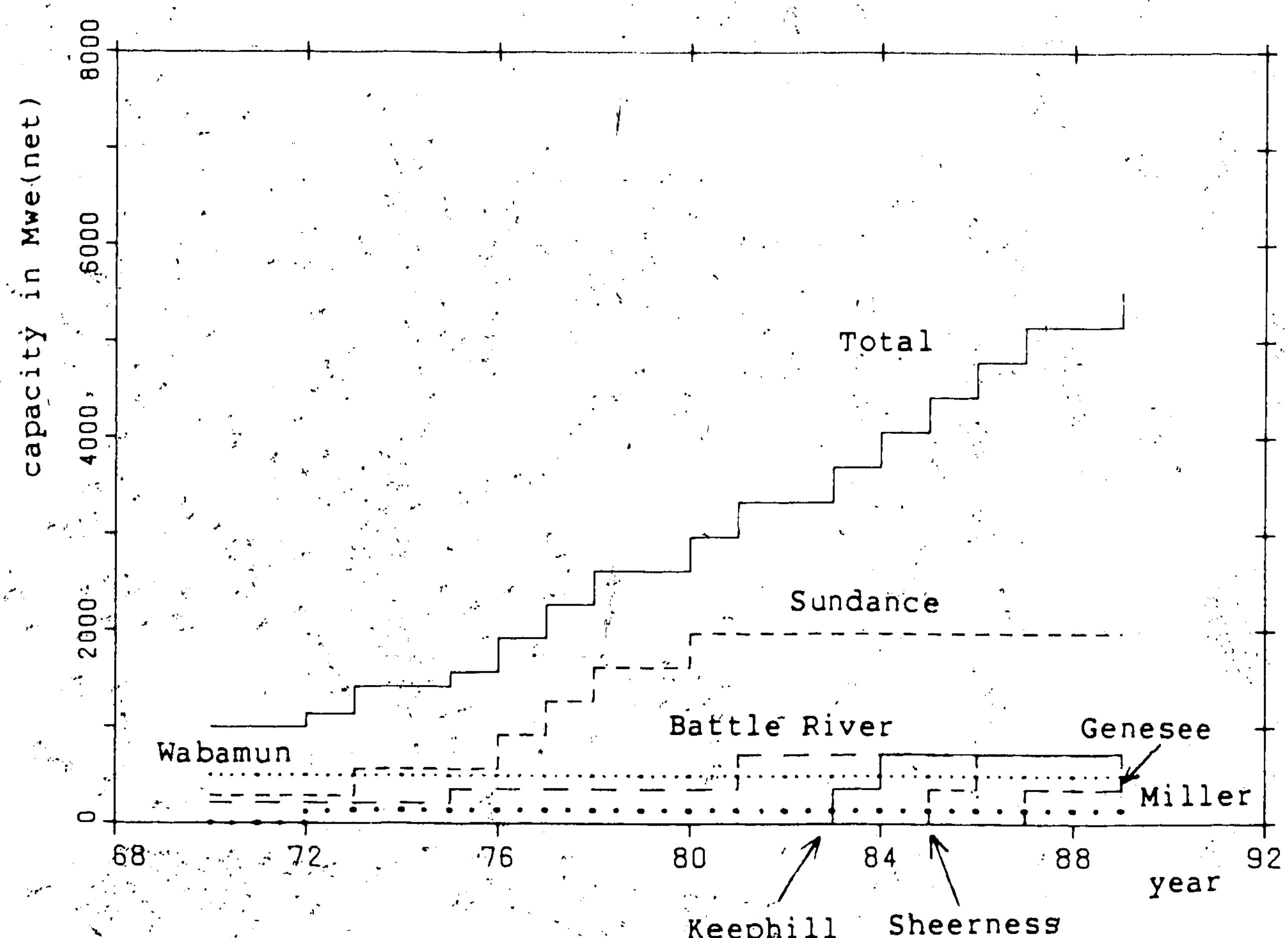


Figure 2.4 The capacity of coal-fired power plants in Alberta

units in each of them. The standard capacity per unit is approximately 350 Mwe(net). Since the last decade, there has been a unit of this standard capacity commissioned almost every year (Figure 2.4). To be compatible with Foulkes's[1982, p.II-5] analysis, it is assumed that the new coal-fired power stations are composed of three units, each of which is 0.371 Gwe(net) with scrubbers. For comparison purposes, Komanoff[1978, p.7] estimated that the optimum capacity for utilities in the United States ranges from 500 to 600 Mwe(net). TOSCA uses 1.0 Gwe(net) for all types of power plants. Similar to Foulkes[1982, p.I-1], a nuclear power station is assumed to have two power units each of which is 0.6 Gwe(net). This capacity for a power unit is also estimated by Komanoff[1978, p.7]. The capacity factor (c.f.) of nuclear and coal-fired power plants is assumed to be 0.8.

2.4 Service life of power plants

The service life of power plants is quite a controversial issue because service life depends on the original design and management practice — either up-grading out-dated plants or just keeping them at running condition. Some older power plants are used to handle peak demand before they are decommissioned, which has the tendency to lengthen their service lives.

The service life of power plants is expected to be in the range of 30 to 40 years. Phung[1976, p.1] reported the service life of power plants in the United States varied from 20 to 40 years. Foulkes[1982, p.6-4] used 30 years as the service life of power plants. Gaines et al [1979, p.28] and Barrager et al[1976, p.31] used 35 years as the estimate of service life in their studies. In this thesis, a service life of 35 years is used for both coal-fired and nuclear power plants.

3. Traditional Costs

Traditional costs are capital C, operating and maintenance M, fuel F, and research costs R. They are levelized over the service life of the power unit. The annual total costs for plant type/unit i, in study year m, $A_{i,m}$ is the sum of these four costs and social costs S, some of which depend on the year of commission z. It is expressed as

$$A_{i,m} = \sum_{z=1983}^{m} (C_{i,z,m} + M_{i,z,m} + F_{i,z,m}) + R_{i,m} + S_{i,m} \quad \ldots\ldots 3.1$$

In the total cost analysis, the total cost p, is the present equivalent value of sum $A_{i,m}$ over plant/unit i, or:

$$p = \sum_{m} \left[\frac{1}{1+d} \right]^{m-1982} \sum_{i} A_{i,m} \quad \ldots\ldots 3.2$$

where

p = total cost

m = study year

d = interest rate

i = plant type/unit

for example

i = 1 refers to coal power plant unit 1

i = 2 refers to coal power plant unit 2

i = 3 refers to coal power plant unit 3

i = 4 refers to nuclear power plant unit 1

i = 5 refers to nuclear power plant unit 2

3.1 Capital cost

Capital cost includes all the facilities up to the station step-up transformers but not the high-voltage switchyard or transmission cost.

In TOSCA, a computer program developed by Gaines et al[1979] for total cost analysis, the capital cost is assumed to be constant in real terms and paid in the full amount when the power unit starts production, Gaines et al[1979, p.17].

For Alberta, the following are adopted:

1. The capital costs of the existing power plants at the beginning of the study period are included.
2. The total capacity from the existing coal-fired power units is 2.353 Gwe in 1982 (ERCB, 1982, p.7]) in Alberta. The increase of a unit capacity, which is assumed to be 0.6 and 0.371 Gwe for nuclear and coal-fired power plants respectively, is quite significant compared to the total capacity. The new power unit commissioned close to the end of the period would cause a sudden jump in capital cost. For reducing the effect due to these initial and final conditions, and for comparison purposes, annual equivalent capital cost of each unit (or levelized cost) is used. Since real rates of increase are

included in this thesis, this levelized cost would also spread the effect of any real rates of increase for any of the cost factors evenly over the service life of the power unit as shown in Figure 3.1.

All new power units commissioned during the year are assumed to be in operation at the beginning of the same year and all the costs are accounted for at the end of the year. Their capacities may not be fully utilized because supply is always slightly more than the demand for electricity.

Coal-fired and nuclear power stations are assumed to be multi-unit systems each having the advantage of lowering the capital costs of the whole power station due to the sharing of common facilities among the units of the same station. These facilities are required right from the first power unit. The capital cost of the first power unit is, therefore, higher than the others (refer to the cash flow in Appendix 1, A.1.2 and Figure 3.2). The levelized capital cost in year m of a new unit ($C_{i,z,m}$), of plant type/unit i, commissioned in year z, is projected from a plant commissioned in 1982, by using the real escalation rate of construction cost, cash flow rate, and allowance for funds used during construction. This capital cost is levelized over its service life of 35 years by using the real interest rate.

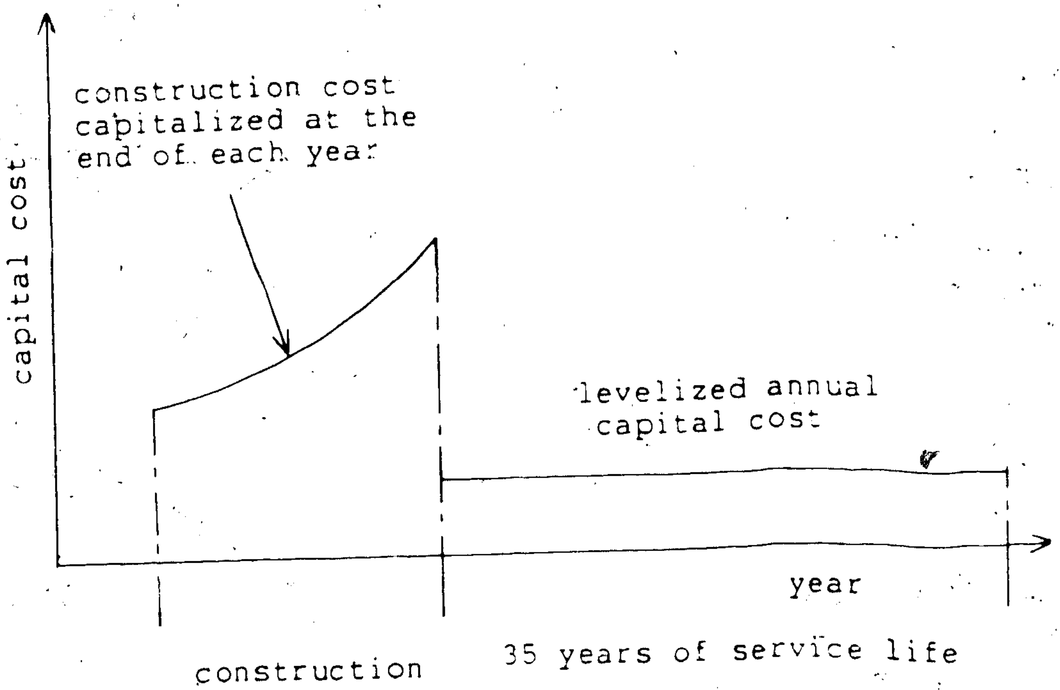


Figure 3.1 A schematic diagram showing the relationship of capital cost at the year of commission and its levelized cost

Mathematically the capital cost of a new unit commissioned in year z can be expressed as

$$C_{i,z,m} = \frac{a}{(CPI)_z}\left[\sum_{t=1}^{y_i} U_i k_{z-y_i+t} f_{i,t} (1+AFUDC)^{y_i - t}\right] \quad \ldots\ldots\ldots 3.3$$

where:

U_i is the capital cost of a power station for plant type/unit i, commissioned in the beginning of 1982.

$f_{i,t}$ is the cash flow rate for plant type/unit i, in construction year t, expressed in percentage of the capital cost for the whole power station commissioned in the beginning of 1982.

y_i is the number of construction years required for plant type/unit i.

k_{z-y_i+t} is the nominal rate (current dollars) of construction cost for the beginning of the year $z-y_i+t$ relative to the beginning of 1982.

$(CPI)_z$ is the consumer price index, at the beginning of the commission year z, relative to the beginning of 1982.

AFUDC is the allowance for funds used during construction (market rate).

a is the factor for levelizing the capital cost over 35 years into annual equivalent cost by interest rate d (that is the annual equivalent over the present value factor).

$$a = \left[\frac{d(1+d)^{35}}{(1+d)^{35}-1}\right] \qquad \text{.......................3.4}$$

The estimates of the above factors, which are similar to Foulkes[1982], are listed in Appendix 1, A.1.1 to A.1.3.

It has to be stressed that the levelized capital cost of a power unit is the same throughout its service life. Different units have different levelized capital costs because of varying commission dates (refer to equation 3.3). The effect of levelizing the costs is shown in Figure 3.1.

The cash flow rate is expressed as a percentage of the capital cost of the power plant and is based on Foulkes's estimates except that the cash flow rate has been changed for units of a power station rather than for the whole station (Figure 3.2). Details of estimating the cash flow rates for each unit are given in Appendix 1, A.1.4.

Allowance for funds used during construction, AFUDC, is capitalized at 12% (interest rate adjusted for inflation) which is consistent with recent financing and regulatory conditions experienced by an investor-owned utility in Alberta(Foulkes 1982, p.6-5).

As is the usual practice, the complete inventory of heavy water and a half charge plus 100 bundles of fuel have been included in the capital costs for each unit (Foulkes 1982, p.4-3). Similar to the studies by Rahamana [1982, p.16], Gaines et al[1982, p.2,17] and Foulkes[1982, p.2-2],

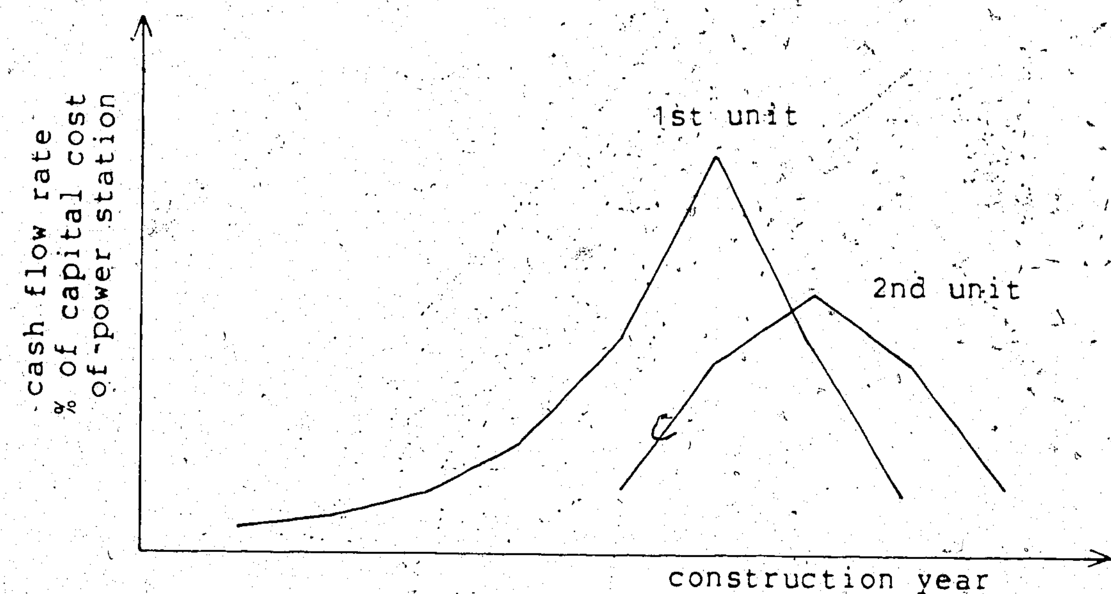


Figure 3.2 A schematic diagram showing the cash flow rate for nuclear power plant

cost for decommissioning and the effect of income taxes are not included. An example of estimating $C_{i,z,m}$ using equation 3.3 is given in Appendix 1, A.1.5.

All power units which have been operating or are committed to be built in 1981 are called existing power units. They are assumed to have the same annual equivalent capital cost as if commissioned in January 1982. The levelized capital costs for an existing power unit, $C_{i,z,m}$ is expressed as

$$C_{i,1982,m} = U_i \frac{a}{u_i} \quad \text{.......... 3.5}$$

where:

u_i is number of units per plant for plant type/unit i.

The capacity of existing power units is assumed to be 0.375 Gwe(net) without scrubber. The number of these existing power units, $N_{i,m}$ is equivalent to $G_{i,m}/q_i$, where:

$G_{i,m}$ is the total electricity generated by existing power plant/type i, in the year m.

q_i is the electricity generated by a unit of plant/type i in one year.

The total annual capital cost due to existing plants in the year m is $C_{i,1982,m} \times N_{i,m}$.

3.2 Operating and maintenance costs

Wages, materials and consumables, waste disposal, and services for smooth and safe operation are included in these factors.

At the beginning of the study period, the total base load capacity in Alberta is 2.353 Gwe. An increase of one nuclear power unit of 0.6 Gwe assumed in this thesis would cause a 25% increase in the base load capacity. Such an increase in capacity is usually not fully utilized by the base load demand and a considerable amount of surplus capacity may exist. In TOSCA Gaines et al [1979, p.17] assumed annual operating and maintenance costs are directly proportional to the annual electricity output. If this assumption is applied to Alberta, then operating and maintenace cost due to this surplus capacity would be neglected. In this thesis, all annual operating and maintenace costs are assumed to be fixed costs and directly proportional to the number of operating units.

Gaines et al also assumed that the operating and maintenance costs for a power unit are constants in real terms. In this thesis, similar to Foulkes's study[1982, p.6-3], the labour cost is allowed to escalate and material cost is maintained constant in real terms; the different costs associated with different power units of the same station are also incorporated; the real annual cost of insurance, interim replacements, and property taxes I_i are included and estimated to be 1.35% of the total capital cost for coal and 1.1% for nuclear plants (Foulkes, 1982, p.6-3). The operating and maintenance costs are levelized over the service life of the power units and the effect of the escalation rate is spread over the service life.

The levelized operating and maintenace cost, M, in the study year m for a new unit commissioned in year z can be expressed as :

$$M_{i,z,m} = a \sum_{j=1}^{35} \left[(L_i l_{z+j} + H_i + C_{i,z,m} \frac{I_i}{a100}) \frac{1}{(1+d)^j} \right] \quad \ldots .3.6$$

Where:

L_i is the labour cost for a power plant type/unit i, in January 1982 dollars.

l_{z+j} is the real labour escalation rate in the beginning of year z+j (or the end of year z+j-1), relative to the beginning of 1982.

H_i is the material cost for a power plant, type/unit i, in January 1982 dollars.

The estimates of these factors are listed in Appendix 1, A.1.6.

For existing units, the equation is exactly the same as that of new plants except that the levelized capital cost is considered to be the same as those commissioned in 1982, i.e. $C_{i,z,m} = C_{i,1982,m}$. Similar to the capital cost, the equivalent number of operating units is $N_{i,m}$ and the total annual operating and maintenance costs for existing plants is $M_{i,1982,m} \times N_{i,m}$.

3.3 Fuel cost

In this study the total annual fuel cost is assumed to be directly proportional to the amount of electricity generated and is allowed to undergo a real rate of increase as a function of time. The fuel cost is levelized with the result that the effects of fuel escalation rate are spread evenly and is compatible with the procedure used for other costs. The levelized fuel cost for plant type/unit i, commissioned in year z, operating in study year m, can be expressed as

$$F_{i,z,m} = a\left[\sum_{j=1}^{35} \frac{\Psi_i(1+\beta_i)^{z-1982+j}}{(1+d)^j}\right]\Delta E_{i,z,m} \quad \ldots\ldots\ldots 3.7$$

where:

Ψ_i is defined as fuel cost per unit electricity generated for plant type i in the year 1982 which are estimated to be 64.02 and 41.46 million January 1982 dollars per GweY for coal and nuclear fuel respectively (Foulkes, 1982, p.4-4, 5-3).

$\Delta E_{i,z,m}$ is the total electricity generated by a unit commissioned in the beginning of year z, of plant type/unit i, in the year m.

β_i is defined as the real fuel escalation rate.

The total costs and the unit costs are very sensitive to the real increase of fuel prices (Gaines, 1979, p.39, Rahnama, 1982, p.44). The forecast of fuel prices differs from study to study. Rahnama[1982, p.24] assumed that the coal price escalates at a rate of 1% per year and then 2% after 1990, and that the uranium price is constant but escalates at a rate of 1% after 1990 (all in real terms). Rahnama[1982, p.42] also added that the price of uranium was falling in 1982. Bancroft[1982, p.14] in the study of "Nuclear Energy for Oil Sands" assumed both coal and nuclear fuel prices to remain at 1981 price levels. Foulkes[1982] assumed the escalation rate for coal to be 1.5% and the price of uranium to remain unchanged at the 1982 price level and then to increase at a rate of 1.5% after 1989 (all in real terms). ERCB [Sept., 1982, p.13] predicted that price of coal would remain unchanged in real terms, but in the long term it would increase due to the influence of international demand. The above indicates that the escalation rate of coal is either at a rate lower than or at the same rate as the escalation rate of uranium. For the initial case study, the escalation rates for both coal and nuclear fuel are the same as those of Foulkes's study above. For the base case analysis, the real fuel escalation rates are assumed to be 1.5% and 0% for coal and uranium respectively. Since these rates are independent of time, the temporal effect on fuel escalation rates is isolated, which facilitates the sensitivity tests for fuel prices.

3.4 Research cost

Research has the effect of improving either the reliability, efficiency, durability and/or safety of the operation. Though there were functions established in TOSCA, they are considered to be zero in the base case study. Gaines et al[1979, p.1] concluded that the total costs are not sensitive to research cost. When research cost is compared with other costs, it only contributes a small portion to the total costs. In this thesis, research cost is assumed to be absorbed in overhead and is not included in this study.

4. Estimation of Social Cost due to the Power Industry in Alberta

4.1 The functional relationship between social cost and electricity generation

There are many different types of social costs due to electricity generation. Some of them may be directly proportional to power plant output, power plant capacity, cumulative output or any combination of them. For example, social costs due to land use for nuclear or coal power plants will be proportional to plant capacity (Hill, 1977, p.2.8); social costs due to acid damage from coal mining is roughly proportional to the amount of coal removed, i.e. to the cumulative output of the power plants using coal (Hill, 1977, p.2.8). Nevertheless, for a first approximation, relationships other than those to annual power plant output are not incorporated into this study. All social costs for both types of power plants are assumed to be proportional to the amount of electricity generated.

Mathematically, the relationship between social costs and electricity output is assumed to be

$$S_{i,m} = s_i \sum_{z} (\Delta E_{i,z,m}) \qquad \text{4.1}$$

where:

$S_{i,m}$ is the annual social costs due to plant type/unit i, in study year m.

$\Delta E_{i,z,m}$ is the amount of electricity generated by plant type/unit i, commissioned in the beginning of year z, and operating in study year m.

s_i is the social cost per GweY and is constant over the study period and is estimated in the following sections.

The relationships shown in equation 4.1 can be justified. Alberta is subject to the guidelines of the National Air Quality Standard set by the Federal-Provincial Committee on Air Pollution. These guidelines are set in order to protect people with existing medical conditions, such as patients with chronic lung disease, which air pollutants may further aggravate. The pollution levels at these guidelines become the thresholds below which no damage can be observed. With the exception of particulates and ozone, the pollution levels in Alberta for the past several years were well below these guidelines, as shown in Table 4.1 and Table 4.2. When compared to the increase of electricity production during the same period, 1975 to 1979, the pollution levels do not change significiantly (Table 4.2). In this thesis, the ambient pollution levels are assumed not to change in the future. Also, the costs for a death, an injury day and an illness are assumed to be constant in real terms. With these two assumptions, the

Table 4.1 Secondary Air Quality Standard (yearly average)

suspended particulates $\mu g/m^3$	SO_x $\mu g/m^3$(ppm)	NO_x $\mu g/m^3$(ppm)	CO $\mu g/m^3$(ppm)	O_3 $\mu g/m^3$(ppm)
60	55(0.02)	100(0.053)	5.77(5)	30(0.015)

source: Federal-Provincial Committee on Air Quality
Ontario Research Foundation

Table 4.2 The pollution levels in Alberta

Pollutants	power plant contribution in %	Year '75	'76	'77	'78	'79
Calgary						
NO_x	0	0.0367	0.0300	0.0300	0.0333	0.0333
O_3	0	0.0207	0.0180	0.0153	0.0160	0.0180
CO	0	2.3000	1.7670	1.8330	1.7667	1.8330
SO_x	0		0.1200	0.1600	0.1600	0.1500
Susp. Part.	0	59.700	64.800	76.310	74.110	96.00
Edmonton						
NO_x	30.3	0.0333	0.0267	0.0267	0.0300	0.0300
O_3	0	0.0223	0.0233	0.0147	0.0143	0.0180
CO	0	1.5000	1.3333	1.3000	1.3000	1.8670
SO_x	0	0.1700	0.0900	0.1300	0.1100	0.1000
Susp. Part.	4.0	64.800	69.700	60.400	58.970	74.000

Source: 1979 Air Monitoring Report
note: all in parts per million, ppm, annual average except, SO_x which is expressed as SO_3 equivalent mg/100cm^2/day for it cannot be measured in ppm scales or $\mu g/m^3$
Suspended particulates $\mu g/m^3$/day high volume.

social costs, for example health costs, can be assumed to be directly proportional to the number of people exposed to the polluted environment.

If the electricity used per person is further assumed to be constant during the study year (Snell, 1982, p.10), the health cost is then directly proportional to the electricity generated (Lees, Dunn, Ersil, 1980, p.50). Since health cost is the major social cost (Hill, 1977, p.49; Barrager, 1976, p.49) and for a first approximation, all social costs are assumed to be directly related to the annual output of electricity.

4.2 Method for estimating the social cost constants

In this thesis, information from the literature is used as the primary source for social cost estimates. The basic procedures for using the estimates from the literature survey are listed as follows:

1. If possible, the methods used or suggested by the literature are used.
2. If the application of these methods is not possible because of insufficient raw input data, or the derived results do not make sense, the methods are not used. Instead, the ratio of the damage potentials between the locations mentioned by the literature and Alberta is used to pro-rate the cost estimates from the literature to those of Alberta (Justus, Williams, Clement, 1973). The details and

application of damage potential functions can be found in Appendix 5, A.5.2.

3. If the information required for obtaining the damage potentials is not available, the above mentioned method for pro-rating the estimates into those of Alberta is abandoned.

4. In most studies, two steps can be observed in estimating the health costs. They are: a) the physical damages, for example number of deaths; and b) the monetary value per physical damage, for example the cost per death, cost per illness and cost per injury day. Since the social background and the health care system can affect the monetary value per physical damage, only the physical damages from the literature are adopted and the cost per physical damage is assumed to be constant. In studies where health costs are given, the costs are used only when the social background mentioned is similar to that of Alberta.

5. The health costs for a death, an injury day and an illness are estimated by taking the average of estimates taken from various studies. Only those cases having a health care system and social background similar to Alberta are taken into consideration. The unit costs are estimated in Appendix 5, A.5.1 and listed as follows:

social cost per:

	*
death	$913,000.00
illness	$12,054.00
injury day	$118.85

* In January 1982 Canadian dollars.

Note: These cost estimates are higher than usually used.

6. If the social cost estimate is considered to be an upper limit or it is abnormally high when compared with other estimates, the expected social cost estimates for Alberta are assumed to be half of this upper limit. This is based on the reasoning that the lowest possible social cost is assumed to be zero.
7. A possible social cost estimate for a particular social cost v, for example health, can be derived from the literature. By reviewing several independent sources, a number of possible cost estimates for the same social cost, v, can be obtained. For example, there are several cost estimates for mining each of which is derived from a different source. If there is no clear indication that one is better than the others, then all the derived cost estimates are treated as being equally likely. The expected cost estimate for a social cost

v, is:

$$v = \sum_{x=1}^{W} w_x v_x \quad \text{......4.1}$$

where: W is the number of estimates
w_x is the weighting factor of v_x
and $w_1+w_2+..=1$
v_x is the cost estimate for social cost v
derived from source x.

The variance σ, for this expected value v, is

$$\sigma^2 = \sum_{x=1}^{W} w_x[\sigma_x^2 + (v - v_x)^2] \quad \text{......4.2}$$

where: σ_x^2 is the variance of each estimate v_x,
derived from source x.
Derivation of equation 4.2 is in Appendix A.6.

All the social cost estimates are normalized in million January 1982 Canadian dollars per GweY (M/GweY) by using the consumer price index listed in Appendix 5, A.5.3. In 1982, Alberta utilities produced 2.353 GweY of electricity from coal-fired power plants, i.e. base load for a population of around 2.3 million. A figure of 1 GweY for a population of one million is often used in the literature, (Snell, 1982, p.10; Hill, 1977, p.5.4). By normalizing the social costs in million dollars per GweY, the estimates also approximate the social costs in dollars per person due to electricity generation. This method has the additional advantage of giving an immediate perspective of the social cost in dollars per person in a year. The social costs in M/GweY can be converted to mills/kwh by a multiplying factor of 0.1142. The overall social cost estimate s_i, due to power generation i, is the sum of all the cost estimates for each social impact:

In this study, estimates of social costs are confined to prominent, regional damages rather than to global ones. In other words, only those having direct concern to Albertans are considered. For all estimates, the estimation method is highlighted in the tables of each social cost estimation section. Detailed calculations are provided in Appendix 5, A.5.2.

The total social cost is assumed not to have negative effects. Its value ranges from zero to infinity. A number of probability density functions could have been used to satisfy this requirement. The log-normal distribution is used in this thesis. The use of this distribution is consistent with Barrager et al[1976, p.16], who also used this normal distribution to represent the range of health costs due to coal-fired power plants.

4.3 Limitations in estimating the social costs

The social costs are very difficult to estimate. This is particularly true when statistical data for the appropriate geographical location are unavailable. Other problems are:

1. The cost for a death and an illness due to pollution and radiation is a controversial issue (Mendelsohn, 1980, p.38; Hill, 1977, p.2.2). Separating the contribution of damages due to different pollution sources presents another problem.
2. The long latent period in response to the pollution changes causes a problem in relating the pollution levels and the corresponding damages.
3. There are some degrees of uncertainty in estimating the risks of nuclear plant accidents, effects of thermal waste, and global effects caused by carbon dioxide concentration in atmosphere (Rahnama, 1982, p.59)
4. The method chosen in estimating the social costs also has some inherent limitations. In using the original method from the literature to estimate the social costs, the Alberta situation may not be truly represented, because of time and social differences or because of the validity of the original methods.
5. The conversion method by a damage potential function also has limitations: since pollutants are not distributed uniformly over the province, using the pollution level of a city to represent the whole province may not be appropriate. The exposure factors of the receivers to each pollutant taken from data particular to the United States may not truly represent the Alberta situation. The damage potential function assumes damage to be zero when the pollution levels are

below the Air Quality Standard. The effects of prolonged exposure to pollution at low level concentrations for a large population has not been established (Lees et al, 1980. p.8).

Nevertheless the uncertainty of total costs is taken into consideration by fitting the estimate with a probability density function, and a log-normal distribution is used.

4.4 The social cost due to CANDU Nuclear power plant assumed to be in operation in Alberta

It is assumed that there is no nuclear fuel processing, milling or enrichment in Alberta. The spent fuel is stored in spent fuel storage bay for ten years (Foulkes, 1982, p.I.7). Social costs due to permanent waste disposal are not included, based on the assumption that spent fuel is disposed permanently outside Alberta.

The social costs related to nuclear power plants are divided into four categories: 1. health, 2. accident, 3. sabotage, and 4. nuclear fuel diversion. This is consistent with a study done by Barrager, Judd, and North[1976, p.49].

4.4.1 Health cost due to operating a CANDU nuclear power plant

The health costs due to normal operations are included in the social cost estimates. That is, only social costs during energy conversion, and the transportation of fuel and spent fuel are considered. With the exception of the cost estimate derived from Snell[1978], all the estimates from the literature are for the whole fuel cycle which includes mining of uranium, fuel processing, fuel transportation, energy conversion and waste disposal. The estimates for the normal operation of nuclear power plants and transportation of nuclear fuel taken from the literature are assumed to be applicable to Alberta. By comparing Barrager et al's [1976] cost estimate for the United States and the cost estimate for Alberta derived from Barrager in Table 4.3, about 10% of the social costs for the whole fuel cycle are due to the normal operation of a nuclear power plant and the transporation of nuclear fuel. In other words, Barrager's estimates of social costs for the whole fuel cycle are mainly due to operations other than energy conversion and fuel transportation. Hill's[1977] and Inhaber's[1978] death and illness estimates are for the whole fuel cycle and 20-80% of their estimates are due to normal operation of the nuclear power plant and transporation of fuel. Inhaber's estimate on disabilities is the same as that for Alberta (Table 4.3). In fact, Inhaber's estimate of these disabilities is slightly higher than that of Alberta by about 0.00005 disabilities per Mwe per year. Hill and Inhaber used the results from a

Table 4.3 Health cost due to normal operation of CANDU nuclear power plants in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GwY
Hill 1977	0.127 - 0.437 deaths 1060-2060 injury days per 1000 Mwe plant Year	By literature survey then adjusted to CANDU power plant in Ontario. same damage as light water reactor power plants, LWR, extraction of uranium included.	0.072-0.379 deaths 260-460 injury days for 1000 Mwe-Yr assuming no extraction of uranium in Alberta.	0.311(0.110)
Barrager et al 1976	0.012 mills/kwh	No detailed method given, for U.S. assuming same damage as LWR, for whole fuel cycle, 1000 Mwe, 0.75 capacity factor, c.f., using 3.3% enriched uranium, cost due to occupational hazard & low level radiation, in 1975 U.S.D.	0.0013 mills/kwh 1975 U.S.D. due to occupational harzard and low level radiation, excluding damages due to reprocessing, fuel fabrication mining, milling and enrichment, converted to 1982 dlr. by US CPI then to CD.	0.025 *

Inhaber 1978	$(3.1-13.3)\times10^{-4}$ deaths $(2.02-6.34)\times10^{-3}$ disabilities or equivalent to 2.1-8.4 man-days lost (MDL) per Mwe-Year *	By literature survey, for Ontario, for public and occupational, whole fuel cycle, assuming CANDU having the same damage as LWR.	Only considered reactor operation, $(2.57-7.0)\times10^{-4}$ deaths $(2.02-6.34)\times10^{-3}$ disabilities or equivalent to 1.81-4.61 MDL per Mwe-Year using the same unit damage cost, then by normalization, mainly due to the social cost of disabilities.	0.382(0.096)
Snell 1978	1% of the AECB guidelines are usually met.	Based on guidelines set by the Atomic Energy Control Borad, AECB, for normal operation & for CANDU power plant system in Onatrio, irrespective to plant capacity, same limits as International Commission on Radiological Protection. the max. permissible population dose is 10,000 man-rem/year which causes 1.5 cases of fatal cancer 1 case of curable cancer, and 0.6 to 15 hereditary diseases * per nuclear plant year.	Assuming the damages are half of the max. permissible limits	0.738(0.426)
			Average	0.364(0.340)

figures in brackets are standard deviations
* point estimate
one million 1982 dollars/GwY, M/GweY
= 0.1142 mills/kwh for same year dollar value
all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5, A.5.2.

literature survey and studies for light water reactors in the United States. The estimates derived from Hill and Inhaber for Alberta on the number of deaths are of the same order, but health impairments cannot be compared because of different classifications.

Snell's[1978] estimates on illnesses and deaths are based on the radiation exposure limits for the normal operation of a reactor set by the Atomic Energy Control Board AECB. The established dose-response function is used to estimate the number of fatal and curable cancers. Snell[1978, p.9] reported that 1% of the guideline set by AECB is the design target for nuclear power plants and added that this target is usually met. The cost estimate for Alberta derived from Snell is not based on 1% of the AECB guidelines but is assumed to be half of the estimates derived from the guidelines.

The cost estimates for Alberta derived from Hill[1977], Inhaber[1978] and Snell[1978] are of the same order of magnitude, although the methods of estimation are different. The cost estimates for Alberta derived from Barrager et al is the smallest among all the other cost estimates. There is no obvious reason why the cost estimates for Alberta vary to this large extent except that different methods have been used. The expected health cost due to the normal operation of a CANDU nuclear power plant in Alberta is estimated to be 0.364 million dollars per GweY and has a standard deviation of 0.340.

4.4.2 The social cost due to the the possiblity of nuclear power plant accidents

An accident in a nuclear power plant can be caused by mechanical failure and/or human error during the operation of the power plants or by external forces (for example being attacked). In this study only accidents due to mechanical failure and human error are considered. This is because there is no literature on social costs due to nuclear power accidents by external forces available, except for the case of sabotage which is dealt with separately.

Nuclear power accidents, in this study, are classified into two types, radiation and non-radiation related (Barrager, 1975, p.49). If an accident is radiation related, it can be regarded as any incident during the operation of a nuclear power plant and the related support services (for instance during transportation of fuel to the station) which will result in a sudden release of radiation at a dosage higher than the approved safety limits. A nuclear power accident usually causes the shut down of the reactor. Other accidents can be considered as non-radiation related.

There are four health cost estimates due to nuclear power plants accidents which can be found in Table 4.4. Hill[1977] used a literature survey to estimate the social costs due to nuclear power plant accidents. Inhaber[1978] also used a literature survey, but for the accidents involving the whole fuel cycle. Barrager et al[1976] have

Table 4.4 Health cost due to the possibility of nuclear power plant accidents in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GwY
Hill 1977	Max. 0.02 deaths per 1000 Mwe plant-year	By literature survey, for Ontario, no estimate for site personnel	Assume same max no. of deaths as that of Hill's but delay deaths are included, i.e. 0.02 deaths for 1000 Mwe plant-year at 0.8 capacity factor, c.f.	0.019(0.011)
Barrager et al 1975	0.003 mills/kwh 1975 USD	For United States based on probability of reactor and expected consequences, using discrete rather than continuous form for the probability distribution of consequences, included health and property damages, primary referred to core meltdown, for the whole cycle. probability of accident estimated in the order of 10^{-4}, based on WASH 1400 study on LWR	Same health cost as that of Barrager's, except no fuel fabrication 0.00254 mills/kwh 1975 USD converted to 1982 dollar by US CPI, then to Canadian Dlr using his ratio to split cost estimates into health and property damages costs.	Health 0.003 property 0.046
Inhaber 1978	$(3.12-7.72)\times10^{-4}$ deaths $(16.11-29.11)\times10^{-4}$ disabilities (2.58-6.08) MDL for Mwe-year	for Ontario by literature survey, for the whole fuel cycle, assuming social costs due to CANDU and LWR to be the same.	Excluding gathering and handling of fuel, $(1.9-2.02)\times10^{-4}$ deaths $(12.7-13.11)\times10^{-4}$ disabilities (1.68-1.88) MDL for Mwe-year	0.212(0.007)

Snell 1978	No estimates except quoted from AECB's guidelines,	For Ontario CANDU, based on AECB guidelines per reactor, For single failure, once in 3 years max. allowable population dose is 10' man-rem causes 1.5 cases of fatal cancer, 1 case curable cancer 0.6-15 hereditary diseases, for dual failure, once in 3000 years max. allowable population dose is 10' man-rem which causes 30 to 750 fatal cancers 80 to 2000 hereditary diseases.	Since the estimates are for upper limits, the expected value is half of this limit.	0.318(0.184)
			Average	Health 0.138(0.161) Property 0.046(0.000)

figures in brackets are standard deviations
all 1982 dollars refer to January price level
figures without standard deviation are point estimates
details in the Alberta cost estimates can be found in Appendix 5, A.5.2.

carried out a study on the possibilities of each event leading to an accident, and the consequences of each accident. They estimated that the social cost of property damage due to nuclear accidents is higher than that of health impairment by about ten times (no reason given). The health cost estimate for Alberta derived from Barrager et al is the lowest (Table 4.4).

The cost estimate derived from Snell[1978] is, as expected, the highest for it is taken to be half of the upper allowable limits set by AECB; but this cost estimate is of the same order of magnitude as the cost estimate derived from Inhaber. The cost estimates for a nuclear power plant accident varies from 0.003 to 0.318 M/GweY – a hundred times difference between these two limits. This wide range reflects a high degree of uncertainty in the cost estimates. The standard deviation of the expected social cost due to accident is larger than the expected value as shown in Table 4.4.

4.4.3 Social cost due to sabotage and nuclear fuel diversion of a nuclear power plant

Although CANDU uses natural uranium fuel (Foulkes, 1982, P.I-1) and plutonium is assumed not to be extracted in Alberta, as it is in the United States, some plutonium exists in the spent fuel bundles stored in the storage bays (Dalziel, 1981). The hazard of diversion is assumed to exist.

Barrager et al [1976] have carried out a study on the probability of sabotage and "plutonium" diversion for light water reactors LWR, in the United States. Barrager's estimates are based on the number of attempts per unit time per reactor, number of events per attempt, and consequences of each event. Hill[1977, p.3.17] suggested that sabotage and diversion are unlike mechanical failure and human error, and added that these type are unpredictable. Hill did not have social cost estimates on sabotage and diversion. Inhaber[1978] did not have any estimate or comment on sabotage and nuclear fuel diversion. Snell[1978] did not include this issue in the study on the safety of the CANDU nuclear power stations and no comment is given. Only Barrager et al have estimates regarding sabotage and "plutonium" diversion.

The social costs due to sabotage and nuclear fuel diversion are related to the security of the whole nuclear industry. A trade-off situation exists where by society is willing to pay for a system that will reduce this risk. In Alberta, and thus Canada, the political relationship with other countries is more moderate than that of the United States. The cost estimate derived from Barrager et al is considered by this thesis to be on the high side. The cost is assumed to be in the range of zero to Barrager's estimate. The expected value will be half of this upper limit. The cost estimates due to nuclear diversion and sabotage are listed in Table 4.5.

Table 4.5 Social cost due to sabotage and fuel diversion during the operation of nuclear power plants in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GwY
Barrager et al 1976	Sabotage 0.05 mills/kwh Diversion 0.03 mills/kwh (1975 USD)	For both health and property damages, for whole fuel cycle, first order model, study each event, motive and chance of success, from there generating several possible consequences, diversion mainly due to fuel transportation of plutonium, sabotage mainly came from operation of reactor.	No fuel fabrication and reprocessing in Alberta. Sabotage 0.05 mills/kwh Diversion 0.005 mills/kwh (1975 USD) estimates are considered to be high. CANDU uses natural uranium, expected values are assumed to be half of Barrager's estimates	Health(diversion) 0.003(0.002) Property(diversion) 0.045(0.026) Health(sabotage) 0.031(0.018) Property(sabotage) 0.451(0.260)

all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5, A.5.2

4.5 The social cost due to coal-fired power plants in Alberta

In the estimation of social costs due to coal-fired power plants, it is convenient to classify the social costs into three categories: human health, property damage, and natural resources. Human health cost is further sub-divided into two sections, those costs due to air-pollution and those due to mining. Mining is considered separately because different mining methods will have different social costs. The social costs due to an accident in mining and in the operation of coal-fired power plants are not considered separately but are included in each of the estimates. This is consistent with most of the literature used in estimating the social cost due to coal-fired power plants.

Property damage is sub-divided into four sections: building materials, textiles, vegetation, and animals. This classification was influenced by similar studies in Ontario (Ontario Research Foundation, 1980; Lees, Dunn, Ersil, 1980; Acres Consulting Services Ltd., 1980). In addition to the above mentioned damages, damages affecting the natural resources are added. Since surface mining has a large impact on the land usage and causes acid drainage, the social costs for natural resources are, similar to that of Barrager et al[1976, p.27], further sud-divided into land and water. Other social costs due to coal-fired power plants, for example acid rain (Chalmers, 1985), are assumed to be comparatively insignificiant and are not included in the social cost estimates.

4.5.1 Health cost of coal-fired power plants operation

The main pollutants that coal-fired power plants produce which are harmful to human beings are sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulates (Barrager et al, 1976, p.14-18). Some researchers, for instance Barrager et al[1976, p.18], consider that the interaction of pollutants causes more harm than each pollutant alone. Mendelsohn[1980, p.37] established dose-response functions by correlating air pollution related diseases to the pollution levels. These functions are expressed in damages per pollutant level, for example, number of deaths per pollutant level. On the other hand, the social cost estimated by Barrager et al is based on the emission of NO_x from the stack and the sulphur content of the coal. Mendelsohn's dose-response functions are applied to estimate the health costs due to coal-fired power plants in Alberta. A high probability of negative deaths resulted. The health cost estimate on mortality derived from Mendelsohn's dose response functions is, therefore, disregarded (refer to Appendix 5, A.5.2.); but the health cost due to illnesses is found to be 12.047 M/GweY and is adopted.

Barrager et al[1976, p.18] assumed the harmful effects of SO_x and NO_x were largely associated with particulates and so the health cost due to particulates was already included in those of SO_x, and NO_x. The health cost estimate derived from Barrager et al's cost functions, is found to be 11.141 M/GweY which is of the same order of magnitude as the cost estimates derived from Mendelsohn.

The estimates derived from Lees et al[1980] and Hill[1977] are 1.348 and 3.002 M/GweY respectively (Table 4.6). Lees et al applied three different methods which are based on studies done in the United States. These methods consider the gross provincial product, the total health expense, and the reduction in damages due to a 50% reduction in air pollution level. Hill also conducted a literature survey based mainly on the United States studies. This may explain the closeness of health costs derived from Hill and Lees et al. When health costs due to normal operation of nuclear and coal-fired power plants in Alberta are compared (Table 4.3 and 4.6), the estimated deaths derived from Hill due to coal-fired power plants in Alberta are less than those due to nuclear. Hill[1977, p.5.40,5.41] estimated that the nuclear power plant during the conversion stage causes more occupational deaths per 1000 Mwe-year than by coal-fired plants (0.06 → 0.12 and 0.01 → 0.03 for nuclear and coal-fired plants during energy conversion, respectively). The cost estimate derived from Inhaber[1978] is 22.582 M/GweY and is highest when compared with others, it is of the same order of magnitude as the second largest estimate (12.049 M/GweY). Since Inhaber's study is very comprehensive and the lower values of Inhaber's estimates are used for estimating the health cost for Alberta, this cost

Table 4.6 Health cost due to the operation of coal-fired power stations in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Mendelsohn 1979	40 Deaths 25,000 cases of illness both equivalent to 400,000 healthy days lost each year or $4-$40 million/year 1979 USD	For uncontrolled 500 Mwe plant in New Haven, mainly due to sulphur oxide, cost of health day $10 to $100, establishing dose-respose function by epidemiology, expressed in deaths per ug/m³ person-year no interaction among pollutants, for different age groups, linear relationship.	The coefficient for no. of deaths is not applicable, high probability for negative deaths, due to morbidities	12 047(11.489)
Lees, Dunn, Ersil, 1980	$263-$279/fossil-fired Gweh 1978 dollar or$3 35-$3.655 M/GweY	For southern tip of Ontario, 4 power stations produced 28,838 Gweh in 1978 from coal, GPP was $90.8 billion, power generation responsible for 1.24% ground level Conc., health cost $2,970,993, using 3 methods: 1. 0.705% of GPP was due to air pollution, derived from Lave and Seskin 2. 9% of total economic burden of ill health was attributed to air pollution 3. derived from Lave and Seskin, based on changes of each pollution related illnesses after 50% reduction in air pollution levels.	Alberta GPP 1982=$45,338 M health care expense estimated from 1981, i.e. from $1,924,934,000 electricity generation in 1982=20,616.6 Gweh due to coal. Method: 1. gives 1.684 M/GweY 2. gives 1.011 M/GweY 3. no estimate due to lack of local estimate on the cost of each pollution related disease.	1.348(0.194)

Hill 1977	0.56-2.08 deaths 1250 - 43,800 injury days per 1000 Mwe plant year	For Ontario, assuming sulphate, meeting the particulates standard, sulphate 5 15 ug/m³, one million people exposed to pollutant from 1000 Mwe plant, for whole cycle except mining, by literature survey: CEQ, Sagan, Wash 1224, high estimates (0.5 - 2 deaths) on transportation and waste disposal	Mine-to-mouth operation in Alberta, thus no social cost due to transportation, i.e. cost due to conversion only, 0.01 - 0.03 deaths 150 - 39,950 injury days for 1000 Mwe plant at 0.80 c.f. for a year	3.002(1.713)
Barrager et al 1976	1.3 mills/kwh or 25.130 M/GwеY	Assuming no scrubber, no damage due to particulates for rural area near New York, low Sulphur, S, content coal, 9.5 to 33.2 cents per pound, lb, of S for 0.1 to 1%/h rate of sulphation which is very important 2 cents per lb of nitrogen oxide emission, all in 1975 USD	Assuming 0.3% sulphur, S, content coal, 35% S removal by scrubber gave 10.166 thousand tons of S/GweY at 0.1 to 0.5 %/hr. rate of sulphation 110.69 thousand tons of nitrogen oxide/GweY at 0.8 c.f. by same damage value per lb of S & nitrogen oxide	11.111(1.692)
Inhaber 1978	0.016-0.047 deaths 94-280 disabilities	Based on literature survey, a disability is equivalent to from 1 to 5 days lost, one death = 6000 man-days lost	Lower values of Inhaber's estimates are considered to be the estimates for Alberta	22.582(0.000)
			Average	10.024(9.227)

Note: 1/1000 of a dollar equal to 1 mill
M/GweY is a million 1982 dollars per GweY
all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5, A 5.2

estimate is adopted as one of the estimates. The expected health cost due to coal-fired power plants in Alberta is 10.024 M/GweY and its standard deviation is 9.227 M/GweY. In 1982, the health care expense is approximately 1,925x110.8/100=2,133 million dollars (Appendix 5, A.5.2), or the social cost due to coal-fired power plants in Alberta is about 0.5% of the health care expense. This estimate is of the same order of magnitude as that estimated by Lees et al[1980],(Appendix 5, A.5.2, 1.24%x9%=0.117%).

4.5.2 Health cost of surface mining for coal

Coal for electricity generation in Alberta is obtained by surface mining. The occupational risk of surface mining is lower than that of underground mining (Inhaber, 1978, p.61). Transportation of coal from mining site to the power plants is minimal for it is a mine-to-mouth operation. Also, this short transportation trip eliminates the public risk at the railway lines and crossings. The social burden of surface mining is mainly due to the suspended particulates generated during mining. Barrager et al[1977] and The Council on Environmental Quality quoted by Hill[1977] have cost estimates for surface mining in the United States. These cost estimates are mainly due to occupational health costs and are adopted as cost estimates for surface mining in Alberta. This is based on the assumption that the surface mining in Alberta is similar to that in the United States. The cost estimate derived from

Table 4.7 Health cost due to surface coal mining in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Hill 1977	0.308 deaths 499 WDL for 1000 Mwe plant-year	0.75 c.f. surface mining, mainly occupational quoted from Council on Environmental Quality, 1973	Assuming same social damage one WDL = one injury day	0.455(000)
Barrager et al 1975	0.02 mills/kwh or 0.380 M/GweY	Appalachia location, mainly occupational.	assuming same type of surface mining.	0.380(000)
Inhaber 1978	16.6-105 man-days lost	For both surface and underground coal mining for one MweY	Assuming the lowest values as for surface mining in Alberta i.e. 16.6 man-days lost	1.973(0.000)
			Average	0.936(0.734)

all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5, A.5.2.

the lowest estimates of Inhaber[1978] is about four times higher than the others (Table, 4.7). The expected health costs due to surface mining in Alberta is 0.936 M/GweY and has a standard deviation of 0.734.

4.5.3 The social costs due to air pollution; building materials

Particulates are the main cause of the erosion effect on building materials. Other pollutants cause corrosion damages due to their acidic nature, for instance, NO_x and SO. (Acres, 1980, p.3).

Mendelsohn[1980, p.37] established a materials damage cost function in terms of mills per $\mu g/m^3$ of pollutant per person. By applying Mendelsohn's cost function to Alberta's environment, a lowest estimate is derived (Table 4.8). Acres[1980] has estimated the social costs of building material damages for the southern tip of Ontario. Acres modified Salmon's damage cost equation and established a soiling equation for estimating the social cost on building materials. Acres's method is difficult to apply because of insufficient data support, so the damage potential function is used to pro-rate Acres's estimate from Ontario to Alberta. By using this pro-rating method, the derived estimate is very close to that derived from Mendelsohn[1979] as shown in Table 4.8.

Hill reviewed several studies and normalized the social costs on building materials damage into cost per capita.

Table 4.8 The social cost for building materials due to air pollution from coal-fired power plants in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Mendelsohn 1979	$584(522)x$10^{3}$ 1979 dlr or 2.55 M/GweY	For all materials subject to air pollution, coefficient expressed as mills per ug/m^{3} per person other details same as health cost	Applying Mendelsohn's dose-reponse function	0.094(0.252)
Acres 1978	Damage cost-$1,710,195 Soiling cost=$97,618 in 1978 dlr or 0.754 M/GweY	For Southern end of Ontario, damage due to 4 coal-fired power stations. in 1978, 28,838 Gweh generated. Salmon damage cost equation was modified to suit Ontario economic and social activities, established their own soiling equation.	Because of insufficient information Acres's method was not used, but pro-rated Acres's soiling cost estimates by damage potentials.	0.034(000)
Hill 1977	In the order of $1M 1977 dollar/1000 Mwe plant-Year or $1/capita/year near Lakeview, edge of Toronto or less than 2.173 M/GweY	1 million people exposed to air pollution by 1000 Mwe plant year, by reviewing a Zerbe(1965) $90/capita for all sources in Toronto, high estimate, for high pollution level b Various US studies qouted by Wadell (1974) from Council on Environment Quality, came up $10 to $20 per capita US nation wide and $100 per capita in severe polluted Urban areas for all pollutant sources. c Acrces 1974a, based on Salmon's figures quoted by Yougstan 1975, estimated in the order of $1 per capita	Pro-rated by damage potentials, social cost on building materials is in the order of 1.195 M/GweY	1.195(000)
			Average	0.441(0.553)

Hill[1977, p.6.13, 6.14] believed Acres's 1974 estimate was the upper limit of the damage cost for building materials in Ontario. Pro-rating Hill's estimate by damage potential ratio between Ontario and Alberta, the social cost on building materials derived from Hill is 1.195 M/GweY.

The expected social cost estimate on building materials is 0.441 M/GweY and has a standard deviation of 0.553.

4.5.4 The social costs due to air pollution; textiles

Social costs on textiles are considered separately because they require frequent cleaning and are less durable than other materials (Ontario Research Foundation, 1980). The clothings, curtains, and all the fabrics associated with buildings are grouped in this category. Ontario Research Foundation[1980] carried out a study on this issue for the southern tip of Ontario. This study is pertinent to one of the most densely populated areas in Canada. Ontario Research Foundation[1980] had three estimates based on different approaches, and all of these were derived from studies done in the United States. These approaches are adopted in this study. The estimates based on textile damage cost per capita (method 2 in Table 4.9) were considered to be too high and were disregarded by Ontario Research Foundation. By using the same method for Alberta, the estimate is also quite high so it is disregarded too.

The other two estimates for Alberta are based on Salvin's estimate for the U.S. in 1970, and Ontario Research

Table 4.9 The social cost for textiles due to air pollution from coal-fired power plants in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Ontario Research Foundation (ORF) 1980	0 - 10 M/Y 1978 dollar	Using 3 different methods, as descripted below, accept the results from the 3rd method.	attempt all 3 methods, as descripted below, but accept the results from the 3rd method.	0.0659(0.038)
	Method 1 2.77-51.34 M/Yr 1978 dollar	For damage in 1978, and for all pollutant sources, 3.27 million people affected, for 25 mile radius from each of the three stations, Lakeview, Nanticoke, Lambton, using Salvin estimate on textiles for USA 1970, then rated by pollution concentration difference, population, and assuming linear inflation.	Textile damage mainly due to particulates, pro-rated from Salvin's estimates for U.S. by damage potential method, using US CPI, then normalized to common unit	0.054(000)
	Method 2 0.0 - 26.16 M/Yr 1978 dollar	For the 3 sites mentioned, only particulates in Lakeview exceeded the standard of 60 ug/m³. based on Michelson and Tourin's work, reported by STAR as $12.5 per capita, for a unit exceeding the air quality standard, then adjusted for inflation, and then using Lakeview estimate to find Nanticoke and Lambton by population differences, giving the low estimates, for high estimates, using 1/3 of Liu and Yu's estimates of $12/capita for all soiling cost on textiles, then adjusted for inflation.	Following the same procedure as Michelson and using Tourin's estimate of $12.5 per capita per unit for an exceedance of particulates, after normalizing gives 0.224 M/GweY, using Liu and Yu's estimate i.e. 1/3 of $12 / capita due to soiling in a year, after normalizing gives 0.472 M/GweY, high estimates and similar to ORF discarded.	0.224-0.472*

Method 3			
0.0 - 10 M/Y 1978 dollar	Considering soiling from particulates only, mainly due to extra cleaning, using Salvin's estimate that 46% of total cleaning costs was represented by professional cleaning cost, 40% of textiles was unaffected by air pollution, and 5% of total cleaning cost was resulted from coal-fired plants, allowing for fabric degradation caused by extra laundering, lower limit assumed to be zero.	Alberta estimate is pro-rated by damage potential from 9.25 M/Y	0.065(0.038)
		Average	0.065(0.038)

* estimates from method 2 are considered to be unreasonably high and discarded so not included during averaging the estimates.
all 1982 dollars refer to January price level
M/Y=million dollars/year

Foundation's estimates for Ontario in 1980. Pro-rating directly from Salvin's estimate by damage potential for the Alberta situation, the estimate is found to be quite similar to that pro-rated from the estimate which is believed to be the best by Ontario Research Foundation (method 3 in Table 4.9). The expected social cost for textile damages in Alberta is 0.065 M/GwY and has a standard deviation of 0.038 shown in Table 4.9.

4.5.5 The social cost due to air pollution; vegetation and animals

Vegetation and animals are also subjected to air pollution. Acres[1980, p.83] conducted a study on the social costs for vegetation and animals due to pollution from power plants for Ontario and concluded that damages were insignificant. Mendelsohn[1980, p.37] had a social cost function for vegatation damages which is in terms of dollars per ton of pollutant emitted from the stack. By applying this function to the Alberta situation, the social cost for vegetation is 0.013 Million '82 dollars per GwY, or appromixately one cent per person in the year of 1982, Table 4.10. This cost is quite small when compared to the total agricultural output and is quite uncertain as the standard deviation is 20 times higher than the expected value. Since the cost estimate for vegetation damage due to air-pollution does not conflict with the conclusion of Acres, this estimate is considered to be the vegetation damage cost due

Table 4.10 The social cost for vegetation and animals due to air pollution from coal-fired power plants in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Mendelsohn 1979	$197(184)k/Y or 0.86 M/GweY	Same conditions as health cost, mainly due to sulphur oxide, no damage to animals.	Using Mendelsohn's dose-reponse function for vegetation	0.013(0.260)
Acres 1979	No significant damage	For southern tip of Ontario, study the effect of various pollutants to crop, forest, and animals	For lower pollution level, damage insignificant	
			Result	0.013(0.260)

note:k, thousand dollars
all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5.-A.5.2.

to coal-fired power plants in Alberta. The social cost for animals is assumed to be insignificant (Acres, 1980, p.83).

4.5.6 Social costs for land and water

The social costs on land and water refer to the loss of recreation, game habitat, esthetics, and the impacts on the ecosystem. These social costs refer to the costs necessary to restore the polluted land and water to their original function or to reduce the unpleasant effects to a level acceptable by the public. These costs are primarily due to surface mining where large areas of land are defaced. The acid drainage can pollute the rivers and streams and reduce the fresh water supply. Barrager's cost estimates for land and water are considered by this thesis to be high when compared with other social costs. The cost estimates for Alberta are assumed to be half of Barrager's estimates. Since there is no other estimate to compare with and there is no other better method known at the time of this study that can be applied, these cost estimates for land and water damages derived from Barrager et al are adopted (Table 4.11).

Table 4.11 The social cost for land and water due to coal-fired power stations in Alberta

Author of the literature	Estimates taken from the literature	Methods & particulars of the literature	Conversion to Alberta situation	Alberta estimates Million 1982 dollars per GweY
Barrager et.al 1976	Land			
	0.10 mills/kwh 1975 USD	For surface mining, due to lost of recreation, game habitat, esthetics, no detailed method given	Considered to be upper estimates, the expected value would be half of Barrager's cost estimate	0.967(0.568)
	Water			
	0.04 mills/kwh 1975 USD Dlr	Estimating the cost in public facilities, water treatment effects on ecosystem and esthetics	Similar to land estimate, considered to be high, so half of this estimate gives the expected value	0.387(0.223)

all 1982 dollars refer to January price level
details in the Alberta cost estimates can be found in Appendix 5, A 5.2.

4.6 Summary on the estimation of social costs due to power generation in Alberta

The social costs for Alberta are estimated from various studies by: a.) either adopting their estimates which are appropriate to the environment and the operation of power plants in Alberta or, b.) using the methods of these studies to estimate the social costs. In cases where the estimates from these studies are based on pollution levels, population density, and social activities, which differ from those of Alberta, a damage potential is used to pro-rate the estimates to those of Alberta. After reviewing various studies, a number of independent estimates for a social costs are collected. The expected values for that social cost is the average of these independent estimates.

By using the above approach, the social costs for electricity generation in Alberta are estimated and summarized in Table 4.12. The distribution of these social costs are plotted in Figures 4.1. The expected social costs due to nuclear and coal-fired power plants in Alberta are found to be 1.078 and 13.049 $M/GweY or 0.123 and 1.490 mills/kwh respectively. The expected social cost due to coal-fired power plants is about 12 times higher than that due to nuclear power plants (the expected ratio of social costs between coal and nuclear is 14.538). The above social cost ratios estimated by Kim[1981, p.115,116] and Hill [1977, p.ii] for Ontario are approximately 5.6 and 10, respectively.

Table 4.12 Summary of social cost constants for power plants which were assumed to be operating during the study period.

		Cost in Million per GwY	'82 dollars Jan., price
		Nuclear	coal
Health			
normal plant operation		0.364(0.340)	10.240(9.227)
mining	**	0.231(0.035)	0.936(0.734)
accidents		0.138(0.161)	
sabotage		0.031(0.018)	
diversion		0.003(0.002)	
Property Damages			
building materials			0.441(0.553)
textiles			0.065(0.038)
vegetation & animals			0.013(0.260)
accidents	*	0.047	
sabotage		0.451(0.260)	
diversion		0.045(0.026)	
Natural Resources			
land	**	0.967(0.568)	0.967(0.568)
water	**	0.387(0.233)	0.387(0.223)
Totals		1.078(0.458)	13.049(9.296)
	**	2.664(0.764)	
or in mills/kwh			
		0.123(0.052)	1.490(1.062)
	**	0.304(0.087)	

figures in brackets are standard deviations
blank means not applicable
* point estimate
** for Nuclear only
They are not included in the initial and base cases, but are listed mainly for comparison purposes.
Mining is derived form Hill [1977, p.5.41].
Land and water are assumed to be the same as those of coal.

The social costs estimated by Kim for both electricity generation methods are for the whole fuel cycle and Kim's estimates are:

	mills/kwh
Nuclear	0.02 to 0.30
Coal (with abatement)	0.10 to 1.70

Note: assumed to be in 1981 Canadian dollars because Kim did not clearly specify the dollar value.

The above Kim's estimates are within 70 and 95% of the confidence level of the Alberta social cost estimates for coal and nuclear respectively (Figure 4.1). Lower confidence level for Kim's estimates for coal corresponds to the wider variation of social cost estimates derived from various studies.

If the social costs due to nuclear fuel mining is assumed to be similiar to Hill's estimate [Hill 1977,p.5.41] and pollution on water and land are assumed to be same as those of coal, the total social cost due to operating nuclear power plants in Alberta becomes 2.664 M/GweY. Then the ratio of the expected social costs of coal and nuclear will be 4.9, which bring the ratio slightly closer the ratio estimated by Kim.

Lower social cost due to coal-fired power plants in Alberta than that in Ontario is expected because of the lower sulphur content of the coal used, mine-to-mouth operation, and lower population density. The social cost estimates for coal-fired power plants in Alberta agree with the above expectation.

The social costs derived from various sources are most likely to occur in 7.5 and 1.0 M/GweY for nuclear and coal respectively as shown by the modes of the curve in Figure 4.1.

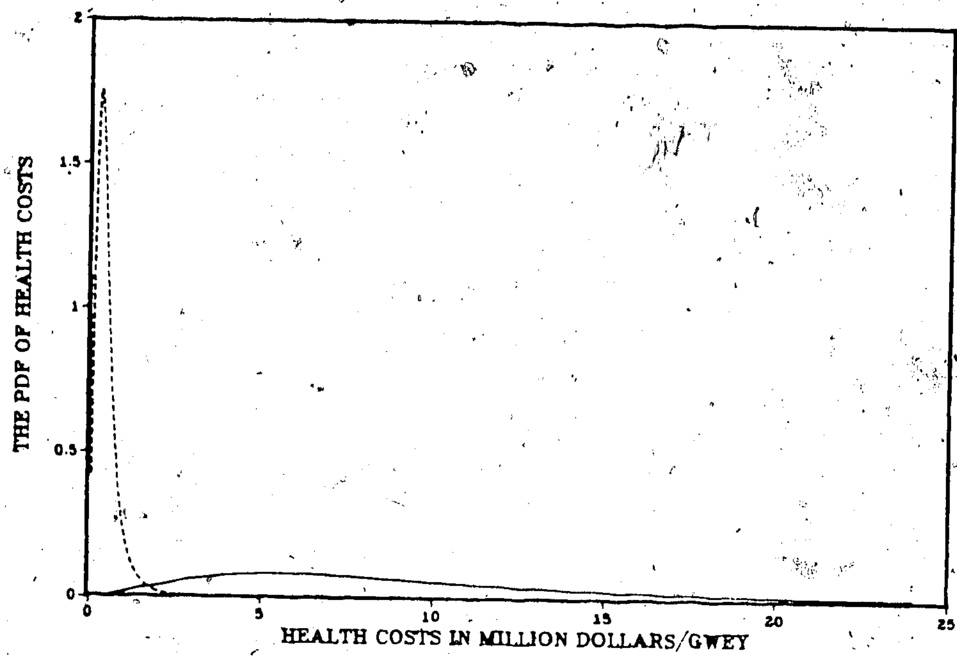
From table 4.12, the health cost due to coal-fired power plants is the major contributor to the total social cost. Approximately 85% of the total social cost is health cost. The high health cost estimate for coal-fired power plants is a result of including the high cost estimate derived from Inhaber (Appendix 5, A.5.2). Inhaber's study is very comprehensive and Inhaber's lowest values are used the estimates for Alberta. The inclusion of health cost derived from Inhaber for the Alberta estimates are, therefore, not unreasonable, but increases the final cost estimate. This health cost estimated due to the coal-fired power plants is approximately 0.5% of the Alberta health care expense in 1982, which is of the same order of mangnitude as the result estimated by Lee et al [1980] for Ontario.

Kim[1981] adopted Barrager's[1976] lower values as the estimates for Ontario. Barrager's cost for illness is approximately the same as the cost used in estimating the health cost for Alberta, but the cost for a death assumed by Barrager is approximately 30% smaller than the one used in this thesis (Appendix 5, A.5.1). The expected social cost due to coal-fired power plants in Alberta is, therefore, not much lower than those estimated by Kim for Ontario.

Apart from health costs due to normal operation of power plants, the social costs on health and on land due to coal mining are the highest (Table 4.12). Higher social costs for coal mining are expected because surface mining for coal has a strong impact to the environment than underground mining does (Hill, 1977, p.5.38).

The social cost due to nuclear power plants assumed to be operating in Alberta is, as expected, lower than the estimate of the literature because it is assumed that no nuclear fuel mining and processing will take place in Alberta. This lower social costs causes the social costs ratio between coal and nuclear to be higher than that estimated by Kim. From table 4.12, the major portion of social cost due to the operation of nuclear power plants is due to the high cost estimate of sabotage of nuclear power plants. These social costs are derived from Barrager[1976] and half of Barrager's estimates are assumed to be the estimates for Alberta. Since there is no other literature available, the validity of the estimates for Alberta cannot be compared and assessed properly.

The cost estimates for Alberta are derived from the estimates of the available literature. The methods used by the literature differ and the uncertainty of the derived estimates is high as shown by the large standard deviations of the expected social costs (Table 4.12). The uncertainty of the social cost estimate for coal is higher than that of nuclear (Figure 4.1).



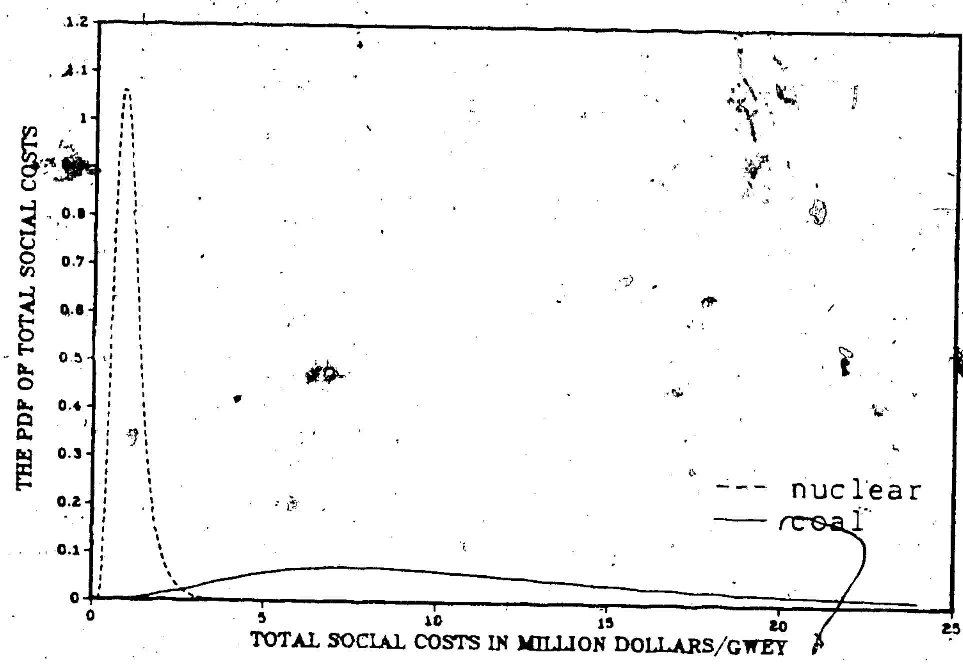
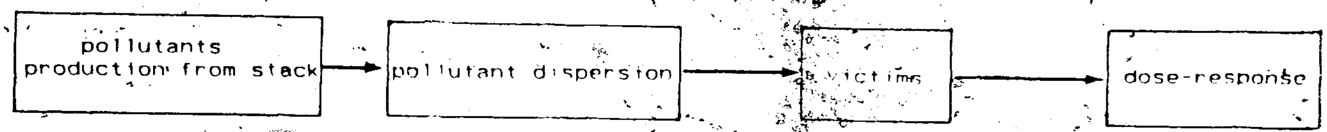


Figure 4.1 The probability density function of health & social costs represented by log-normal distribution

Figure 4.2 Various factors that affect the social cost of coal fired and nuclear power plants



Pollutants production from stack

1. abatement devices
2. type of fuel
3. type of system
4. regulation
5. technical advancement over time

Pollutant dispersion

1. stack height
2. direction and speed of wind
3. rate of chemical change in atmosphere
4. interaction between pollutants
5. location from victims

Victims

1. desnsity
2. exposure
3. population
4. age distribution
5. economic and social activities and their changes over time

Dose-response

1. cost per unit damage
2. fluctuating concentration
3. time-lag response
5. difficult in estimating low dose but high population response

note: cost per unit damage varied by
1. lost of earning power
2. personal and expert opinion
3. willing to pay to avoid level of pollution (or repair)

The social cost estimates are assumed in the region greater than zero and less than infinity. A log-normal distribution function (Miller and Freund, 1977, p.115) is used to approximate the social cost estimates. This distribution is often used by literature to describe the variation of pollutant concentrations. Using this distribution function, the social cost estimates are better described because one can derive a confidence level for a given range of estimate. Based on the expected values and standard deviations of health and total social costs, the distribution function for health and social costs can be calculated and are plotted as shown in Figure 4.1. The health and total social costs curves in Figure 4.1 have the same pattern; the curves for coal are "flatter" than those of nuclear or there is a wider variation or higher uncertainty in the estimation of social costs for coal-fired power plants in Alberta. This wide variation in social cost estimate due to coal corresponds to the wide variation in social cost estimates derived from different sources (Table 4.12). To the author's knowledge this is the first time that social cost due to electricity generation in Alberta is estimated and the estimates are described by a disturbution function.

Physically, the wide variation in the social cost estimates due to coal-fired power plants can also be explained. In the process of estimating the social costs, there are four steps (Mendelsohn[1980, p.37]):

1. The quality and quantity of pollutants from the stack
2. The dispersion of the pollutants
3. The number of victims and their chances of coming in contact with the pollutants.
4. The response of the victims to the dosage.

In each of these steps, there is a number of factors that affect the final outcome as shown in Figure 4.2. Some of the factors relating to nuclear industry, for example the amount of radiation, can be accurately measured (Cohen, 1981). "Radiation is far better understood than other much more serious threats to public health like air pollution...." (Cohen, 1981). The social costs due to coal-fired plants are, therefore, more uncertain than those due to nuclear power plants.

5. Experimental design

The unit cost analysis is not limited by the length of the study period and is ideal for studying the effects of cost factors on the unit costs. The total cost analysis, on the other hand, is limited by the length of study periods because the decommissioning cost of the old power plants is not included; this analysis includes the influence of demand for electricity and unit capacity sizes.

5.1 Unit cost analysis

5.1.1 Base case study

Similar to Foulkes' [1982, p.2-2] and Rahnama's [1982, p.16] study, the effects of income taxes are excluded. The time frame for this unit cost study is from 1990 to the year twenty years after the year when nuclear power plants become more economical than coal-fired power plants, otherwise known as the break-even point. Analyses with and without the social costs are carried out in order to measure the effect of including social costs on the break-even point. In the base case study, all the costs and their rate of changes for both nuclear and coal-fired power plants are based on expected values.

The initial case variable values are:

1. interest rate in real terms....................6%
2. real escalation rate for coal................1.5%
3. real escalation rate for nuclear fuel........1.5% (0% before 1990)
4. real escalation rate for construction cost...1.5%
5. real escalation rate for labour cost............1%
6. real escalation rate for material..............0%

From the discussion in section 3.3, the escalation rate for coal has been estimated in other studies to be either the same as or higher than that of nuclear. For the base case study the escalation rate for nuclear is assumed to be zero.

5.1.2 The effects of including the social costs

The total cost Q, is the sum of the traditional cost T, and social cost S. That is:

$$\text{For coal: } Q_k = T_k + S_k$$

$$\text{For nuclear: } Q_n = T_n + S_n$$

The probability of nuclear power being more economical than that of coal P, is then expressed as

$$P(\text{nuclear more economical than coal}) = P(Q_k \geq Q_n)$$

$$\text{and } P(Q_k - Q_n \geq 0) = P[(T_k + S_k) - (T_n + S_n) \geq 0]$$

The expression becomes:

P(nuclear more economical than coal)= $P[(S_k-S_n)\geq(T_n-T_k)]$

That is, the probability of nuclear power being more economical than coal, when the social costs are included in the cost analysis, is equal to the probability of the difference between their social costs equal to or greater than the difference between their traditional costs. For each year (T_n-T_k) is a constant ΔT, and social costs for both coal and nuclear are random variables represented by the log-normal distribution having mean and standard deviation μ and σ, respectively.

The probability can be expressed as:

$$P[(S_k-S_n \geq \Delta T)] = \int_{\Delta T}^{\infty} f_x(x;\mu,\sigma^2)dx \quad \text{.............} 5.1$$

Where:

$$x = S_k - S_n$$

$$\mu = \mu_k - \mu_n$$

$$\sigma^2 = \sigma_k^2 + \sigma_n^2$$

By integrating f_x numerically, the results are found to be similiar to normal distribution. Normal distribution is then used as an approximation to f_x.

The values of μ and σ for both the social costs of coal and nuclear have been estimated in Chapter 4. The difference in traditional costs between nuclear and coal is a function of the commission year and is obtained using values from the base case study given in the previous section. The probability, $P[(S_k-S$ [illegible] $\Delta T)]$, and its probability density function (PDF), can be plotted against either ΔT and/or the commission years. The sensitivity of the break-even point to social costs can then be shown clearly by examination of the PDF.

5.1.3 Sensitivity tests for interest rate

The capital cost of nuclear power plants is known to be higher than that of coal as shown in Appendix 1, A.1.1. Rahnama[1982, p.44] reported that the interest rate would have a significant effect on the economic viability of nuclear power plants.

Alternative values of 4% and 8% as the real rate of return or interest rate are used for testing the sensitivity of the break-even point to the interest rate.

5.1.4 Sensitivity tests for coal escalation rate

Gaines et al[1979, p.49] reported the economic viability of coal-fired power plants is sensitive to the escalation rate of coal prices.

Real escalation rates of 1% and 2% for coal prices are used to study their effects on the break-even point. The sensitivity test for nuclear fuel is not conducted because there is no indication from other studies that the break-even point is sensitive to nuclear fuel escalation rate, the sensitivity test for nuclear fuel is not conducted. Foulkes[1982] had estimated the escalation rates for coal and uranium prices. A test using Foulkes's escalation rates is conducted in order to see the corresponding change of the break-even point.

5.1.5 Capital cost of nuclear power plant

The effect of the capital cost of a nuclear plant on break-even point is achieved by doubling the base case estimate. The coal fuel escalation rate at which nuclear power becomes as economical as nuclear power in the base case is found by increasing the coal fuel escalation rate until the break-even point returns to the break-even point of the base case. The effect of nuclear capital cost and the coal price escalation rate on the break-even point can be compared.

5.2 Total cost analysis

5.2.1 Base case study

The parameter estimates of the base case study with a 30 year study period (1983 to 2012 inclusive) are used so that the results from the base case study of unit cost analysis can be compared with the results of the total cost analysis.

5.2.2 Building strategy

In total cost analysis, there are five scenarios, each of which represents a possible plant mix of nuclear and coal-fired power plants. In all the scenarios, both plants are built according to a pre-deterimed building strategy, or building cycle. Since nuclear power becomes more economical later in the study period, a coal-fired power plant is assumed to be built first in the building cycle for the base case. To assess the sensitivity of the results to this assumption the building cycle is reversed so that the nuclear power plant is built first. In the 1/2 nuclear and 1/2 coal scenario, for example, the building cycle is changed from C,C,N,N, to N,N,C,C (where N and C refer to nuclear and coal-fired power plant respectively).

The break-even point is the year starting from which nuclear power plants become more economical than coal-fired power plants. The total cost of the all nuclear scenario can be lower than that of the all coal scenario when nuclear power plants are allowed to be built after this break-even year. To ensure the existance of minimum total cost, the interest rate must be at a rate such that the break-even point is close to the beginning of the study period. By varying the year of starting to build nuclear power plants in the all nuclear scenario, the effects of surplus capacity, demand and length of study period on the break-even point can be studied.

5.2.3 The effect of demand on total costs

In total cost analysis, the electricity capacity is assumed to increase by unit capacity to meet the demand for electricity. This increase in unit capacity causes the total capacity to be higher than the demand and therefore there is always surplus capacity. The unit capacity and demand for electricity can affect the amount of this surplus capacity which becomes significant when the demand for electricity is low. They are considered to be factors that cause the break-even point to appear later than it would be for cases where the unit capacity is small relative to the demand. The effect of demand on the break-even point is estimated by calculating the total costs under the 3% log and base case demand for electricity. Three study periods of 30, 35, and 40 years are used because the length of study period can affect the results. The effects of demand on total costs can be studied by comparing the total costs of different demands for the same study period.

5.2.4 The effect of social costs and study period on break-even point

In total cost analysis, the search for the break-even point can be conducted by an iterative technique. By varying the year after which all new plants to be built are nuclear power, a minimum total cost will be found. The year corresponding to this minimum total cost is the break-even point. Using study periods of 30 and 40 years, the changes of this break-even year can be found and the effect of the length of the study period on break-even point can be studied. The effect of social costs on the break-even point can also be studied by including the social costs in the analysis.

5.3 Optimum plant mix

In order to determine the plant mix at which lowest total costs exist, five plant mixes, or scenarios are implemented in the total cost analysis. In TOSCA, the plant mix is a combination of coal, nuclear, gas, and new technologies, but in this thesis, only two energy alternatives are assumed. The scenarios are redefined as follows:

1. All Nuclear scenario:

   All the new plants including the replacement of the decommissioned ones are nuclear type, i.e. CANDU reactor type.

2. 3/4 nuclear and 1/4 coal scenario:

   The new plants to be built will be in the mix of 3/4 nuclear and 1/4 coal-fired. The building sequence will be in the cycle of one coal-fired power station first then three nuclear power plants or C,N,N,N; C,N,N,N and so on (where C and N refer to coal and nuclear power plant).

3. 1/2 nuclear and 1/2 coal:

   Similar to second scenario except the building sequence is in the cycle of two coal-fired power stations first then two nuclear power plants, or C,C,N,N; C,C,N,N, and so on.

4. 1/4 nuclear and 3/4 coal:
Similar to second scenario except the building sequence is in the cycle of three coal-fired power stations first then one nuclear power plant, or C,C,C,N; C,C,C,N and so on.

5. All coal scenario:
Those new and replacement power plants are all coal-fired type.

5.4 Computer Model for the Total Cost Analysis

In TOSCA, the increase in capacity was assumed to be continuous and exactly equal to the demand. Four future energy sources for electricity generation were implemented. With the exception of coal and nuclear fuel there was no real rate of increase for the costs. The capacity of a power plant, regardless of differences in types and design, was assumed to be one Gwe.

The TOSCA program has been modified to suit the Alberta electricity generation characteristics. The changes of the functional cost factors have been discussed in Chapters three and four. Further modifications of the TOSCA program are listed as follows:

1. Once a new power unit is ready for production, the total capacity will be increased by the unit capacity.

Historically, the capacity in Alberta increases by the unit capacity and in this study the unit capacity is assumed to be 0.371 and 0.6 Gwe(net), for coal and proposed CANDU power plant respectively. In Alberta, the assumptions of continuous increase in capacity and capacity equal to the demand are not appropriate. The demand and its growth rate are expected to be low relative to the United States case. The increase of the total capacity as a result of an additional unit is a significant change. At low demand growth rate, the time period for the next unit to become operational is longer. The TOSCA computer program is modified so that the capacity increases in discrete steps representing the capacity of the units.

2. In the TOSCA computer program research cost is assumed to be a function of time and total electricity output. Research cost is assumed to be absorbed in overhead and is indirectly accounted for in the traditional operating cost in this thesis and the subroutine for estimating the research cost is deactivated.
3. The original sensitivity tests have also been suppressed for they are not clearly documented and generate data which are not useful for the present analysis.
4. Subroutines to find the levelized capital, operation and maintenance, and fuel costs for a new plant/unit are added. Real rates of increase for these cost items

can be used.

5. Only coal and nuclear power are considered.
6. TOSCA uses different formulations for different social cost factors. The social cost functions are simplified so that they are a function of the annual electricity output.

There are six subroutines in the computer model. The main program provides for initialization and reading the existing available annual capacity including those plants already committed but not operational. The VARC subroutine calculates the annual costs costs based on the annual demand for electricity and converts these costs into present equivalent values. The accumulation of these present equivalent values is the total cost for a particular scenario. A flow chart, showing the interaction of the main program is shown in Figure 5.1. The computer program for the total cost analysis is listed in Appendix 2.

5.5 Computer model for unit cost analysis

Subroutines in the computer model of the total cost analysis are used to calculate the levelized annual capital costs, operation and maintenance costs, and fuel costs. The levelized annual cost for the whole power station is equal to the sum of levelized traditional and social costs. This levelized annual cost is then divided by the annual electricity output from the new power plant and is expressed in mills per kwh. This levelized cost per unit electricity

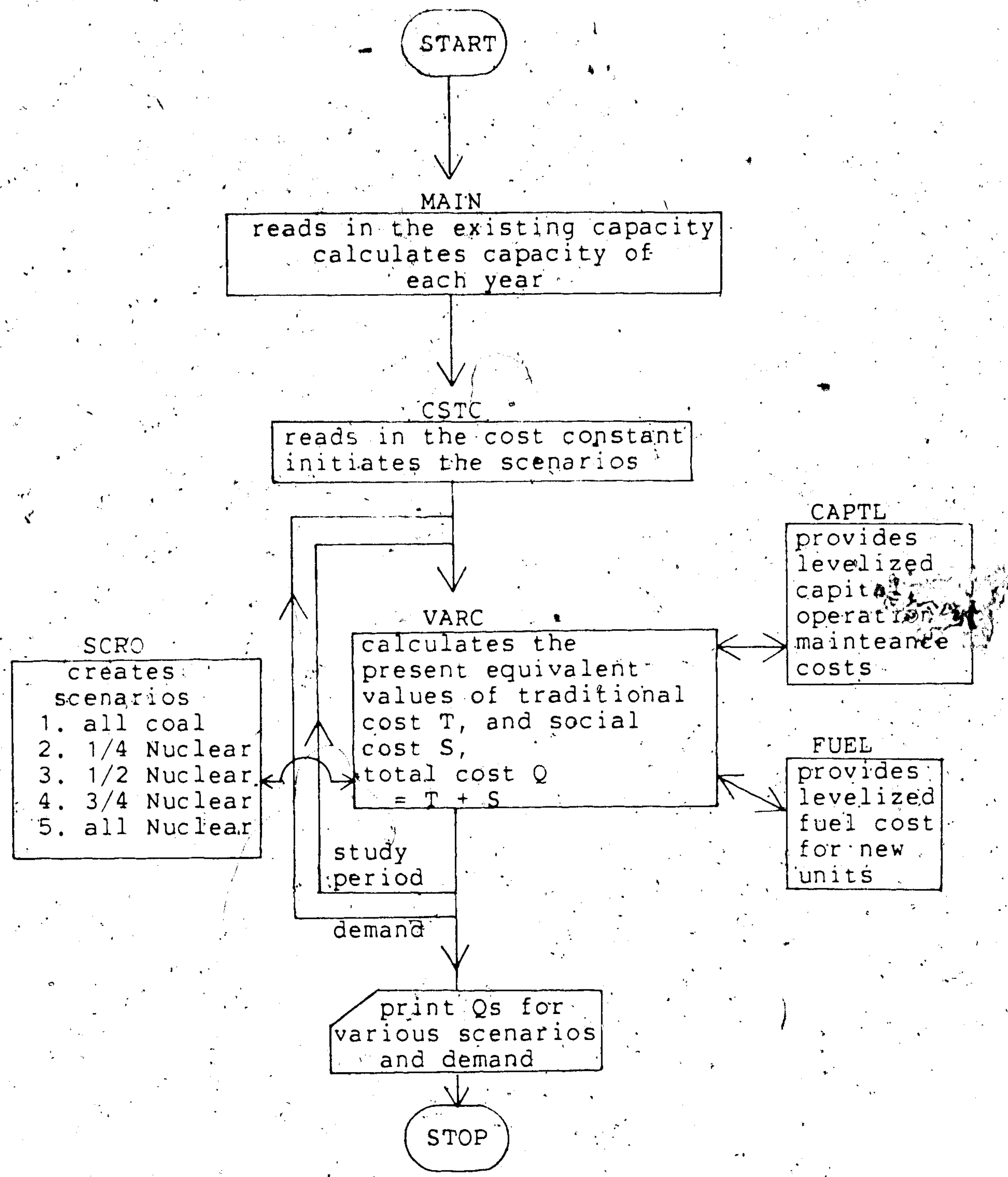


Figure 5.1 Macro flow chart for total cost analysis

becomes the basis of comparison between coal-fired and nuclear power plants. The program for unit cost analysis is listed in Appendix 3.

6. Results and discussion

6.1 Unit cost analysis

A levelized unit cost represents the cost per unit electricity generated by a new power station during its service life of 35 years. In all the comparisons between the nuclear and coal-fired power plants, dotted lines and solid lines in all the figures refer to nuclear and coal respectively.

6.1.1 Initial and base case studies

The levelized unit costs for both energy sources increase every year. These increases are expected because there are real rates of increase for some of the traditional costs. For the initial case, nuclear power is not economical as shown in Figure 6.1, where no intersection between the curves can be seen. The inclusion of social costs causes the curves to shift upwards equally for all the years because social costs are assumed to be constant in real terms.

For the initial case study the difference in the expected social costs which favour nuclear is not sufficient large enough to overcome the levelized cost gap between the two alternatives. Based on this result, all further analyses are conducted with the base case study.

For the base case, intersection of the curves exists as shown in Figure 6.2. The shift of the unit costs of coal-fired power plants is about 12 times more than that of nuclear power plants and corresponds to the ratio of their social costs.

Before the break-even point nuclear power is more expensive. The real rate of increase in coal prices causes the unit cost of electricity generated by a coal-fired power plant to escalate faster than that for a nuclear power plant. The break-even year based on traditional costs only is 2032, but when the expected social costs are included in the unit cost analysis nuclear power becomes favourable

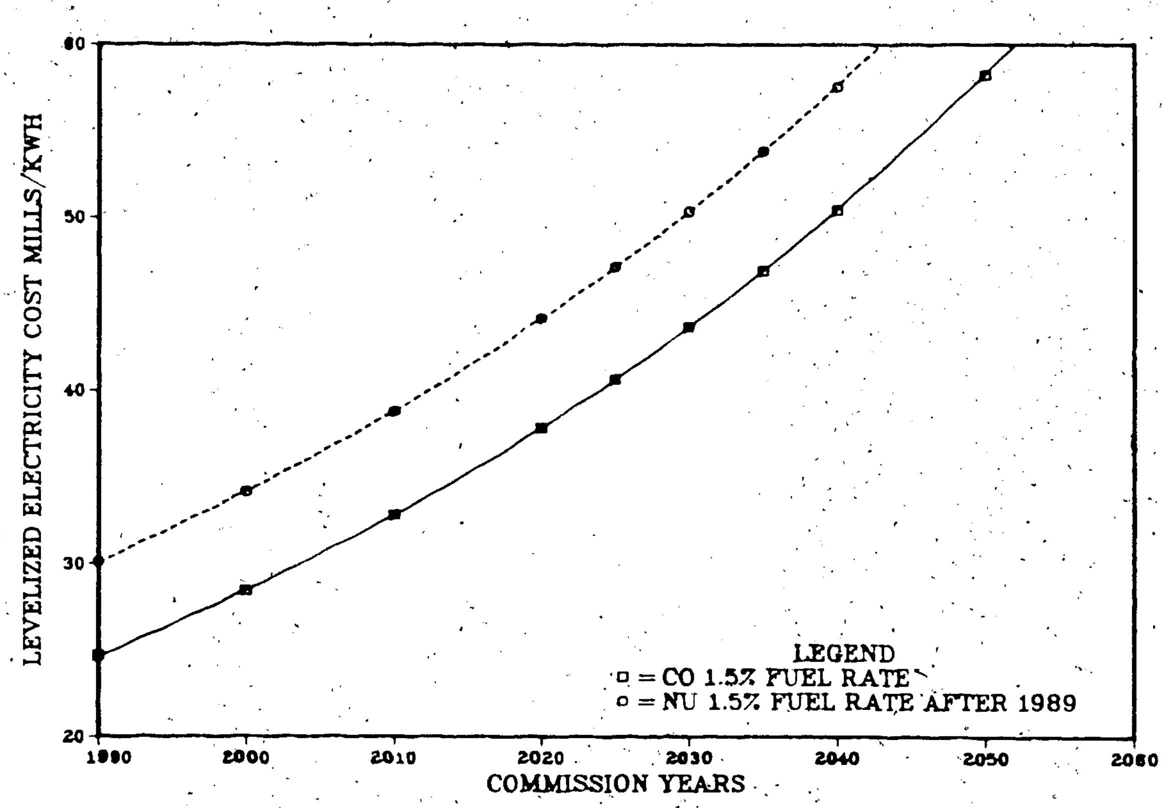


Figure 6.1 The unit electricity costs at fuel escalation rates similar to Foulkes[1982] for various commission years initial case

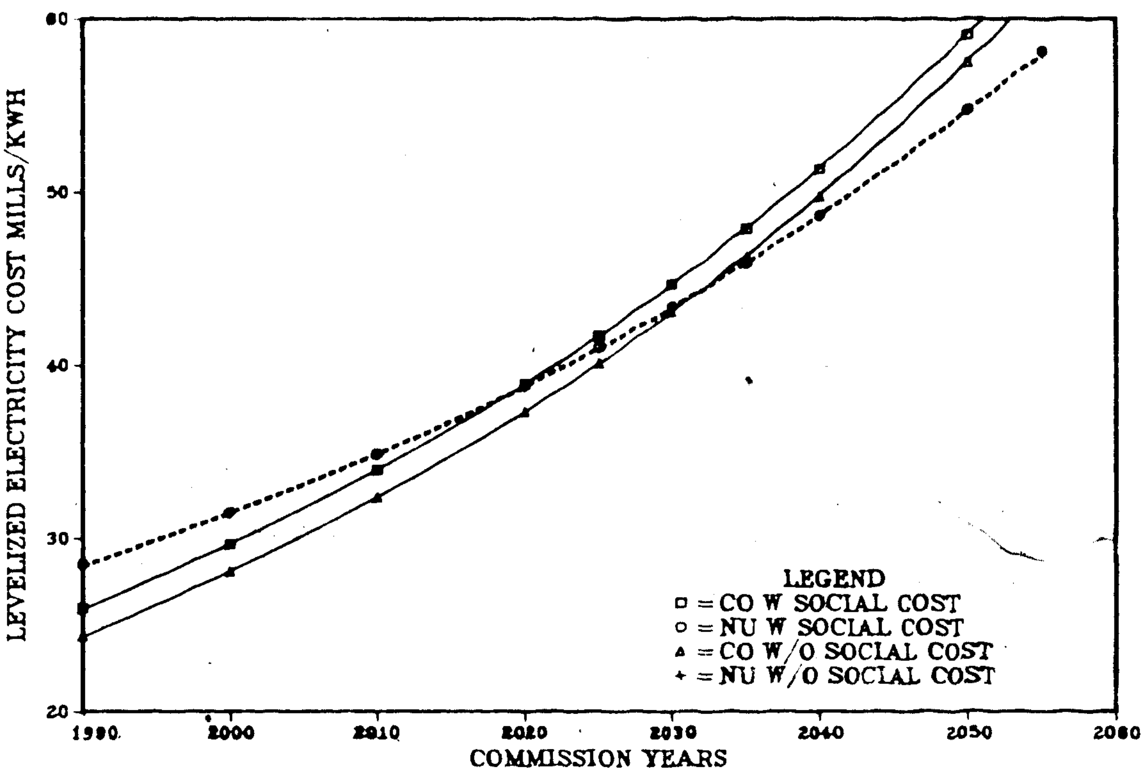


Figure 6.2 The unit electricity costs for both nuclear and coal generation methods with and without social costs for various commission years, base case

twelve years earlier, that is 2020. If social costs due to mining and polluted land and water are included into the expected social costs for nuclear power plants, the breakeven point occurs two years later (i.e. 2022).

The included angles between the nuclear and coal unit cost curves with or without including social costs are sharp as shown in Figure 6.2, that is less than 10 degrees. A shift of either curve would have a great effect on the position of the intersection, or the break-even point. After the break-even point the slopes of unit cost curve for coal follow the trend of escalation and become steeper than those of nuclear. The coal price escalation rate is the major reason for the rapid rise of unit costs.

Based on Foulkes's[1982] escalation rates for the coal and uranium prices (inital case), and a service life of 30 years, the units costs are calculated by using the same computer program used in the unit cost analysis. The results are listed in Table 6.1. Foulkes' figures are within 1.5% of those calculated by the computer program, and are used as a validity check of the accounting procedure. This small difference in levelized unit cost is expected because computer program allows the power units to start production before the whole plant is completed; but Foulkes assumed that the power unit only started production when the whole power station is completed. Such small different in unit costs is expected to have small effect to breakeven point (less than one year).

Table 6.1 The electricity unit costs based on coal and nuclear fuel escalation rates assumed by Foulkes

Year	Unit costs in mill kwh 1990	2000
Nuclear capacity factor .8	30.11 (30.20)	34.14 (33.90)
Coal with FDG capacity factor .8	24.68 (24.70)	28.44 (28.00)

Notes:
1. Figures in brackets are Foulkes's estimates.
2. In this study, service life and escalation rates for both coal and uranium are similar to those of Foulkes's study [1982].
3. excluding social costs

6.1.2 Sensitivity of break-even point to social costs

By including the expected social costs in the traditional cost analysis, nuclear power starts to have chances of becoming favourable as early as the year 1990 as shown in Figure 6.3,6.4. Not until 2045, however, does nuclear power definitely become attractive. In other words the range of social cost estimates can cause a 55 year variation in the break-even point. This sensitivity is a result of the sharp included angle of the unit cost curves for both nuclear and coal-fired power plants.

The break-even point at 50% probability is 2020 which is in agreement with the expected break-even point in the

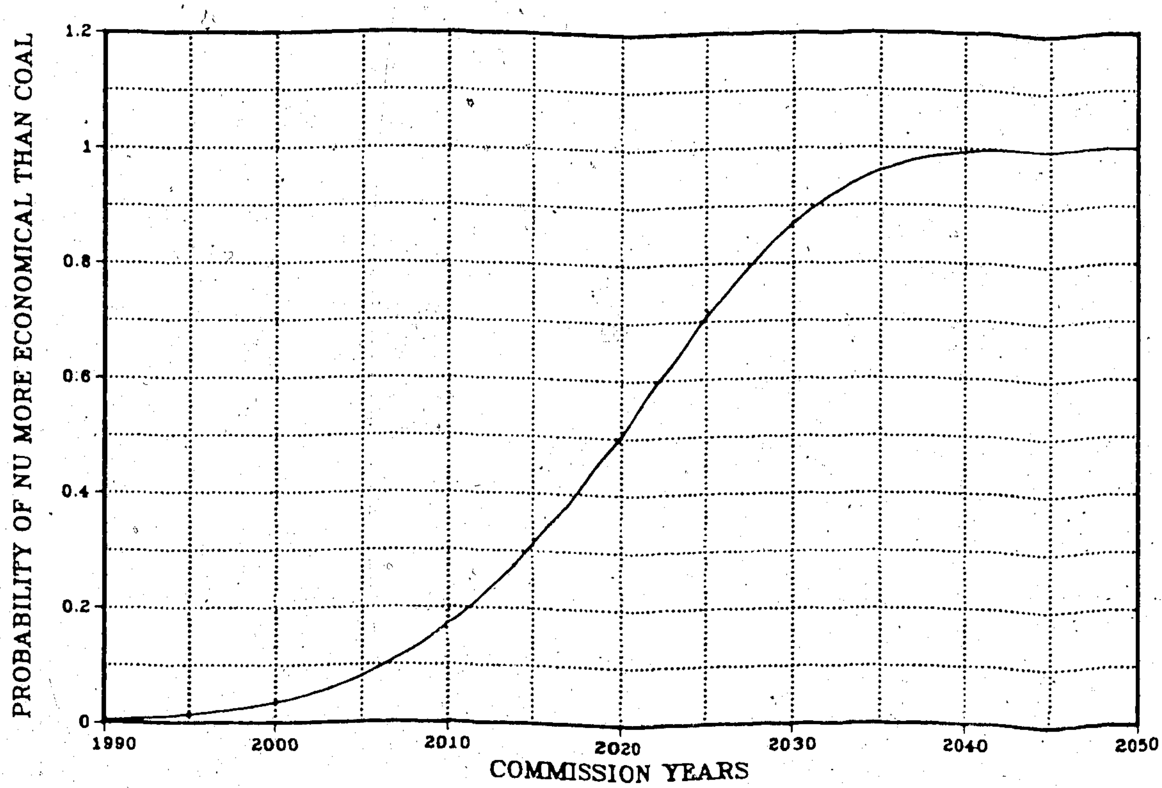


Figure 6.3 The probability of nuclear plants being more economical than coal-fired power plants at various traditional costs and commission years due to the inclusion of social costs

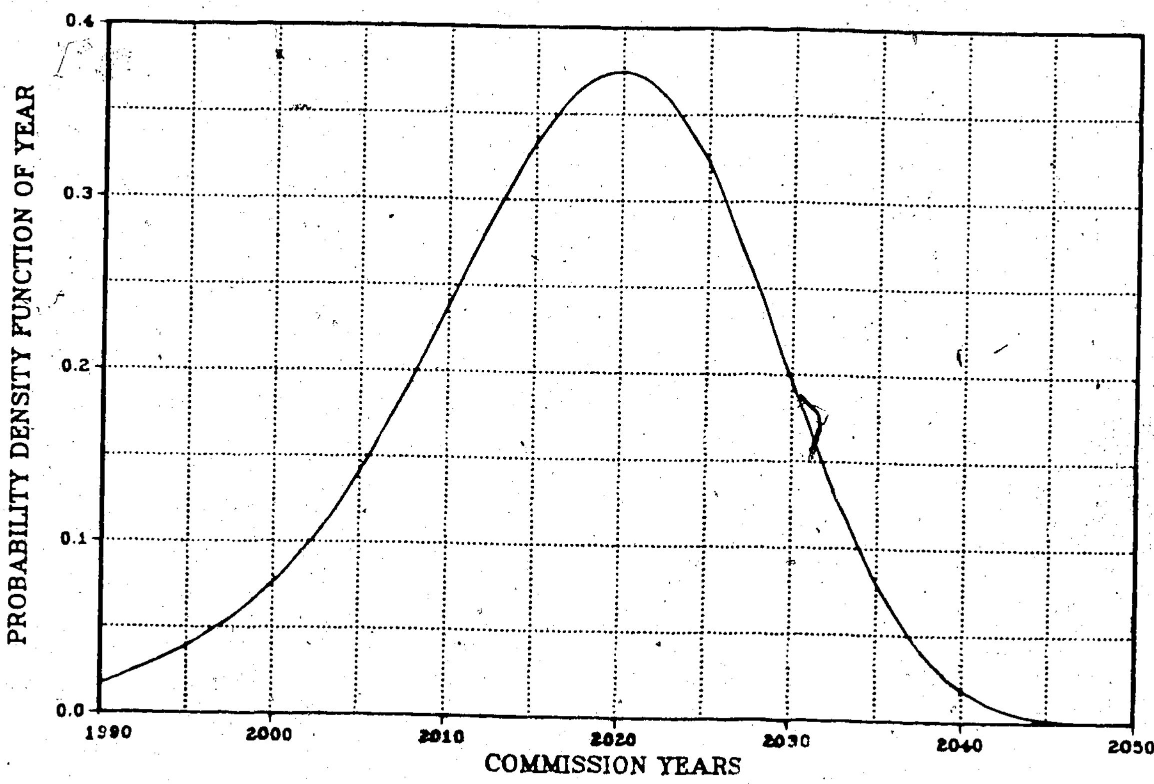


Figure 6.4 The probability density function of the commission year at which nuclear becomes economical due to the inclusion of social costs

base case study.

6.1.3 Sensitivity of break-even points to coal fuel escalation rate

The break-even point is very sensitive to the coal price escalation rate. When the rate is at 2%, the break-even point occurs about 20 years earlier than the break-even point of the base case. That is, the breakeven point moves from 2020 to 2000 as shown in Figure 6.5. This 2% escalation rate corresponds to an addition of 0.5% to the base case of 1.5%. Similarily, 0.5% lower than the base case of 1.5% results in the unit cost curves for both nuclear and coal being almost parallel to each other as shown by the 1% escalation rate in Figure 6.5. Such extreme sensitivity to the fuel costs is because both unit cost lines intersect at a sharp angle. The result is consistent with that of Rahnama[1982, p.44] and Gaines et al[1979, p.49]. The unit costs based on Foulkes escalation rates for coal and nuclear, that is 1.5% for nuclear after 1989 and 1.5% for coal after 1982, are plotted in Figure 6.1. At these escalation rates, nuclear power as an energy source for electricity generation in Alberta is not at all economical because the unit cost curves, though not shown clearly in Figure 6.5, diverge slowly with respect to commission years. The tests show that break-even point is very sensitive to fuel escalation rates.

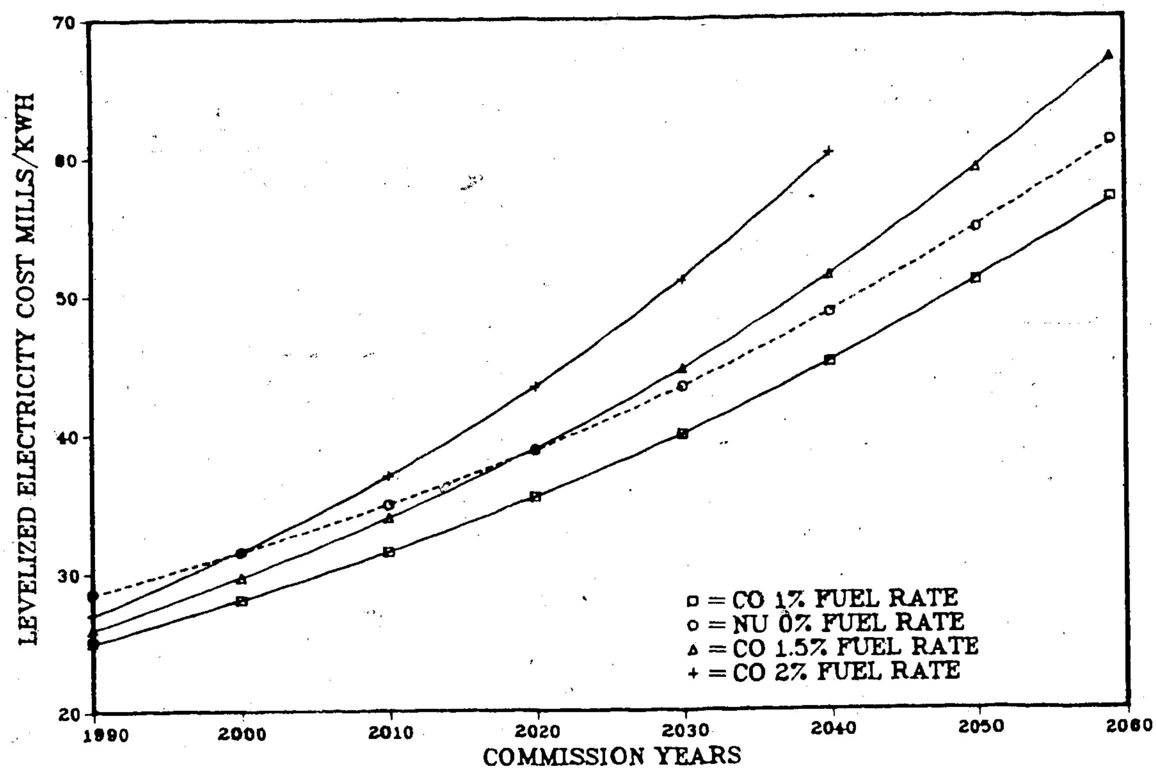


Figure 6.5 The unit electricity costs at various coal fuel escalation rates for various commission years

6.1.4 The effect of interest rates on break-even points

When the interest rate is 2% above the base case of 6%, i.e. 8%, the break-even point occurs 25 years later, that is from the year 2020 to 2045 as shown in Figure 6.6. A high interest rate is not good for the capital intensive nuclear power plants and reduces their economic viability. At an interest rate of 8%, both coal and nuclear units' cost lines shift upwards (from base case of 6% interest rate), because higher interest rates would make the annual equivalent costs higher. When the interest rate is 2% lower than the base case, (i.e. at 4%) the break-even point occurs quite early, the year 2000. Lower interest rate favours the capital intensive nuclear plant. At 4% interest rate, both unit costs shift downwards, because lower interest rates would make the annual equivalent cost lower. The break-even point or the competitiveness of the nuclear power plant is very sensitive to the interest rate.

6.1.5 The capital cost of nuclear power plants

When the capital cost of a nuclear power plant is doubled, the unit costs increase almost two times as shown by the upper dotted lines in Figure 6.7. This indicates that a large share of unit cost belongs to capital costs. At this high capital cost there is no chance of having a break-even point at all. By constructing curves for various increases in capital cost of nuclear power plant, the increase in the capital cost of a nuclear power plant below

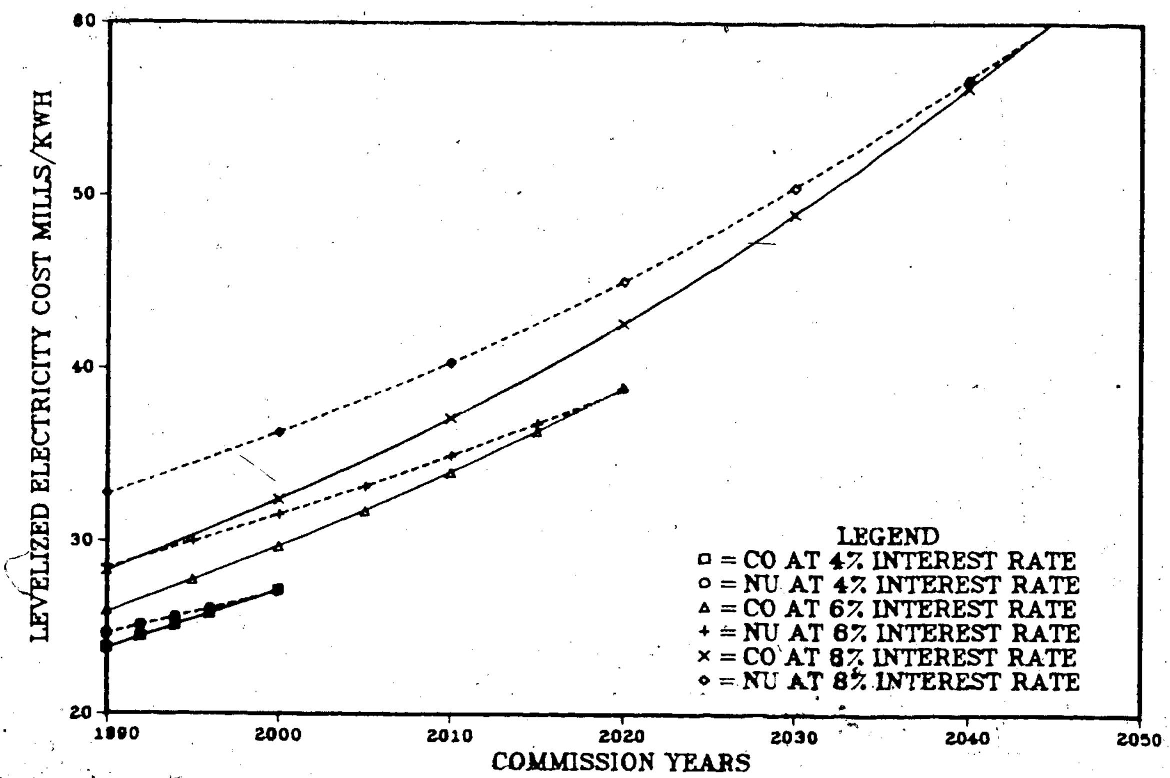


Figure 6.6 The unit electricity costs at various interest rates for various commission years

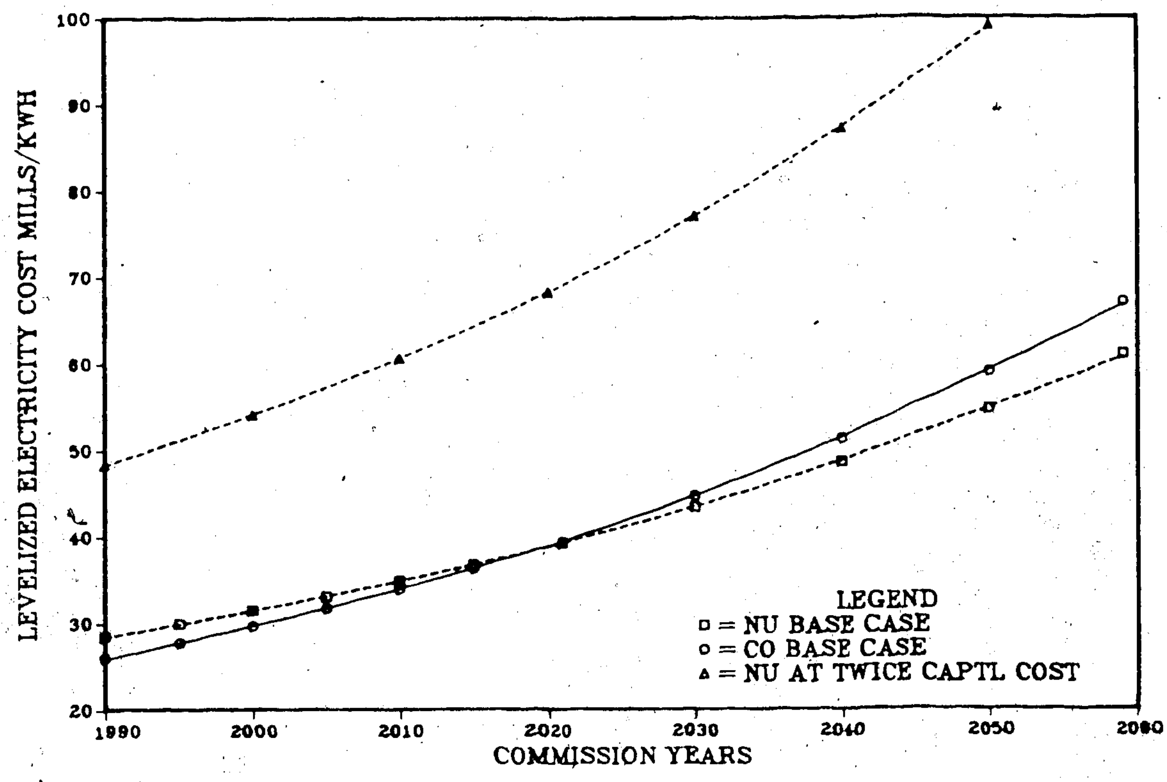


Figure 6.7 The unit electricity cost of nuclear power plants after the capital cost is doubled

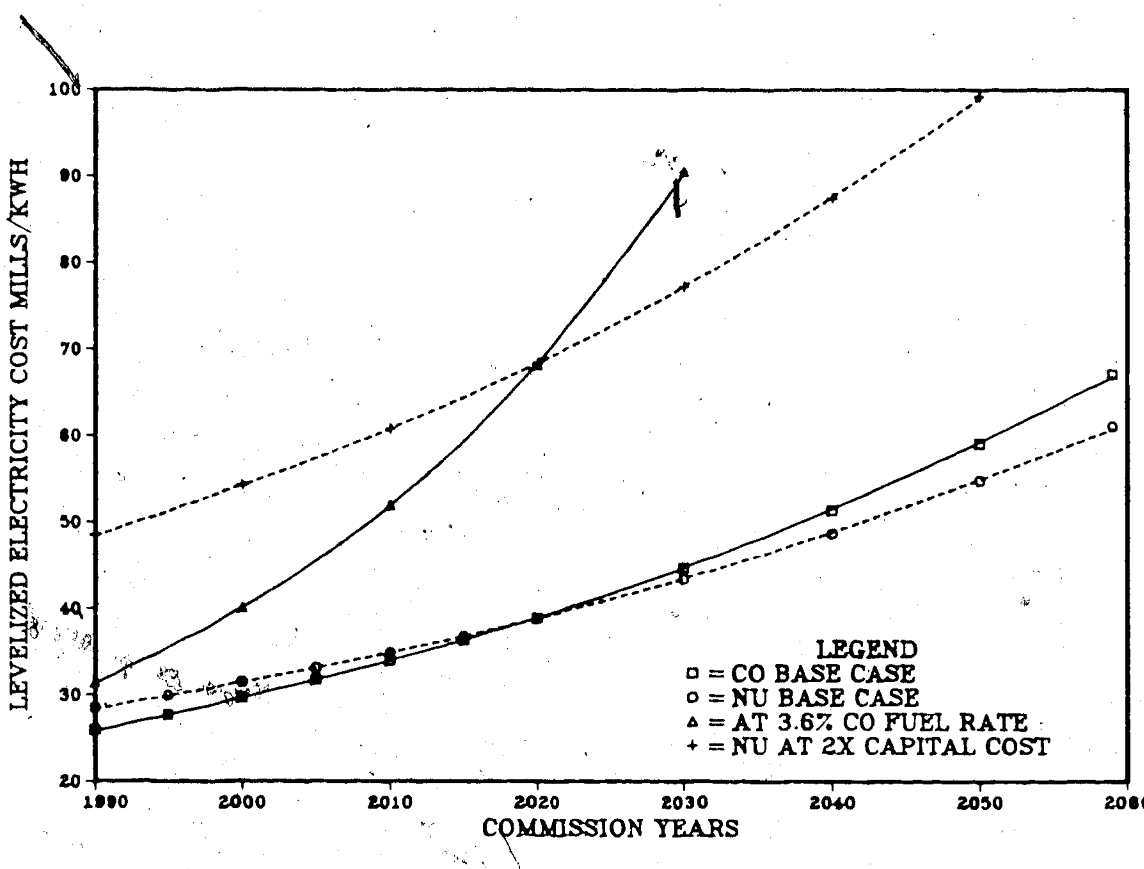


Figure 6.8 The unit electricity cost showing the coal fuel rate at which nuclear power plants remain at the same competitiveness

which nuclear power may have a chance of competing with that of coal, can be estimated. It is found that nuclear power plants have a chance only when the increase of base case value of capital cost is below 50%.

Since break-even points are found to be very sensitive to coal fuel escalation rate, an annual increase of coal price from the base case of 1.5 to 3.60%, would bring nuclear power with doubled capital cost back to its economic viability as that of the base case (shown by the sharp rising curve in Figure 6.8). At these high capital cost and coal price rate the included angle becomes larger than that in the base case. The break-even point is, therefore, not as sensitive to social costs.

6.2 Total cost analysis

6.2.1 Base case study and building strategy

The total costs plotted in Figure 6.9 are dimensionless. These are the results of dividing all the total costs by the total cost of the all coal scenario. The total costs of the all coal scenario are listed in Table 6.2. The dimensionless total costs reflect the degree of change from the all coal scenario.

All the bars from Figure 6.9 show increasing total costs as more nuclear power is added to the plant mix. From the unit cost analysis, the break-even point for the base case is 2020 which is outside the study period (1983 to 2012 inclusive) of this base case study in the total cost analysis. Therefore no plant mix having the lowest total costs is found, which is in agreement with the results found by the unit cost analysis.

Table 6.2 Total costs of the all coal scenario at 6% interest rate, in million dollar per GweY

Demand for electricity	Total costs	
	with social costs	without social costs
4%	10178.0	9508.0
base case	11941.0	11127.0
3% Log	17371.0	16316.0

At the highest demand for electricity, 3% log growth, the total cost of the all nuclear scenario is found to be 2% higher than that of the all coal scenario, shown by the tallest narrow-bar in Figure 6.9. At base case demand, the same percentage of change in total costs is about 1.4% as shown by the tallest wide-bar in Figure 6.9. At the year before the break-even point the capital cost and operation and maintenance costs of a nuclear power plant are more expensive than those of a coal-fired power plant and are the dominant factors. The penalty for nuclear power plants having larger unit capacity, 0.6 Gwe vs 0.371 Gwe, is less severe for higher demand; but this effect is not very prominent at the condition where nuclear power is more inclusive) of this base case study in the total cost analysis. Therefore no plant mix having the lowest total costs is found, which is in agreement with the results found by the unit cost analysis.

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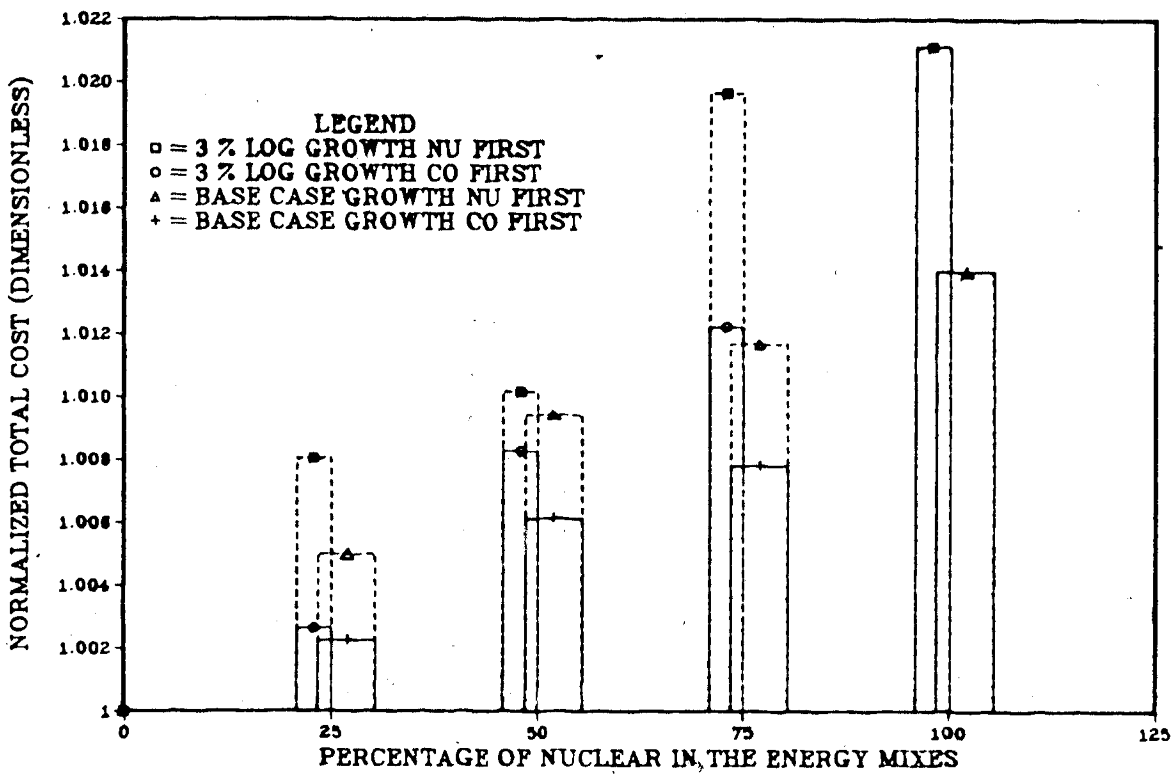

Note: To avoid confusion, 4% demand is not plotted because the bars are too close to those of base case demand

Figure 6.9 The effect of demand and building strategy on total costs in base case at various plant mixes expensive than coal before the break-even point. Higher demand for electricity means higher percentage of electricity is generated by nuclear power. At high demand for electricity and before the break-even point, total costs for those scenarios with nuclear plants are, therefore, higher.

The costs of the building strategy alternative, where nuclear power plants are to be built first, are shown by the bar in dotted lines in Figure 6.9. This building strategy is not favourable, for the bars in dotted lines (nuclear power first) are higher than those in solid lines (coal power first). This is because nuclear power plants are more economical later in the planning horizon. The differences of these two building strategies are small, less than 0.8% of the total cost of the all coal scenario (Figure 6.9). The total cost is not sensitive to the building strategy, and also not sensitive to the changes of the demand for electricity.

6.2.2 The effect of demand on total costs

The total costs based on a 4% (real) interest rate are listed in Table 6.3 and plotted in Figure 6.10. At 3% log demand for electricity all the total costs of the all nuclear scenario (all nuclear after the year 2000) are lower than those for the all coal scenario as shown in Table 6.3. At base case demand, i.e. lower demand for electricity, the total costs of the all nuclear scenario start to become

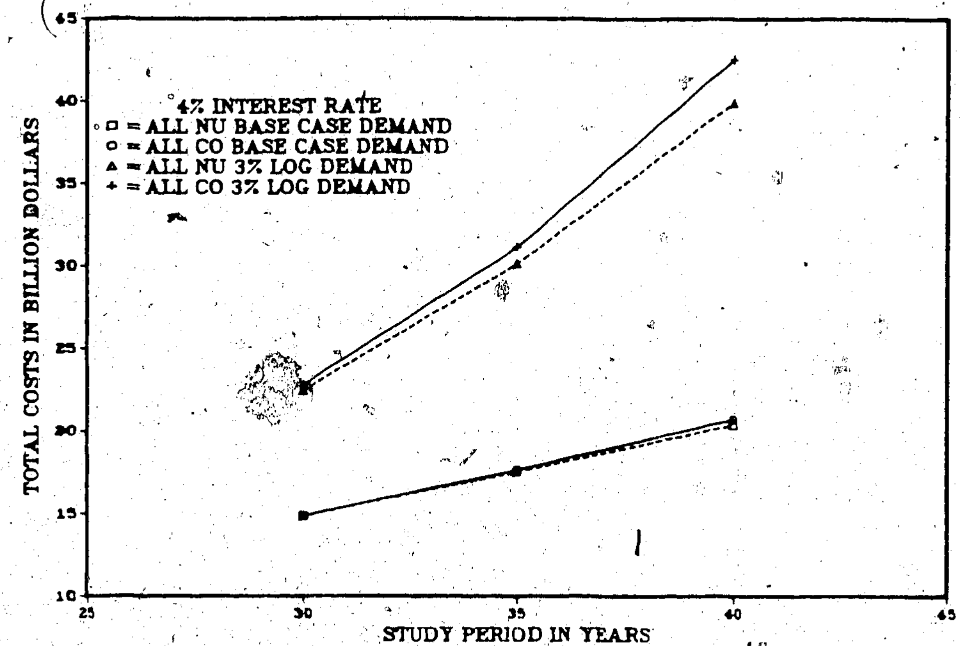

Figure 6.10 Total costs at base demand and 3% log demand for electricity at various study periods at 4% interest rate

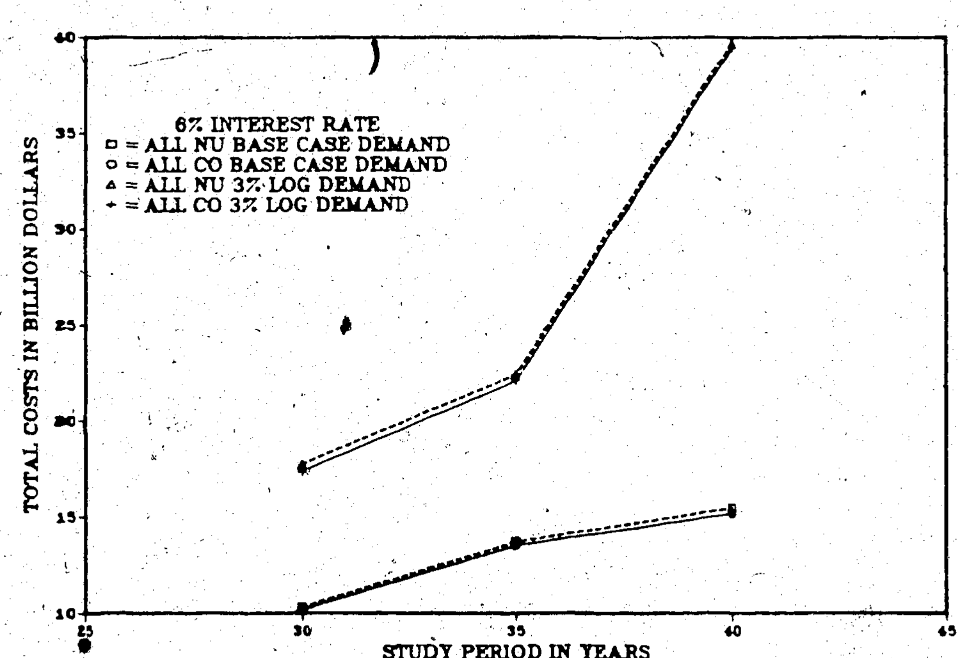

Figure 6.11 Total costs at base demand and 3% log demand for electricity at various study periods at 6% interest rate

smaller than those for the all coal scenario when the study period is longer than 30 years.

Table 6.3 Total costs at various study periods in million January 1982 dollars at 4% interest rate with expected social costs

Study period in years	demands			
	base case scenarios		3% Log scenarios	
	All coal	All nuclear	all coal	all nuclear
30	14,877	14,880	22,822	22,470
35	17,687	17,536	31,165	30,165
40	20,733	20,394	42,521	39,889

Note:
for the all nuclear secnario nuclear power plants start to be built in and after 2000

From the unit cost analysis the break-even point at a 4% interest rate is 2000 which is within the study period for the base case study of the total cost analysis (1983 to 2012 inclusive). The total cost for the all nuclear scenario where nuclear power plants are assumed to be built after the year 2000 should be lower than that of the all coal scenario. The above expected conclusion is found only at higher demand (3% log) shown by the upper two lines in Figure 6.10 and the right column of Table 6.3. At lower demand, the surplus capacity due to nuclear power plants is relatively significant. The significance of surplus capacity can easily be observed from the total surplus capacity and total electricity generated by nuclear power in the 100% nuclear plant mix column listed in Appendix 4. This surplus capacity could cause the break-even point to occur later in the planning horizon.

For comparison purposes, total costs of the all nuclear scenario (all nuclear power plants after 2000) at a 6% interest rate are also plotted and shown in Figure 6.11. The total costs of the all nuclear scenario (dotted lines in Figure 6.11) are higher than those of the all coal scenario (solid lines in Figure 6.11). This is because nuclear power plants are allowed to be built before the breakeven point.

When the study period is extended from 35 to 40 years (as shown in Figure 6.11), there is a slow down in the raise of total costs at low demand rather than a rapid raise of total costs as that of the high demand. The input data have been checked. No satisfactory explanation to this slow down in the raise of total costs has been found. this thesis can find to explain this phenomena. Surplus capacity which is directly related to the changes of demand is suspected to be the cause of this slow down in the raise of total costs.

6.2.3 The effect of social cost and study period on break-even point

The total costs of various all nuclear scenarios for the study period of 30 and 40 years are listed in Table 6.4. These are calculated at an interest rate of 4% for the base case demand for electricity.

Table 6.4 Total costs at various all nuclear scenarios in million dollars at base case demand and 4% interest rate

study period years	Scenarios					
	All nuclear					All coal
	2000*	2005	2010	2015	2020	
30	**14,880** 13,879	**14,861** 13,824	**14,882** 13,813	**14,877** 13,806	**14,877** 13,806	**14,877** 13,806
40	**20,394** 19,293	**20,397** 19,228	**20,523** 19,260	**20,741** 19,423	**20,736** 19,392	**20,733** 19,385

* The year represents the year starting from which all new plants will be nuclear.

Figures in bold are total cost with social costs, other total costs refer to traditional cost only.

For the study period of 30 years and at a 4% interest rate, a minimum total cost (with social costs, figures in **bold** as shown in Table 6.4) of the all nuclear scenario is found to be in the year about 2005. From unit cost analysis, the break-even year is predicted to be the year 2000 at a 4% interest rate with social costs as shown in Figure 6.6. The break-even year of 2000 is for a condition where demand is met exactly by supply. This five year delay is, therefore, due to the presence of a surplus capacity. When the study period is extended to 40 years, the minimum total cost (with social costs) is found at the year 2000 which is similar to the expected break-even point found by the unit costs analysis (figures in **bold** as shown in Table 6.4). These results indicate that the length of the study period can affect the year at which a minimum total cost may exist. In order to find the break-even point by this interative method, the study period should be long enough for the effect due to the surplus capacity to be not significant.

When social costs are excluded from the total cost analysis nuclear power becomes less attractive because the expected social costs due to nuclear are smaller than those due to coal-fired power plants. A study, based on a study period of 30 years, does not show a total cost lower than that of the all coal scenario (refer to the second line of the 30 year study period in table 6.4), but as the study period increases to 40 years a minimum total cost which is smaller than the total cost of the all coal scenario is observed and is found at the year 2005 (Table 6.4). The five year delay in the break-even point occurs because the nuclear power plant is less competitive when social costs are not included in the analysis. After the estimated break-even point the total costs are becoming higher as shown in Table 6.4, because some existing coal-fired plants are still operating and using expensive coal.

7. Conclusion and recommendations for further study

In this thesis, the first objective was to estimate the social costs due to CANDU and coal-fired power plants in Alberta. The second objective was to establish appropriate methods of analysis for studying the economics of coal and nuclear electricity generation. The third objective was to include the social cost estimates in the established methods of cost analysis and investigate the effects of social costs and the uncertainty of their estimates on the choice of and the timings of adopting CANDU for electricity generation in Alberta. The fourth objective was to study the sensitivity of the choice of energy source(s) to other factors, for example interest rates and fuel escalation rates, which gave perspective on the importance of social costs for decisions about electricity generation methods.

7.1 The expected social costs

Social costs were very difficult to estimate, especially with incomplete statistical data. Social costs due to electricity generation in Alberta were estimated by either: a.) adopting the estimates from studies which were appropriate for the environment and the operation of power plants in Alberta; or b.) by using the methods of these studies to estimate the social costs. In cases where the estimates from the studies were based on pollution levels and population density which differed from those of Alberta, a damage potential function was used to pro-rate the estimates to Alberta.

After reviewing various studies, a number of independent estimates for a social cost were collected. The expected value for that social cost was taken to be the average of these independent estimates. The estimates of social costs for both types of power plants in Alberta varied to a considerable extent. The usual method of describing the variation of social costs is to use a range of values. In this thesis, a theoretical distribution function was used to approximate the distribution of social cost estimates so that the variation of the estimates could be modeled and the uncertainty of the social cost estimates on the choice of and the time of adopting the energy source(s) for future electricity generation could be studied. The social costs estimates were assumed to be in the region greater than zero and less than infinity. The log-normal distribution, also used by many studies for representing the variation of pollutant concentration, was adopted. To the author's knowledge, this is the first time that a theoretical distribution was used to model the variation of the social cost estimates. The use of this distribution to describe the social cost estimates is better than the use of a range of values because a distribution discribes the estimates better than a range of values does (Appendix A.6).

Using this approach the expected social costs due to nuclear and coal-fired power plants in Alberta were found to be 1.078 and 13.049 M/GweY or 0.123 and 1.490 mills/kwh, respectively. The standard deviations were 0.458 and 9.296 M/GweY for nuclear and coal respectively. The standard deviations of the social costs for coal and nuclear were high, roughly same as their respective expected values. The standard deviation of the social cost resulting from coal -fired power plants was found to be higher than that resulting from nuclear power plants. This is due, in part, to the fact that radiation is better understood than air pollution (Cohen, 1981).

If the social costs due to mining, land and water are included in the total social cost for nuclear power plants, the total social cost becomes 2.664 M/GweY.

7.2 Methods for cost analyses

In this thesis, two methods of analysis were established: unit and total cost analysis. In the unit cost analysis, a new power plant is assumed to be commissioned every year regardless of the demand. The results from this analysis are equivalent to the situation where demand is exactly met by supply or the demand approaches to infinity when compared to the unit capacity of a power unit. This analysis can be used to determine the year at which one type of electricity generation method becomes more economical than the others (the break-even point), if the surplus supply of electricity is not considered. The effect of other factors, for example, interest rate and fuel escalation rate, on the break-even point can be easily studied with this method. The unit cost analysis is not limited by the study period and is the method most commonly used for cost analysis of power facilities.

In total cost analysis, the demand and supply of electricity during the study period are simulated. Also, in total cost analysis, one includes not only the cost factors but also non-cost factors such as: the annual electricity capacity, the surplus capacity, the forecast of demand for electricity, the consideration of starting to build another type of power plants after the completion of a power station, and the increase in capacity by unit capacity size for meeting the demand. The results from total cost analysis are more realistic and applicable for planning purposes because this analysis provides information on when to build power plants and on what type in order to meet the demand. In total cost analysis, the effect of cost factors on the choice of energy sources sometimes cannot be isolated from non-cost factors because there are a number of factors varying at the same time.

In this thesis, unit cost analysis was used for studying the effect of each cost factor and determining the year at which nuclear power becomes economically viable. Since the surplus capacity at the beginning of study period was significant when compared to the capacity of a unit power plant, total cost analysis was used mainly for studying the effect of demand and surplus capacity on the time of adopting CANDU nuclear power plant in Alberta. It was found that the higher the demand relative to plant size, the more the results of these two methods are similar.

7.3 Effect of social costs

For the initial case study the levelized cost curves did not converge and the nuclear option is not expected to be economically justifiable in the foreseeable future. The difference in traditional costs proved to be so high that the inclusion of social costs did not change this result.

For the base case study of the unit costs analysis nuclear power plants became more economical than coal-fired in the year 2032. The inclusion of social costs caused nuclear power plants to become economically viable twelve years earlier, but only ten years earlier if the social costs due to mining and polluted natural resources were in the toal social costs of nuclear power plants.

The uncertainty of the social costs was found to have a profound effect on the competitiveness of nuclear power plants. The high uncertainty and the sharp included angle of the unit cost curves could cause nuclear power to be favourable as early as the year 1990 or as late as the year 2045, a 55 year difference. This 55 year difference was calculated based on the approximately 98% confidence level of the distribution of the social costs estimates.

7.4 Sensitivity of results to other factors

The above conclusions were found to be sensitive (in descending order) to the price escalation rate of coal and uranium, interest rates and nuclear capital costs. The choice of energy source(s) for electricity generation became more sensitive to social costs when the difference between the traditional costs of coal and nuclear, and the rates of increases in traditional costs became smaller, or the included angle of the unit cost curves became sharper.

From total cost analysis, it was found that surplus capacity would cause about a five year delay in adopting nuclear power in Alberta, and was found to be less significant at higher demand for electricity and at higher growth rates of this demand.

7.5 Recommendations for further research

Further research on social costs due to electricity generation is recommended because the break-even point was found to be sensitive to social costs and the social costs estimates were very uncertain (particularly for coal). The important social costs are: a.) health costs for both types of power plants, diversion of nuclear fuel; b.) sabotage of nuclear power plant; and c.) social costs due to surface mining. Other approaches of estimating these social costs are recommended, for example, one can use a statistical method, or perhaps the Analytic Hierarchy Process (Saaty, 1980).

In this thesis, all the social costs were assumed to be a function of annual electricity output. Certainly, there is room for improving the social cost functions. Some of the social costs may be related to other variables such as the accumulated electricity output. Once improved functions are established a standard process to estimate the coefficents of the functions is recommended so that they can be applied to future studies in other regions.

The computer programs developed in this thesis are only applicable to the Alberta situation. In these programs none of the new plants were allowed to be decommissioned during the study period and the decommissioning costs of the existing power plants were not included. The decommissioning cost of a nuclear power plant is expected to be higher than that of a coal-fired plant. If the programs are modified to include the decommissioning costs, the length of study period is not limited and the effects of the decommissioning cost on total costs and unit costs, though they may not be significant, can be studied. Generalization of the computer programs so that they can be applied to other regional situations is also recommended.

The break-even point was found to be very sensitive to changes of fuel price escalation and interest rates. Research into the techniques of forecasting interest and fuel price escalation rates is highly recommended.

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Appendix one

A.1.1 Capital costs of various power plant units in million dollars, January 1982 Canadian dollars

	nuclear	new coal plant	existing coal plant
unit 1	987	410	359
unit 2	793	267	216
unit 3		265	214
total cost for a plant	1780	942	789

Note: costs of flue gas desulphurization devices for new coal plant are included
costs of heavy water for 1st and 2nd unit are 141, 140 million dollars respectively
half initial nuclear fuel charge for each unit is 9 million dollars
Source: Foulkes[1982]

A.1.2 Cash flow rates for various plant units in percentage of capital cost of a power station

construction year	Nuclear unit 1	Nuclear unit 2	coal-fired unit 1	coal-fired unit 2	coal-fired unit 3
1	1.000		1.000		
2	2.000		3.000		
3	3.000		9.000		
4	6.000		17.760	8.240	
5	10.900	6.090	8.760	9.000	8.240
6	15.342	9.660	4.0	7.000	9.000
7	10.419	13.583		4.000	7.000
8	6.771	9.224			4.000
9		6.0			

Source: Derived from Foulkes's estimates

The escalation rates for calculating the capital cost, operation and maintenance costs are listed as follows:

A.1.3 Escalation rates year by year

year	1982	1983	1984	1985	1986 and beyond
CPI	10.5	8.8	7.9	6.6	6.9
k	12.2	10.4	9.5	8.2	8.5
K	1.5	1.5	1.5	1.5	1.5
l	(1.0)	(1.0)	0.0	0.0	1.0

source: Conference Board of Canada, Medium Term outlook 1981-86, December 1981.

A.1.4 Separating the cash flow rates for units from the whole power station

a. Coal-fired power plant:

Assuming the annual cash flow rates of one unit are in proportion with those of the other units (with the exception of first year). The cash flow rates can be formulated as follows:

construction year	1	2	3	4	5	6	7	8	Capital Costs (m) *
	Cash flow rates in % of total capital costs								
1st unit	1	3	mx	ay	az	a4			410
2nd unit				nx	by	bz	b4		267
3rd unit					x	y	z	4	265
Whole plant	1	2	9	26	26	20	11	4	942

For the same construction year, the sum of the cash flow rates of all the units is equal to the cash flow rate of the whole plant. The sum of the cash flow rates of each unit should equal to the ratio of capital costs of the unit and the whole power station.

Therefore there are seven equations and seven unknowns.

$$x+y+z+0.04=265/942$$
$$nx+bx+bz+.04b=267/942$$
$$z+.04b=.11$$
$$y+bz+.04a=.20$$
$$x+by+az=.26$$
$$nx+ay=.26$$
$$mx=.09$$

By solving the above equations and back substitution, the cash flow rates for a power unit in percentage of the capital cost of the whole power plant can be estimated and they are listed in Appendix one, A.1.2.

b. Nuclear power plant:

Same assumptions as those of coal-fired power plants can be applied because equations are not enough to solve the unknowns. The cash flow rate in the last year of the second nuclear power unit is assumed to be the same as the last cash flow rate of the whole power station. Then the cash flow rates of each power unit can be found and listed in Appendix one, A.1.2.

Note: m in million January 1982 dollars.
* capital costs same as Foulkes[1982]

A.1.5 Estimating the nominal capital cost for a new nuclear station which is to be commissioned in the beginning of 1990

By using the equation 3.3 in Chapter 3, and assuming Y = 9 years

t	m	U f km	AFUDC	C
1	1981	1481x1%	$x1.12^8$ =	36.67
2	1982	1481x2% x1.122	$x1.12^7$ =	73.47
3	1993	1481x3% x1.122x1.104	$x1.12^6$ =	108.63
4	1984	1481x6% x1.122x1.104x1.095	$x1.12^5$ =	212.41
5	1985	1481x17%x1.122x1.104x1.095x1.082	$x1.12^4$ =	581.41
6	1986	1481x25%x1.122x1.104x1.095x1.082x1.085	$x1.12^3$ =	828.29
7	1987	1481x24%x1.122x1.104x1.095x1.082x1.085^2	$x1.12^2$ =	770.31
8	1988	1481x16%x1.122x1.104x1.095x1.082x1.085^3	$x1.12^1$ =	497.49
9	1989	1481x6% x1.122x1.104x1.095x1.082x1.085^4		=180.73
			sub total	3289.41

Plus the heavy water and half fuel charges at the end of construction
(281+18) x 1.105 x 1.088 x 1.079 x 1.066 x 1.069^4 =539.95

capital cost for a plant commissioned at the beginning of 1990 (Jan., 1990 price level) 3829.36

The nominal capital cost calculated is slightly different from that estimated by Foulkes. His estimate is 3843 million dollars in 1990 nominal dollars.

He has been contacted to rectify this dicrepancy. Because the original author of the paper is not available, and it has been confirmed by them that the method employed in this calculation is correct, the above method is used in the computer programs.

All costs are capitalized at the end of the construction year.

Table. A.1.6 Operation and maintenance costs in million dollars, 1982 Canadian dollars

	unit	nuclear	coal-fired
Labour cost	1	10.6	3.6
	2	4.4	3.6
	3		3.6
Material cost	1	6.3	2.4
	2	5.0	2.4
	3		2.4
	total	26.3	18.0

source: Foulkes[1982]

Appendix two

```
C                 PROGRAM TOSCA
C          DISCRETE INCREASE IN POWER PLANTS
C              FOR ALBERTA SITUATION
C     CONSIDER ONLY COAL AND NUCLEAR POWER PLANT
C         1989 IS THE LAST YEAR THAT PLANTS
C     PLANNED IN OR BEFORE 1981 GO INTO SERVICE.
C          ESCALATION RATES ARE INCLUDED
C
       LOGICAL*1 FREEIO(1)/'*'/
       REAL F(11),A(4,3),V(4,31),B(31),C(4,10),
      ,D(31),G(4,31),H(4),K(4),M(4,45),N(4,31),
      ,P(4,31),R(7),Y(4,31),Z(4,31),U(4,7),
      ,X(4,31),W(4)
       INTEGER O(2,2),S(16,11),C1,C2,C3,C5,C8,C9,I1,J1,
      ,T1,T2,T3,T9,P2,R2,R9,B7,S1,S2,S3,S4,D1,O1,O2,
      ,PP(100)
C
       COMMON /VALUES/ F,A,V,B,C,D,G,H,K,M,N,P,
      ,   R,Y,Z,U,X,W,S,O,PP,
      ,   C1,C3,C5,C8,C9,J1,I1,T1,T3,R1,R9,
      ,   P2,Z0,Z1,Z3,Z4,D1,D0,IBASY
C
C READ IN THE YEAR OF THE FIRST COMMISSIONED PLANT
C AND THE COMMISSION YEAR OF THE LAST COMMITTED PLANT
C
       DO 133 J=1,2
       READ(5,FREEIO)(O(J,I),I=1,2)
 133   CONTINUE
C
C READ IN THE YEARLY INSTALLED CAPACITY FROM THE
C FIRST COMMISSIONED TO THE COMMITTED PLANT
C
       READ(5,FREEIO)(M(1,I),I=1,45)
       READ(5,FREEIO)(M(2,I),I=1,45)
C
C FIRST ARRAY SUBSCRIPT IS THE KEY TO THE PLANT TYPE.
C 1= OLD FOSSIL        2=NUCLEAR
C 3= NEW FOSSIL        4=NEW TECHNOLOGY (BREEDER,SOLAR)
C                          (DUMMY PLANT FOR ALBERTA)
C INITIALIZE DATA TABLES, ARRAYS AND CALL SUBROUTINE INIT
C
       DO 4 I = 1,45
         M(3,I) = 0.0
         M(4,I) = 0.0
 4       CONTINUE
C
       C2 = 0
       C3 = 0
       C9 = 0
       P2 = 0
       B7 = 0
       S1 = 0
```

```
      S2 = 0
      S3 = 0
      S4 = 0
      D1 = 0
      T9 = 0
      C8=1
      C5=0
C
      DO 5 I = 1,16
      DO 5 J = 1,11
          S(I,J) =1
 5        F(J) = 1.
C
      READ(5,FREEIO)J1,C1,C9
      READ(5,FREEIO)I1
      IF(I1 .EQ. 1) GO TO 11
      DO 10 I = 1,I1
         READ(5,FREEIO)S(I,1),F(I)
         I2=S(I,1)+1
      DO 10 J = 2,I2
         READ(5,FREEIO)S(I,J),S(I,J+5)
 10    CONTINUE
      DO 15 I = 1,I1
         I2 = S(I,1)+1
 15   CONTINUE
 11   CONTINUE
C
C INITIALIZE FUEL ESCALATION RATE, N/A IN ALBERTA
C
      DO 20 I = 1,4
      DO 20 J = 1,3
 20   A(I,J) = 0.
C
C PRICE RISE PARAMETERS (BETA) N/A IN ALBERTA
C
      A(2,2) = .0003
      A(1,3) = .0003
      A(3,3) = .0003
      READ(5,FREEIO)T1,D0,IBASY
C
C FOR STUDY PERIOD OF 40 DELETE C IN THE NEXT LINE
C     T1=40
C
C
C IBASY...base year, the first year of study peroid
C T1......number of years in the study period
C D0......base demand in Gwe(net) in the first year of
C         study period
C
      T3=T[illegible]1
C
C INITIALIZE SUPPLY (G) FROM PLANT (-, ) IN YEAR
C ( ,-) BEFORE BUILDING PROGRAM
C
```

```
      DO 40 J = 1,J1
      DO 45 T2 = 1,T3
         G(J,T2) = 0.
         B(T2) = 0.
 45    CONTINUE
      READ(5,FREEIO)K(J)
 40    CONTINUE
C
C FIND OUT THE TOTAL CAPACITY G(J,T2) FROM THE EXISTING
C       PLANTS IN GWE(NET)
C FIND OUT THE TOTAL CAPACITY B(J,T2) FROM THE EXISTING
C       PLANTS AFTER DEDUCTED BY THE CAPACITY FACTOR
C
      DO 50 J = 1,2
         O1 = O(J,1)
         O2 = O(J,2)
      DO 55 N1 = O1,O2
         L5 = N1-IBASY
         L6 = L5+34
         IF(L5 .GE. 1) GO TO 51
         L5 = 1
 51      IF(L6 .LE. T3) GO TO 52
         L6 = T3
 52      CONTINUE
      DO 55 T2 = L5,L6
         G(J,T2) = G(J,T2) + M(J,O2-N1+1)
C
C COMPUTE SUPPLY FROM OLD PLANTS
C
         B(T2) = B(T2) + K(J)*M(J,O2-N1+1)
 55    CONTINUE
 50    CONTINUE
      READ(5,FREEIO)R9
      READ(5,FREEIO)(R(R2),R2=1,R9)
C
      CALL INIT
      STOP
      END
C
C
C
C
      SUBROUTINE INIT
C
C INIT INITIALIZES COST CONSTANTS,
C     SETS UP THE FIRST OF TWELVE SCENARIOS.
C     BUT ONLY FIVE FOR ALBERTA
C     SUBROUTINE TO END EXECUTION.
C
      LOGICAL*1 FREEIO(1)/'*'/
      REAL F(11),A(4,3),V(4,31),B(31),C(4,10),D(31),
     ,   G(4,31),H(4),K(4),M(4,45),N(4,31),P(4,31),
     ,   R(7),Y(4,31),Z(4,31),U(4,7),X(4,31),W(4)
      INTEGER O(2,2),S(16,11),C1,C2,C3,C5,C8,C9,I1,J1,
```

```
     ,    T1,T2,T3,T9,P2,R2,R9,B7,S1,S2,S3,S4,D1,PP(100)
C
      COMMON /VALUES/ F,A,V,B,C,D,G,H,K,M,N,P,
     ,    R,Y,Z,U,X,W,S,O,PP,
     ,    C1,C3,C5,C8,C9,J1,I1,T1,T3,
     ,    R1,R9,P2,Z0,Z1,Z3,Z4,D1,D0,IBASY
C
      ENTRY NO1
      CALL CSTC
C
      WRITE(6, 471)
471   FORMAT(////,24X,
     ,'                              COST CONSTANT ',/, 24X,
     ,'  CAPITAL COST    O&M COST     FUEL COST
     ,SOCIAL COST',/,
     ,24X,'  MLN DLR/STN   MLN DLR/STN
     ,MLN DLR/GWY   MLN DLR/GWY')
     WRITE(6,474)C(1,1),C(1,2),C(1,3),C(1,4)
474   FORMAT(//,2X,'EXISTING COAL PLANT',4F14.5)
      WRITE(6,475)C(2,1),C(2,2),C(2,3),C(2,4)
475   FORMAT( 2X,   'NUCLEAR PLANT       ',4F14.5)
      WRITE(6,476)C(3,1),C(3,2),C(3,3),C(3,4)
476   FORMAT( 2X,   'NEW COAL PLANT      ',4F14.5)
C
C CONSUMER DEMAND GROWTH AT 4% - INITIAL SCENARIO
C
      R1=.04
      D1=1
      ENTRY NO2
C
      ENTRY NO3
      D(1) = 0.
      P2 = 0
       DO 747 T2=1,T1
        Z(1,T2)=0.0
        Z(2,T2)=0.0
 747    Z(3,T2)=0.0
       IF (P2 .EQ. 0) GO TO 255
C
C CALCULATE MIX OF PLANTS FOR FIRST SCENARIO.
C Z( , )=0. IS ZERO RESEARCH COST.
C
      DO 70 T2 = 1,T1
         Z(1,T2) = 0.
         Z(2,T2) = 0.
         Z(3,T2) = 0.
         P(1,T2) = 0.
         P(2,T2) = 0.
         IF(T2 .GE. T1/2) GO TO 71
         P(3,T2) = 1
         P(4,T2) = 0.
         GO TO 70
 71      P(3,T2) = 1. - FLOAT(T2/T1)
         P(4,T2) = FLOAT(T2/T1)
```

```
 70     CONTINUE
C
255       CONTINUE
        IF(P2 .EQ. 0) CALL SCRO
C
       RETURN
       END
C
C
C
C
       SUBROUTINE VARC
C
C THIS SUBROUTINE CALCULATES AND WRITES OUT THE COST
C      OF EACH SCENARIO,
C      INCLUDING DEMAND CHANGES
C
       LOGICAL*1 FREEIO(1)/'*'/
       REAL F(11),A(4,3),V(4,31),B(31),C(4,10),D(31),NI(30),
     ,      G(4,31),H(4),K(4),M(4,45),N(4,31),P(4,31),
     ,      GD(30),Q(4)
     ,      R(7),Y(4,31),Z(4,31),U(4,7),X(4,31),W(4),
     ,      AECC(3,10),NP(4,31),
     ,      RERF(4),AC(31),PREW(4),PY1(50),ALPH(20),PX(50),
     ,      RLEROP(50),
     ,      DOUT(7,5)
       INTEGER O(2,2),S(16,11),C1,C2,C3,C5,C8,C9,I1,J1,UNIT,
     ,      T1,T2,T3,T9,P2,R2,R9,B7,S1,S2,S3,S4,D1,PP(100),
     ,      YR,T10,
     ,      PXX
C
       COMMON /VALUES/ F,A,V,B,C,D,G,H,K,M,N,P,
     ,   R,Y,Z,U,X,W,S,O,PP,
     ,   C1,C3,C5,C8,C9,J1,I1,T1,T3,
     ,   R1,R9,P2,Z0,Z1,Z3,Z4,D1,D0,IBASY
C
C DR.......the discount rate
C LT.......service life of power plant
C SURPUS...surplus of power capacity in each year
C RERF.....real escalation rate for fuel
C NN.......controlling the type of power plant to be built
C US.......accumulated total cost after discounted
C UU.......accumulated total economic cost after discounted
C AC.......total annual economic cost without discounted
C YAD......yearly additional demand
C IBASY....base year, in this case 1982
C W(J).....the accumulated electricity generated from
C          the beginning
C PREW(J)..total annual electricity  generated to meet
C          the demand on top of the existing supply.
C          It increases every year
C          for plant type J
C NI.......total installed capacity after increased to meet
C          the demand by discrete manner
```

```
C NP.......new units added during the whole study period
C CAP......total capacity after deducted by C.F. in GW
C FIT......Total difference of supply and demand in GW,
C          as an indicator of how good the supply fits
C          the demand. Small value means better fit.
C RLEROP...real labour escalation rate for old plant
C
C       WRITE(6,FREEIO)D1
        DATA RLEROP/.99,.99,1.0,1.0,1.01/
        DO 809 KKK=6,50
809     RLEROP(KKK)=1.01
        DO 10 J = 1,J1
          W(J) = 0.
          PREW(J)=0.0
 10     CONTINUE
C
C THE CAPACITY FOR STANDARD UNIT
C
        Q(1)=.375
        Q(2)=.6
        Q(3)=.371
        DR=0.06
C
C FOR 4% DISCOUNT DELETE C OF THE NEXT LINE
C
C       DR=0.04
        SUMNI=0.0
        LT=35
        SURPUS=0.0
        RERF(1)=0.015
        RERF(2)=0.0
        RERF(3)=0.015
        RERF(4)=0.0
        NN=0
        US=0.0
        FIT=0.0
        DO 20 T2=1,T1
           NI(T2)=0.0
        DO 21 KK=1,4
 21     NP(KK,T2)=0.0
 20     AC(T2)=0.0
        C7=0.0
        C20=0.0
C
C FIND THE ANNUAL CAPITAL COST FOR THE EXISTING PLANT BY
C SPREADING THE COST TO EACH YEAR OF ITS LIFE TIME FOR
C THE DISCOUNT RATE SPECIFIED
C
        IF(DR .EQ. 0.0) GOTO 55
        AECO=C(1,1)*(DR*(1+DR)**LT)/((1+DR)**LT-1)
        OCSTO=0.0
        DO 1190 NXX=1,LT
        AA=1.0
        DO 1120 NXY=1,NXX
```

```
      AA=AA*RLEROP(NXY)
1120  CONTINUE
      ODUM=(C(1,2)*.6*AA + C(1,2)*.4 +C(1,1)*.0135
     ,     /(DR+1))**NXX
      OCSTO=ODUM+OCSTO
1190  CONTINUE
      OCSTO=OCSTO*DIR*(1+DR)**LT/((1+DR)**LT-1)
      CALL FUEL(1,C(1,3),AFCO,RERF(1),DR)
      GOTO 57
55     AECO=C(1,1)/LT
57    CONTINUE
      LABC=C(1,2)*.6
C
C 60% OF O&M IS LABOUR COST
C
      DO 30 T2 = 1,T1
C
C INCREASE THE LABOUR COST IN OPERATION AND MAINTENACE COST
C FOR THOSE EXISTING PLANTS ONLY
C
      LABC=LABC*RLEROP(T2)
C
      YR=T2+IBASY
      IF(D1 .EQ. 1) GO TO 101
      IF(D1 .EQ. 2) GO TO 102
      IF(D1 .EQ. 3) GO TO 103
      IF(D1 .EQ. 4) STOP
C
101    CONTINUE
      IF(T2 .EQ. 1) GOTO 104
      GOTO 106
104   IF (P2 .NE. 6) GOTO 106
      WRITE(6,105)
C
C D(T2) = net demand gross demand - supply in year T2
C GD(T2) = gross demand in year T2
C
105   FORMAT(/////,2X,'BASE CASE DEMAND GROWTH')
106   GD(T2)=2.605 + (T2-1)*.16448
      D(T2)=GD(T2)-B(T2)
      GOTO 107
C
102   CONTINUE
      IF(T2 .EQ. 1) GOTO 108
      GOTO 110
108   IF(P2 .NE. 6) GO TO 110
      WRITE(6,109)
109   FORMAT(/////,2X,'DEMAND AT 4% COMPOUND ANNUAL
     , GROWTH')
110   GD(T2)=D0*1.04**(T2-1)
      D(T2)=GD(T2)-B(T2)
      GOTO 107
C
103   CONTINUE
```

```
      IF (T2 .EQ. 1) GOTO 112
      GO TO 111
112   IF(P2 .NE. 6) GOTO 111
      WRITE(6,113)
113   FORMAT(/////,2X,'DEMAND AT 3% LOG ')
111   GD(T2)=D0*10.0**(0.03*(T2-1))
      D(T2)=GD(T2)-B(T2)
      GOTO 107
107   CONTINUE
      IF(D(T2) .LE. 0.0) GOTO 31
      IF(D(T2-1) .LE. 0.0 .AND. D(T2) .GE. 0.0) GOTO 32
      YAD=D(T2)-D(T2-1)
      IF(SURPUS .GE. YAD/K(J)) GO TO 35
      YAD=YAD-SURPUS*K(J)
      PREW(J)=PREW(J)+SURPUS*K(J)
      GO TO 33
32    YAD=D(T2)
33    CONTINUE
C
C CAPACITY NOT ENOUGH TO MEET THE DEMAND
C NEW PLANT IS REQUIRED
C
C FIND THE TYPE OF PLANTS TO BE BUILT
C AND ITS CAPITAL COST IN THE YEAR OF COMMISSION
C
C NBYR IS THE YEAR STARTING FROM WHICH ALL
C    NEW PLANTS WILL BE NUCLEAR
C    FOR THIS CONTROL DELETE ALL Cs BELOW
C
C     NBYR=2000
C     IF(YR .LT. NBYR) GOTO 321
C     IF(UNIT .NE. 3 .AND. J.EQ. 3) GOTO 321
C     IF(UNIT .EQ. E .AND. J.EQ. 3) NN=0
C     DO 123 KNN=1,100,2
C     PP(KNN)=21
C     PP(KNN+1)=22
C123  CONTINUE
C     NN=NN+1
C     J=PP(NN)/10
C     UNIT=PP(NN)-J*10
C     NI(T2)=NI(T2)+Q(J)
C     NP(J,T2)=NP(J,T2)+1
C     GOTO 124
C321  CONTINUE
C
C
      NN=NN+1
      J=PP(NN)/10
      UNIT=PP(NN)-J*10
      NI(T2)=NI(T2)+Q(J)
      NP(J,T2)=NP(J,T2)+1
124   CONTINUE
      CALL CAPTL(J,UNIT,YR,CX,OCST,1,DR)
      CALL FUEL(T2,C(J,3),AFC,RERF(J),DR)
```

```
      IF(J .EQ. 2) AFC=AFC*.60
      IF(J .EQ. 3) AFC=AFC*.371
      IF(DR .EQ. 0.0) GOTO 56
      AEC=CX*(DR*(1+DR)**LT)/((1+DR)**LT-1)
      GOTO 58
 56   AEC=CX/LT
 58   CONTINUE
      DO 36 NT2=T2,T1
         AC(NT2)=AC(NT2)+AEC
         AC(NT2)=AC(NT2)+AFC
         AC(NT2)=AC(NT2)+OCST
 36   CONTINUE
      PREW(J)=PREW(J)+Q(J)*K(J)
      IF(NI(T2) .LE. YAD/K(J)) GOTO 33
      SURPUS=NI(T2)-YAD/K(J)
      PREW(J)=PREW(J)-SURPUS*K(J)
      AC(T2)=AC(T2)-SURPUS*AFC
      GO TO 38
 35   CONTINUE
C
C THERE IS SURPLUS OF CAPACITY
C NO NEW PLANT IS REQUIRED
C
      AC(T2)=AC(T2)-SURPUS*AFC
      AC(T2)=AC(T2)+YAD*AFC
      SURPUS=SURPUS-YAD/K(J)
      PREW(J)=PREW(J)+YAD
 38   CONTINUE
      AC(T2)=AC(T2)+G(1,T2)*OCSTO/Q(1)/3.
      AC(T2)=AC(T2)+G(1,T2)*K(1)*AFCO
      W(1)=W(1)+G(1,T2)*K(1)
      PREW(1)=G(1,T2)*K(1)
      GOTO 39
 31   CONTINUE
C
C NEGATIVE D(T2) MEANS SUPPLY IS HIGHER THAN DEMAND
C NO PLANT TO BE COMMENCED IN THAT YEAR
C COSTS ARE ICCURRED FROM EXISTING PLANTS ONLY
C
      YAD=0.0
      AC(T2)=AC(T2)+G(1,T2)*(AECO+OCSTO)/Q(1)/3.
      AC(T2)=AC(T2)+GD(T2)*AFCO
      PREW(1)=GD(T2)
      W(1)=W(1)+GD(T2)
 39   CONTINUE
       W(2)=W(2)+PREW(2)
       W(3)=W(3)+PREW(3)
       USDUM=AC(T2)+PREW(1)*C(1,4)+PREW(2)*C(2,4)
             +PREW(3)*C(3,4)
       SUMNI=SUMNI+NI(T2)
       CAP=(SUMNI+G(1,T2))*.8
       SUMPRW=PREW(1)+PREW(2)+PREW(3)
       US=US+USDUM/(1+DR)**T2
       PX(T2)=T2
```

```
C       WRITE(6,FREEIO) T2,YR,D(T2),YAD,AC(T2),NI(T2),
C      , NP(2,T2),NP(3,T2),
C      , GD(T2),G(1,T2),SURPUS,PREW(1),PREW(2),PREW(3),
C      , W(1),W(2),W(3),
C      , USDUM,US,YAD,SUMNI,SUMPRW,CAP,PX(T2)
        PY1(T2)=CAP
        FIT=(CAP-GD(T2))+FIT
 30     CONTINUE
       VINCRE=3.0
        IF(D1 .EQ. 3) VINCRE=6.0
        AUTO=8
C
C PLOT THE SUPPLY AND DEMAND
C         CALL CGPL2(PX,PY1,T1,1,4,0.0,AUTO,4.0,2.0,
C     ,VINCRE,3.0,ALPH)
C         CALL CGPL2(PX,GD,T1,2,14,0.0,AUTO,4.0,2.0,
C     ,VINCRE,3.0,ALPH)
C         CALL CGPL2(PX,B,T1,3,34,0.0,AUTO,4.0,2.0,
C     ,VINCRE,3.0,ALPH)
C         CALL CGPL2(PX,B,T1,0,2,0.0,AUTO,4.0,2.0,
C     ,VINCRE,3.0,ALPH)
C
        UU=0.0
       DO 70 T2=1,T1
         UU=UU+AC(T2)/(1+DR)**T2
 70     CONTINUE
C
       IF(C5 .NE. 1) CALL SCRO
       IF(C8 .NE. 2) CALL SCRO
        C6 = W(1) + W(3)
        DO 71 KZ=1,T1
        C7 = NP(3,KZ) + NP(1,KZ) + C7
71      C20=NP(2,KZ)+C20
       DOUT(1,P2-1)=UU
       DOUT(2,P2-1)=US
       DOUT(3,P2-1)=FIT
       DOUT(4,P2-1)=C6
       DOUT(5,P2-1)=C7
       DOUT(6,P2-1)=W(2)
       DOUT(7,P2-1)=C20
       IF(P2 .NE. 6) GO TO 461
        WRITE(6,198)
198     FORMAT(/, 40X,'PERCENTAGE OF NUCLEAR IN THE
      , PLANT MIX',
      ,        /,37X,' 0 ',10X,'25',10X,'50',10X,'75',9X,
      ,'100')
       WRITE(6,462)DOUT(1,2),DOUT(1,4),DOUT(1,3),DOUT(1,5),
      ,DOUT(1,1)
462    FORMAT(/,2X,'TOTAL ECONOMIC COST (MILLION)',5F12.4)
       WRITE(6,463)DOUT(2,2),DOUT(2,4),DOUT(2,3),DOUT(2,5),
      ,DOUT(2,1)
463    FORMAT(1X,'TOTAL COST (MILLION)',5F12.4)
       WRITE(6,464)DOUT(3,2),DOUT(3,4),DOUT(3,3),DOUT(3,5),
      ,DOUT(3,1)
```

```
 464    FORMAT('SUM OF SUPPLY MINUS DEMAND GW ', 5F12.4)
        WRITE(6,465)DOUT(4,2),DOUT(4,4),DOUT(4,3),DOUT(4,5),
       ,DOUT(4,1)
 465    FORMAT(/,1X,'TOTAL ELECT GNTED BY COAL GWY ',5F12.4)
        WRITE(6,466)DOUT(5,2),DOUT(5,4),DOUT(5,3),DOUT(5,5),
       ,DOUT(5,1)
 466    FORMAT(1X,'TOTAL NEW COAL UNITS ADDED',4X,5F12.4)
        WRITE(6,467)DOUT(6,2),DOUT(6,4),DOUT(6,3),DOUT(6,5),
       ,DOUT(6,1)
 467    FORMAT(/,1X,'TOTAL ELECT GNTED BY NUC GWY  ',5F12.4)
        WRITE(6,468)DOUT(7,2),DOUT(7,4),DOUT(7,3),DOUT(7,5),
       ,DOUT(7,1)
 468    FORMAT(1X,'TOTAL NEW NUC UNIT ADDED',6X,5F12.4)
        WRITE(6,469)DR,RERF(1),RERF(2)
 469    FORMAT(//,
       ,8X,'THE DISCOUNT RATE..........................',
       ,F10.5,/,
       ,8X,'THE REAL ESCALATION RATE FOR COAL FUEL.....',
       ,F10.5,/,
       ,8X,'THE REAL ESCALATION RATE FOR NUCLEAR FUEL..',
       ,
     F10.5,/)
 461    CONTINUE
        CALL SCRO
        RETURN
        END
C
C
C
        SUBROUTINE CSTC
C
C THIS SUBROUTINE READS THE INITIAL COST CONSTANTS OF
C THE RUN.
C
        LOGICAL*1 FREEIO(1)/'*'/
        REAL F(11),A(4,3),V(4,31),B(31),C(4,10),D(31),
       ,   G(4,31),H(4),K(4),M(4,45),N(4,31),P(4,31),
       ,   R(7),Y(4,31),Z(4,31),U(4,7),X(4,31),W(4)
        INTEGER O(2,2),S(16,11),C1,C2,C3,C5,C8,C9,I1,J1,
       ,   T1,T2,T3,T9,P2,R2,R9,B7,S1,S2,S3,S4,D1,PP(100)
C
        COMMON /VALUES/ F,A,V,B,C,D,G,H,K,M,N,P,
       ,   R,Y,Z,U,X,W,S,O,PP,
       ,   C1,C3,C5,C8,C9,J1,I1,T1,T3,
       ,   R1,R9,P2,Z0,Z1,Z3,Z4,D1,D0,IBASY
C
        IF(C5 .EQ. 0) GO TO 31
        IF(C5 .EQ. 1) GO TO 11
C
        S1 = S(C6,1)+1
        DO 10 S2 = 2,S1
           S3 = S(C6,S2)
           S4 = S(C6,S2+5)
           C(S3,S4) = C(S3,S4) / F(C6)
```

```
 10    CONTINUE
C
 11    CONTINUE
      C6 = C5
      C5 = C5+1
      IF(C6 .GT. I1+2) GO TO 31
      IF(C6 .LT. I1+1) GO TO 12
      Z3 = Z3*2.
      RETURN
 12    CONTINUE
      S1 = S(C6,1)+1
      DO 20 S2 = 2,S1
         S3 = S(C6,S2)
         S4 = S(C6,S2+5)
         C(S3,S4) = C(S3,S4)*F(C6)
 20    CONTINUE
      RETURN
 31    CONTINUE
      C8 = C8+1
      IF(C8 .GT. C9+1) STOP
      DO 40 J = 1,J1
         READ(5,FREEIO)(C(J,C2),C2=1,C1)
 40   CONTINUE
C
      IF(C8 .LE. 2) GO TO 41
      I1 = 1
 41   READ(5,FREEIO)Z0,Z1,Z3,Z4
      C5 = 1
      RETURN
      END
C
C
C
      SUBROUTINE SCRO
C
C SCRO CALCULATES COST RATIOS OF POSSIBLE CASES.
C SUBROUTINE RSCH CALCULATES THE COST OF RESEARCH
C FOR NEW TECHNOLOGY, N/A IN ALBERTA
C
      LOGICAL*1 FREEIO(1)/'*'/
      REAL F(11),A(4,3),V(4,31),B(31),C(4,10),D(31),
     ,   G(4,31),H(4),K(4),M(4,45),N(4,31),P(4,31),
     ,   R(7),Y(4,31),Z(4,31),U(4,7),X(4,31),W(4)
      INTEGER O(2,2),S(16,11),C1,C2,C3,C5,C8,C9,I1,J1,
     ,   T1,T2,T3,T9,P2,R2,R9,B7,S1,S2,S3,S4,D1,TC,PP(100)
C
      COMMON /VALUES/ F,A,V,B,C,D,G,H,K,M,N,P,
     ,   R,Y,Z,U,X,W,S,O,PP,
     ,   C1,C3,C5,C8,C9,J1,I1,T1,T3,
     ,   R1,R9,P2,Z0,Z1,Z3,Z4,D1,D0,IBASY
C
496     P2 = P2+1
        IF(P2 .GT. 11) CALL VARC
        IF(P2 . EQ. 1) GOTO 496
```

```
C
C DELETE NOT SUITABLE SCENARIO
C
      IF(P2 .GT. 1) GO TO 20
      WRITE(6,444)
444   FORMAT(/,2X,'ALL NUCLLEAR TO NEW TECH SCENARIO N/A
     , ALBERTA')
      TC=6
C
      DO 10 T2 = TC,T1
         P(3,T2) = 0.
         IF(T2 .GT. T1/2) GO TO 11
         P(2,T2) = 1.
         P(4,T2) = 0.
         GO TO 10
 11      P(2,T2) = 1. - FLOAT(T2/T1)
         P(4,T2) = FLOAT(T2/T1)
 10    CONTINUE
       CALL VARC
C
 20    CONTINUE
       IF(P2 .GT. 2) GO TO 30
C
C 1ST DIGIT PLANT TYPE
C 2ND DIGIT UNIT
C
 445  FORMAT(/,2X,'ALL NUCLEAR')
       TC=7
       DO 802 T2=1,100,2
       PP(T2)=21
       PP(T2+1)=22
 802   CONTINUE
      CALL VARC
C
 30    CONTINUE
      IF(P2 .GT. 3) GO TO 40
C      WRITE(6,446)
446   FORMAT(/,2X,'ALL FOSSIL')
      DO 31 T2 = 1,99,3
       PP(T2)=31
       PP(T2+1)=32
       PP(T2+2)=33
 31   CONTINUE
      CALL VARC
C
 40   CONTINUE
       IF(P2 .GT. 4) GO TO 50
C      WRITE(6,447)
447   FORMAT(/,2X,'HALF NUCLEAR, HALF FOSSIL')
       DO 803 T2=1,100,5
       PP(T2)=21
       PP(T2+1)=22
       PP(T2+2)=31
       PP(T2+3)=32
```

```
      PP(T2+4)=33
 803  CONTINUE
      CALL VARC
C
 50   CONTINUE
      IF(P2 .GT. 5) GO TO 60
C     WRITE(6,448)
448   FORMAT(/,2X,'1/4 NUCLEAR AND 3/4 FOSSIL')
      DO 804 T2=1,99,11
      PP(T2)=21
      PP(T2+1)=22
      PP(T2+2)=31
      PP(T2+3)=32
      PP(T2+4)=33
      PP(T2+5)=31
      PP(T2+6)=32
      PP(T2+7)=33
      PP(T2+8)=31
      PP(T2+9)=32
      PP(T2+10)=33
 804  CONTINUE
      CALL VARC
C
 60   CONTINUE
      IF(P2 .GT. 6) GO TO 70
C     WRITE(6,449)
449   FORMAT(/,2X,'3/4 NUCLEAR AND 1/4 FOSSIL')
      DO 805 T2=1,99,9
      PP(T2)=21
      PP(T2+1)=22
      PP(T2+2)=21
      PP(T2+3)=22
      PP(T2+4)=31
      PP(T2+5)=32
      PP(T2+6)=33
      PP(T2+7)=21
      PP(T2+8)=22
 805  CONTINUE
      DO 61 T2 = TC,T1
         P(2,T2)  =  .75
         P(3,T2)  =  .25
         P(1,T2)=0
 61   CONTINUE
      CALL VARC
C
 70   CONTINUE
      IF(P2 .GE. 7) GOTO 800
      WRITE(6,450)
450   FORMAT(/,2X,'NUC,NEW TECH FAIL,COAL  N/A TO ALBERTA')
      DO 71 T2 = 1,T1
         IF(FLOAT(T2/T1) .GE. .5) GO TO 72
         P(2,T2)  =  1.
         P(3,T2)  =  0.
          GO TO 71
```

```
 72         P(2,T2) = 1. - FLOAT(T2/T1)
            P(3,T2) = FLOAT(T2/T1)
 71       CONTINUE
         CALL VARC
C
 80       CONTINUE
         IF(P2 .GE. 8) GO TO 90
         WRITE(6,451)
451      FORMAT(/,2X,'COAL WITH NEW TECH FAIL N/A ALBERTA')
         DO 81 T2 = 1,T1
            P(3,T2) = 1.
            P(2,T2) = 0.
  81     CONTINUE
         CALL VARC
C
 90       CONTINUE
         IF(P2 .GE. 9) GO TO 100
         WRITE(6,452)
452      FORMAT(/,2X,'1/2 NUCLEAR & 1/2 COAL TO NEW TECH N/A
        ,TO ALBERTA')
         DO 91 T2 = 1,T1
         IF(T2 .GT. FLOAT(T1/2)) GO TO 92
            P(2,T2) = .5
            P(3,T2) = .5
            P(4,T2) = 0.
            GO TO 91
 92         P(3,T2) = .5 - .5*FLOAT(T2/T1)
            P(2,T2) = P(3,T2)
            P(4,T2) = FLOAT(T2/T1)
 91         CONTINUE
         CALL VARC
C
 100        CONTINUE
         IF(P2 .GE. 10) GO TO 191
         WRITE(6,453)
453      FORMAT(/,2X,'1/4 NUCLEAR TO NEW TECH N/A TO ALBERTA')
         DO 101 T2 = 1,T1
            IF(T2 .GE. FLOAT(T1/2)) GO TO 102
            P(2,T2) = .25
            P(3,T2) = .75
            GO TO 101
 102        P(3,T2) = .75 * (1. - FLOAT(T2/T1))
            P(2,T2) = .25 *(1. - FLOAT(T2/T1))
            P(4,T2)=FLOAT(T2/T1)
 101      CONTINUE
         CALL VARC
C
 110      CONTINUE
         WRITE(6,454)
454      FORMAT(/,2X,'3/4 NUCLEAR TO NEW TECH N/A TO ALBERTA')
         DO 111 T2 = 1,T1
            IF(T2 .GE. FLOAT(T1/2)) GO TO 112
            P(2,T2) = .75
            P(3,T2) = .25
```

```
          GO TO 111
 112      P(3,T2) = .25 *(1. - FLOAT(T2/T1))
          P(2,T2) = .75 *(1. - FLOAT(T2/T1))
          P(4,T2)=FLOAT(T2/T1)
 111    CONTINUE
 191    CONTINUE
        CALL VARC
 800    D1=D1+1
        CALL NO3
        RETURN
        END
C
C
C
C
        SUBROUTINE CAPTL(J,U,YR,RCPCYN,AOCYN,NYAC,DICN)
        LOGICAL*1 FREEIO(1)/'*'/
C
C THIS SUBROUTINE CAN ESTIMATE  THE CAPITAL COST OF A
C POWER PLANT WHEN THE YEAR OF COMMISSION AND
C THE FLAT CAPITAL COST IN JAN 1982 DOLLARS ARE GIVEN.
C THIS ESTIMATE WILL INCLUDE THE REAL ESCALATION
C RATE. THE OPERATING AND MAINTENANCE COST
C IS ALSO ESTIMATED IN REAL TERM JAN 1982 DOLLARS
C
C
C J.......Plant type 1=coal,  2=Nuclear
C U.......plant unit, 3 units in coal power station
C         2 units of Nuclear station
C RCPCYN..Real capital cost in year n
C AOCYN...annual operation & maintenance cost including
C         property tax
C NYAC....Number of years after commission
C DICN....Discound rate
C RLER....Real labour escalation rate from 1981
C CPI.....Consumer price indix from 1981
C CF21....Cash flowrate for unit 1 of nuclear,2
C CF( , ).Cash flowrate (plant type J, unit U)
C CF12....Cash flowrate for unit 2 of coal 1
C CER.....Construction escalation rate from 1981
C RCER....Real construction escalation rate, same for
C         all years
C AFUDC...Allowance for fund used during construction in
C          percent of total capital
C FCC.....one time capital cost in Jan 1982 dollars
C HWC.....cost of heavy water which goes to capital cost at
C         the end of construction
C FUELC...Fuel cost (nuclear), half of its intial charge
          is capitalized
C A.......Annual equivalent operation and maintenance cost
C         capitalized at the end of construction
C NCY.....Number of years required  for construction
C         (plant type,unit)
C LT......Service life time of a plant, 35 years
```

```
C LABOC...Labour cost (plant type, unit)
C STP.....Study period in years, 30
C MATOC...Material charges in operation cost
C         (plant tupe, unit)
C RPT.....Real peroperty tax in percent of total
C         capital cost
C         added to annual operation cost
C CPLCYN..Capital cost in year n
C RCPCYN..Real capital cost in year n
C P.......Total O&M for the whole service life of the
C         plants
      DIMENSION CF(2,3,10),CER(100),RLER(200),CPI(200),
     , RPT(2),
     , NCY(2,3),FCC(2),CF11(10),CF12(10),CF13(10),
     , CF21(10),CF22(10)
      REAL LABOC(2,3),MATOC(2,3)
      INTEGER STP,YR,U
      DATA RLER/1.0,.99,.99,1.0,1.0,1.01/
      DATA CPI/1.0,1.105,1.088,1.079,1.066,1.069/
      DO 7 N=7,200
      CPI(N)=1.069
 7    RLER(N)=1.01
C
C CAPITALIZE THE NUCLEAR FUEL AND HEAVY WATER COST
C       BY INCLUDING HALF OF THEIR COSTS
C       DUE TO INITIAL CHARGING OF THE SYSTEM
C
      FUELC=18.0/2.0
      HWC=281.0/2.0
      DATA CF22/.0609,.0966,.13583,.09224,.06/
      DO 15 I=1,5
         CF(2,2,I)=CF22(I)
 15   CONTINUE
      DATA CF21/.01,.02,.03,.06,.109,.15342,.10419,.06771/
      DO 16 K=1,8
         CF(2,1,K)=CF21(K)
 16   CONTINUE
      DATA CF11/.01,.03,.09,.1776,.0876,.04/
      DO 17 I=1,6
         CF(1,1,I)=CF11(I)
 17   CONTINUE
      DATA CF12/.0824,.09,.07,.04/
      DO 18 I=1,4
         CF(1,2,I)=CF12(I)
 18   CONTINUE
      DATA CF13/.0824,.09,.07,.04/
      DO 19 I=1,4
         CF(1,3,I)=CF13(I)
 19   CONTINUE
      DATA CER/1.0,1.122,1.104,1.095,1.082,1.085/
      DO 5 N=7, 200
 5       CER(N)=1.085
      RCER=1.015
      AFUDC=.12
```

```
      FCC(1)=942.0
      FCC(2)=1780.0 -FUELC*2.0-HWC*2.0
      NCY(2,1)=8
      NCY(2,2)=5
      NCY(1,1)=6
      NCY(1,2)=4
      NCY(1,3)=4
      LABOC(2,1)=10.6
      LABOC(2,2)=4.4
      MATOC(2,1)=6.3
      MATOC(2,2)=5.0
C
C LABOC IS 60% OF TOTAL O&M COST
C MATOC IS 40% OF TOTAL O&M COST (COAL ONLY)
C O&M COST INCLUDES FGD
C
      LABOC(1,1)=.6*6.0
      LABOC(1,2)=.6*6.0
      LABOC(1,3)=.6*6.0
      MATOC(1,1)=.4*6.0
      MATOC(1,2)=.4*6.0
      MATOC(1,3)=.4*6.0
      RPT(1)=.0135
      RPT(2)=.011
C     WRITE(6,111)
 111  FORMAT(/,'PLANT TYPE,UNIT #, YR, YR AFTER
     , COMMISSION?',/)
C      READ(5,1)J,U,YR,NYAC
      IF(J .EQ. 3) J=1
 1    FORMAT(4I5)
C
C ESTIMATE THE CAPITAL COST COMMISSIONED IN YEAR YR
C
      CPLCYN=0.0
      NY=YR-NCY(J,U)-1981
      NCDUM=NCY(J,U)
      DO 20 N=1,NCDUM
         TEM1=FCC(J)*CF(J,U,N)*(1+AFUDC)**(NCY(J,U)-N)
C     WRITE(6,109) CF(J,U,N)
 109  FORMAT(F10.5)
      NNN=N+NY
         DO 21 NN=1,NNN
 21      TEM1=TEM1*CER(NN)
 20   CPLCYN=CPLCYN+TEM1
C
C FOR NUCLEAR THE HEAVY AND FUEL COST WERE ADDED TO
C THE CAPITAL
C AT THE END AFTER THEY WERE ESCALATGED
C
      TEMP2=0.0
      IF(J .NE. 2) GO TO 30
      TEMP2=HWC+FUELC
      NNY=YR-1981
      DO 30 N1=1,NNY
```

```
      TEMP2=TEMP2*CPI(N1)
30    CONTINUE
      CPLCYN=CPLCYN+TEMP2
C
C CAPITAL COST IN REAL TERM
C
      RCPCYN=CPLCYN
      NN=NY+NCY(J,U)
      DO 23 N=1, NN
 23   RCPCYN=RCPCYN/CPI(N)
C
C ESTIMATE THE OPERATING AND MAINTENANCE COST
C
      LT=35
      STP=30
      SAA=0.0
      SBB=0.0
      NN=YR+NYAC-1981
      DO 24 N=1,NN
 24      LABOC(J,U)=LABOC(J,U)*RLER(N)
C     WRITE(6,101)LABOC(J,U)
      DO 22 N=1, LT
         AA=1/(1+DICN)**N
         BB=(RLER(N+NN+1)/(1+DICN))**N
         SAA=SAA+AA
 22   SBB=SBB+BB
      P=LABOC(J,U)*SBB+MATOC(J,U)*SAA
C     WRITE(6,101)P
      IF(DICN .EQ. 0.0) GOTO 55
      A=P*DICN*(1+DICN)**N/((1+DICN)**N-1)
      GOTO 57
 55   A=P/LT
 57   CONTINUE
C     WRITE(6,101)A
 101  FORMAT(/,F10.5,/)
      AOCYN=0.0
C
C INCLUDING PROPERTIES TAXES
C
      DO 114 N=1,LT
      AOCYN=AOCYN + RCPCYN*RPT(J)/(1+DICN)**N
114   CONTINUE
      AOCYN=AOCYN*DICN*(1+DICN)**LT/((1+DICN)**LT-1)
       AOCYN=A+AOCYN
C     WRITE(6,104)U,J
 104 FORMAT(/,'FOR UNIT',I2,'AND PLANT TYPE',I2)
C      WRITE(6,102) CPLCYN,RCPCYN,YR
 102  FORMAT(/,
     , 'THE CAPITAL COST IN CURRENT DOLLAR = ',F10.5,
     , ' MILLION',/,
     , '                       IN 82  DOLLAR = ',F10.5,
     , ' MILLION',/,
     , '      WHEN THE PLANT COMMISSIONED IN.',I5,/)
C     WRITE(6,103) AOCYN,NYAC,YR
```

```
 103   FORMAT(/,
     , 'THE OPERATING AND MAINTENANCE COST IN 82 DOLLAR
     ,= ',F10.5,
     , ' MILLION',/,
     , '      AFTER',I5,'  YEARS OF THE PLANT COMMISSIONED
     , IN',I6,/)
C
C FOR UNIT COST ANALYSIS, CHANGE J=3 TO J=1
C
       IF(J .EQ. 1) J=3
       RETURN
       END
C
C
C
C
C
       SUBROUTINE FUEL(T2,BFC,AFC,B,D)
       DIMENSION FC(200)
C      INTEGER T2
C
       DO 100 N=1,200
          FC(N)=BFC*(1.0+B)**N
 100   CONTINUE
C
       A=0.0
C
       DO 200 N=1,35
          A=FC(T2+N)/(1+D)**N+A
 200   CONTINUE
       AFC=A*D*(1+D)**35/((1+D)**35-1)
C
C       WRITE(6,103) AFC
 103   FORMAT(//,2X,F10.5)
       RETURN
       END
```

```
C
C TO FIND THE LEVELIZED UNITS COSTS IN MILL/KWH
C       ONLY FOR NEW PLANTS
C
        DIMENSION Q(2),SOCC(2),B(2),FC(2),PEC(2),PECL(2)
        INTEGER UNIT(2),YR,YN,TEMPYR,C,X(100)
        DATA Q/0.371,0.6/
C       DATA SOCC/12.46,0.0/
        DATA SOCC/6.013,1.723/
C       DATA SOCC/0.0,0.0/
        DATA B/0.015,0.0/
C       DATA B/0.010,0.0/
C       DATA B/0.020,0.0/
C       DATA B/0.0348,0.0/
        DATA FC/63.68,41.46/
        DATA UNIT/3,2/
        DATA PECL/0.0,0.0/
        DICN=0.06
C       DICN=0.02
C       DICN=0.04
C       DICN=0.08
C       YR=1982
        YR=1990
C
C LT SERVICE LIFE OF POWER PLANT
C
C       LT=30
        LT=35
        F=.8
        DICN1=DICN*(1+DICN)**LT/((1+DICN)**LT-1)
        WRITE(6,14)SOCC(1),SOCC(2),DICN,B
 14     FORMAT(4F14.6)
        DO 16 KX=1,200
C
        DO 2 J=1,2
        YN=YR-UNIT(J)+1
        PEC(J)=0.0
        N=UNIT(J)
        AC=0.0
        DO 3 NN=1,N
        CALL CAPTL(J,NN,YN,RCPCYN,AOCYN,0,DICN)
C          WRITE(6,26)J,NN,YN,RCPCYN,AOCYN
C26        FORMAT(3I6,2F14.6)
        XX=RCPCYN+SOCC(J)*Q(J)*F
        IF(J .EQ. 1) NYYR=1982
        IF(J .EQ. 2) NYYR=1990
        YY=FC(J)*(1.0+B(J))**(YN-NYYR)*Q(J)*F
        PEC(J)=PEC(J)+XX+YY
        TEMPYR=YN
        AC=AC+AOCYN
C
```

```
      K1=LT-1
      DO 4 K=1,K1
      TEMPYR=TEMPYR+1
      XX=SOCC(J)*Q(J)*F
      IF(J .EQ. 1) NYYR=1982
      IF(J .EQ. 2) NYYR=1990
      YY=FC(J)*(1.0+B(J))**(TEMPYR-NYYR)*Q(J)*F
      PEC(J)=PEC(J)+(XX+YY)/(1+DICN)**(TEMPYR-YN)
 4    CONTINUE
C
      YN=YN+1
C
 3    CONTINUE
      PEC(J)=PEC(J)*DICN1+AC/UNIT(J)/Q(J)/F
      PECL(J)=PEC(J)/Q(J)/UNIT(J)/F
      PECL(J)=PECL(J)*0.1142
C
C 0.1142 is the conversion factor from million dollars
C     to mills per kwh
C
 2    CONTINUE
C      WRITE(6,10) YR,PECL(1), PECL(2)
C10   FORMAT(I10, 2F14.6)
C
C     IF(PECL(1) .GT. PECL(2)) GOTO 17
      IF(PECL(1) .GT. PECL(2)) WRITE(6,23)
 23   FORMAT(2X,'*')
      YR=YR+1
      IF(YR .EQ. 2060)GOTO 17
 16   CONTINUE
 17   CONTINUE
      RETURN
      END
```

Appendix four

A sample data output from total cost analysis. Base case.

	COST CONSTANT CAPITAL COST MLN DLR/STN	O&M COST MLN DLR/STN	FUEL COST MLN DLR/GWY	SOCIAL COST MLN DLR/GWY
EXISTING COAL PLANT	789.00000	13.90000	64.01999	13.04900
NUCLEAR PLANT	1780.00000	26.30000	41.46001	1.07800
NEW COAL PLANT	942.00000	18.00000	64.01999	13.04900

BASE CASE DEMAND GROWTH

	PERCENTAGE OF NUCLEAR IN THE PLANT MIX 0	25	50	75	100
TOTAL TRADITIONAL COST (MILLION)	11127.3125	11168.3477	11251.1992	11293.0352	11424.4297
TOTAL COST (MILLION)	11941.0195	11968.2539	12014.5039	12034.5391	12108.6133
SUM OF SUPPLY MINUS DEMAND GWY	6.8363	7.3235	7.5211	7.7371	8.1691
TOTAL ELECT GNTED BY COAL GWY	154.6329	149.0299	136.9217	128.8177	111.8368
TOTAL NEW COAL UNITS ADDED	17.0000	14.0000	9.0000	6.0000	0.0
TOTAL ELECT GNTED BY NUC GWY	0.0	5.6031	17.7112	35.8152	42.7961
TOTAL NEW NUC UNIT ADDED	0.0	2.0000	5.0000	7.0000	11.0000

THE DISCOUNT RATE 0.06000
THE REAL ESCALATION RATE FOR COAL FUEL 0.01500
THE REAL ESCALATION RATE FOR NUCLEAR FUEL .. 0.0

DEMAND AT 4% COMPOUND ANNUAL GROWTH

	PERCENTAGE OF NUCLEAR IN THE PLANT MIX 0	25	50	75	100
TOTAL TRADITIONAL COST (MILLION)	9508.4727	9553.5625	9632.3125	9667.3203	9723.9414
TOTAL COST (MILLION)	10178.9258	10215.8789	10272.1250	10293.7891	10315.5430
SUM OF SUPPLY MINUS DEMAND GWY	16.2709	17.0293	17.7253	18.0293	18.2269
TOTAL ELECT GNTED BY COAL GWY	130.6550	127.1281	118.7810	113.3632	101.3869
TOTAL NEW COAL UNITS ADDED	16.0000	13.0000	9.0000	6.0000	0.0
TOTAL ELECT GNTED BY NUC GWY	0.0	3.5270	11.8741	17.2919	29.2681
TOTAL NEW NUC UNIT ADDED	0.0	2.0000	5.0000	6.0000	10.0000

THE DISCOUNT RATE.......................... 0.06000
THE REAL ESCALATION RATE FOR COAL FUEL..... 0.01500
THE REAL ESCALATION RATE FOR NUCLEAR FUEL.. 0.0

DEMAND AT 3% LOG

	PERCENTAGE OF NUCLEAR IN THE PLANT MIX 0	25	50	75	100
TOTAL TRADITIONAL COST (MILLION)	16316.3359	16434.5039	16632.9570	16782.2891	17052.7734
TOTAL COST (MILLION)	17371.6094	17417.8516	17515.4453	17583.7500	17738.7539
SUM OF SUPPLY MINUS DEMAND GWY	8.5876	9.0524	9.8908	10.5644	11.3844
TOTAL ELECT GNTED BY COAL GWY	233.0173	207.2854	174.0459	146.0636	110.1268
TOTAL NEW COAL UNITS ADDED	52.0000	39.0000	26.0000	13.0000	0.0
TOTAL ELECT GNTED BY NUC GWY	0.0	25.7320	58.9714	86.9537	122.8906
TOTAL NEW NUC UNIT ADDED	0.0	8.0000	16.0000	24.0000	32.0000

THE DISCOUNT RATE.......................... 0.06000
THE REAL ESCALATION RATE FOR COAL FUEL..... 0.01500
THE REAL ESCALATION RATE FOR NUCLEAR FUEL.. 0.0

Appendix five

A.5.1

The cost conversion factors for health cost estimates

Cost per death:

	cost per death	for
Hill[1977, p.iii]	$1,000,000 (1977 CD)	Ontario
Barrager[1976, p.36]	$300,000 (1975 USD)	United states
Kim[1982 p.103]	$300,000 (1978 CD)	Ontario

Note:

Hill considers $1,000,000 for death is higher than usually used.

Inhaber converts deaths, illnesses, and injuries into man-days lost, but no specific cost for man-day lost is given. Inhaber[1978, p.19,20] assumes that 6000 Man-days lost for a death and 100 Man-days lost per nonfatal cancer. Kim[1981, p.103], however, quotes Inhaber's report to AECB as 1 man-day lost = $50 (1978 CD)

USD is the United States dollars

CD is Canadian dollars

The social background and the health care system, though different from those of Alberta, are close enough for the purposes of this cost estimation to assume that these estimates are representative figures for Alberta. They are converted to 1982 Canadian dollars and the average of them is the cost per death assumed for Alberta.

The calculation is shown as follows:

$$\frac{1}{3}\left[1.0 \times \frac{110.8^{*}}{68.0} + .3 \times \frac{287.1^{**}}{161.2} \times \frac{1}{.8071''} + .3 \times \frac{110.8^{*}}{74.1}\right]$$

= 0.913 Million 1982 CD

Note: * is the Consumer Price Index, CPI, for Canada listed in A.5.3.

** is the CPI for the United States listed in A.5.3.

" is the ratio of Canadian to United States dollars in 1982 listed in A.5.4.

Cost for a case of illness:

	Cost for a case of illness	for
Hill[1977]	no estimates	
Barrager et al[1976 P.36]		United States
illness	$3,000	
genetic effects	$10,000	
	(1975 USD)	
Kim[1982, p.103]	$5,000 (1978 CD)	Ontario

There are many kinds of illnesses. The social cost of an illness differs from case to case. In this thesis, the average cost of all cost estimates on illnesses is assumed to be the representative figure for all types of illnesses.

The cost for a case of illness in Alberta is assumed to be the average of the above cost estimates, updated to 1982 dollar value

$$\frac{1}{3}\left[(3.0+10.)\times\frac{287.1}{161.2}\times\frac{1}{.8071} + 5.0\times\frac{110.8}{74.1}\right]\times 10^{3}$$

$$= \$12,054 \text{ (1982 CD)}$$

Cost for an injury day :

	Cost for an injury day	for
Hill[1977, p.iii]	$100 (1977 CD)	Ontario
Kim[1981, p.103]	$ 50 (1978 CD)	Ontario

Note: Barrager et al did not have this classification.

Similarly to the cost for a case of illness, the cost for an injury day in Alberta is assumed to be the average of above cost estimates. That is

$$\frac{1}{2}\left[100 \times \frac{110.8}{68.0} + 50 \times \frac{110.8}{74.1}\right]$$

$$= \$118.85 \text{ (1982 CD)}$$

Summary :

	social cost per (1982 CD)
death	$913,000.00
illness	$12,054.00
injury day	$118.85

Note: Although the dollar value is not expressed in the January price level, but it is assumed to be so for it varies by a very small amount.

A.5.2

The estimation of social costs due to electricity generation in Alberta

Health cost due to normal operation of CANDU power plants in Alberta:

Derived from Hill [1977]

Hill's estimates are for the whole fuel cycle. In this thesis nuclear fuel is assumed to be imported to Alberta. The social costs due to mining, and processing are excluded from Hill's estimates leaving damages due to conversion of coal into electricity (power plant operation) and transportation.

The estimates for Alberta derived from Hill[1977, p. 5.40 and 5.41] are

for 1000 Mwe plant-year

	deaths	injury days
public	0.012 → 0.259	60
occupational	0.060 → 0.120	200 → 460
total	0.072 → 0.379	260 → 460

Using the cost conversion factors for death and injury day and normalized into GweY for capacity factor of 0.8.

The cost estimates
=[(0.072 → 0.379)x913,000+(260 → 460)x118.85]/.8
=$(120,796 → 500,872) per GweY

Assuming the estimates within the range are uniformly distributed, the expected health cost is (120,796+500,872)/2 =0.311 million dollars/GweY or M/GweY (1982 CD) and the standard deviation of this expected value is

$$\sqrt{\left[\frac{1}{12}(500,872-120,796)^2\right]} = 0.110$$

Note: If the following cost estimates are expressed in a range form, the expected value of the social cost and its standard deviation are calculated in the same way as above.

For the same dollar value, one M/GweY is equal to 0.1142 mills per kwh.

Derived from Barrager et al[1976]

Barrager et al did not have estimates in terms of physical health damages, i.e. number of deaths, illnesses and injury days, but in terms of cost only. There is no breakdown of costs into number of deaths and injury days. The physical health damage is not able to be calculated although costs per death and per injury day were given. Barrager et al's health cost estimate, leaving accident, diversion, and sabotage, is 0.0121 mills/kwh (1975 United States dollars, USD, Barrager et al, 1976, p.49) but it is for the whole fuel cycle. In this thesis, no nuclear fuel mining, milling, enrichment, fabrication and reprocessing are assumed in the Alberta nuclear fuel cycle. That is social costs are due to conversion and transportation only. Assuming the social costs due to the normal operation of both CANDU (CANDU pressurized heavy water reactor) and LWR (light water reactor) nuclear power plants are similar (Hill, 1977, p. 5.40) and assuming Low level radiation and occupational hazard related to normal operation of nuclear power plants in Alberta are the major factors of health cost estimates. The health cost estimates for Alberta taken from the illustrative data of Barrager et al [1976, p.49] is estimated to be 0.0013 mills/kwh (1975 USD).

The cost breakdown are as follows:

	mills/kwh (1975 USD)
fuel transport	0.00003
reactor	0.00113
spent fuel transport	0.00007
high level waste transport	0.00007
totals	0.00130

This estimate is then further normalized into million 1982 CD per GweY by U.S. consumer price index CPI than to CD.

$$0.0013\frac{\text{mills}}{\text{kwh}}\times\frac{1\ \text{USD}}{1000\ \text{mills}}\times 365\times 24\times 10^{6}\times\frac{\text{kwh}}{\text{GweY}}$$

$$\times\ \frac{287.1}{161.2}\times\frac{1\ \text{CD}}{.8071\ \text{USD}}$$

=0.025 million dollar per GweY or M/GweY

Note: all social cost estimates derived from Barrager et al's are converted to M/GweY in the same way as above.

Derived from Inhaber[1978]

Inhaber included social impacts due to fuel gathering, handling, transportating, electricity production, and waste management in these estimates.

For one MweY, taken from Inhaber[1981, P.81,82]

	Inhaber's estimates Ontario	estimates for Alberta
Deaths	0.00031 → 0.00133	0.000257 → 0.0007
Disabilities	0.02022 → 0.0634	0.02022 → 0.0634
They are equivalent to		
Man-days lost	2.1 → 8.4	1.81 → 4.61

Since there are no fuel gathering and handling in Alberta, the estimates are lower than Inhaber's estimates. Assuming the cost for a man-day lost is same for an injury day and cost for a disability is same for a case of illness.

The health cost for Alberta
=(1.81 → 4.61) x 1000 x $118.85
=0.215 → 0.548 Million dollars per GweY

The expected health cost is 0.382 M/GweY and its standard deviation is 0.096.

Derived from Snell[1978]

Atomic Energy Control Board AECB, has set up the guidelines for normal operation of CANDU reactor. The maximum permissible population dose at the fence of the nuclear power site is 10^4 man-rem/plant-year (Snell, 1978, p.9). This limit is independent to the number of units per plant and their unit sizes. Snell mentioned that the design target of 1% of the above population dose is usually met and, according to Snell[1978, p.9]

10^4 man-rem per nuclear power plant-year causes

1.5 cases of fatal cancer
1.0 case of curable cancer
0.6 → 15 hereditary diseases

Assuming that the cost for a fatal cancer is the same as for a death, the cost for a curable cancer and the cost for a hereditary disease are the same as for an case of illness.

The health cost based on maximum permissible limit

$$= 1.5 \times \$913,000.00 + (1.6 \rightarrow 16) \times \$12,054.00$$

$$= 1.389 \rightarrow 1.562 \text{ M/GweY}$$

The mean of this range is assumed to be the upper limits. The the expected health cost is

$$\frac{0+(1.389+1.562)/2}{2} = 0.738 \text{ million dollars per plant-year}$$

The standard deviation is

$$\frac{[(1.389+1.562)/2]}{\sqrt{12}} = 0.426$$

Each year the nuclear power plant assumed in this thesis produces .96 Gw of electricity at capacity factor of 0.8, but the AECB guideline is for a plant-year and is irrespective to plant size. Since the assumed nuclear power plant produces about 1 Gwe every year, the health cost for Alberta due to normal operation of CANDU power plants in Alberta is 0.738 M/GweY.

Summary on the health costs estimates due to normal operation of CANDU power plants in Alberta

Applying equal weighting to all the cost estimates, the expected health cost

- =(.311+.025+0.382+.738)/4=0.364 M/GweY

The standard deviation of this expected health cost

$$= \sqrt{[\ 0.25(0.110)^2+0.25(0.364-0.311)^2}$$
$$+\ 0.25(0.000)^2+0.25(0.364-0.025)^2$$
$$+\ 0.25(0.096)^2+0.25(0.364-0.382)^2$$
$$+\ 0.25(0.426)\ +0.25(0.364-0.738)^2\,]$$
$$= 0.340$$

Health cost due to the possibility of nuclear power plant accidents in Alberta:

Derived from Hill[1977]

With the consideration of delay deaths (Hill, 1977, p. 3.16), Hill considers 0.02 deaths per reactor year to be the upper limit for the risk of fatality. Based on capacity factor of 0.8 and capacity of 0.6 Gwe for a reactor, the upper limit for health cost due to a nuclear accident assumed in Alberta is

$$\frac{(0.02 \times 0.913)}{0.6 \times 0.8} = 0.038 \text{ M/GweY}$$

The expected value for health cost in Alberta due to nuclear power accident is

$$.038/2 = 0.019 \text{ M/GweY}$$

and its standard deviation is

$$\sqrt{[(0.0-0.038)^2/12]} = 0.011 \text{ M/GweY}.$$

Derived from Barrager[1976]

Barrager estimated that the social cost due to nuclear power accidents is 0.003 mills/kwh (1975 USD) (Barrager, 1976, p.49) which is for light water reactor, LWR, for both health and property damage costs and for the whole nuclear fuel cycle. Assuming that the probability of having accident for CANDU reactor is the same as for LWR, and excluding the cost due to accident during fuel fabrication, the social cost due to nuclear power plant accidents in Alberta is 0.00254 mills/kwh (1975 USD) which corresponds to 0.049 M/GweY (by applying the same conversion as that of health cost due to normal operation). Since the social cost includes both health and property damage costs, this estimate is then further separated into these two costs by applying the ratio of health and properties damages costs estimated by Barrager [1976, p.36].

That is
the properties damages costs due to nuclear power accident in Alberta

$$= 0.049 \left(\frac{13480}{14400}\right)$$

$$= 0.046 \text{ M/GweY}$$

and that for health cost

$$= 0.049 - 0.046 = 0.003 \text{ M/GweY}$$

Derived from Inhaber[1978]

The estimates for both occupational and public social costs are as follows

For one Mwe year, taken from Inhaber[1978, p.81, 82.]

	Ontario	Alberta
Deaths	0.000312 → 0.000772	0.00019 → 0.0002
Disabilities	0.001611 → 0.002911	0.00127 → 0.001311
They are equivalent to		
Man-days lost	2.58 → 6.08	1.68 → 1.88

Since there are no fuel gathering and handling, the estimates for Alberta is lower. Assuming the cost for a man-day lost is same as for an injury day and cost for a disability is same as for a case of illness, one gets

The health cost for Alberta
=(1.68 → 1.88) x 1000 x $118.85
=0.200 → 0.223 M/ GweY

The expected health cost due to nuclear power plant accidents is 0.212 M/GweY and its standard deviation is 0.007.

Derived from Snell[1978]

AECB guidelines for maximum permissible nuclear accident quoted by Snell are

Single failure , one in 3 years
maximum permissible population dose
10^4 man-rem per reactor
at the fence of the site

Dual failure one in 3,000 years
maximum permissible population dose
10^6 man-rem per reactor
at the fence of the site

Snell estimates
at these two maximum
allowable limits
per reactor

	Fatalities	illnesses
Single failure	1.5	0.6 → 15
dual failure	30 → 750	80 → 2000

note: taken from page 9 & 10 of Snell's paper

The health impairment due to these two failures is considered to be high when compared with other estimates on nuclear power plant accident.
The health cost is half of these allowable limits that is

$$= \frac{1}{2}\left[\left(\frac{1.5}{3} + \frac{30 \rightarrow 750}{3,000}\right) x \frac{913,000}{0.6x0.8} + \left(\frac{.6 \rightarrow 15}{3} + \frac{80 \rightarrow 2000}{3,000}\right) x \frac{12,054}{.6x.8}\right]$$

= 0.488 → 0.784 M/GweY

To be consistent with estimates for normal operation of nuclear power plant derived from Snell, the mean of 0.488 and 0.784 is assumed to be the maximum allowable limit. That is (0.488+0.784)/2=0.636 M/GweY.

The expected value of the health cost due to nuclear power plant accident in Alberta

= (0.636)/2=0.318

The standard deviation of the expected value based on the assumption of uniform distribution between the range is

$=\sqrt{[(0.636-0.0)^2/12]}= 0.184$

Summary on the health cost estimates due to nuclear power plant accidents assumed in Alberta

The expected health cost due to nuclear power plant accident

$$= (0.019 + 0.003 + 0.212 + 0.318)/4$$
$$= 0.138 \text{ M/GweY}$$

Its standard deviation

$$= \sqrt{[\,0.25(0.000)^2+0.25(0.138-0.019)^2 + 0.25(0.000)^2+0.25(0.138-0.003)^2 + 0.25(0.007)^2+0.25(0.138-0.212)^2 + 0.25(0.184)^2+0.25(0.138-0.318)^2\,]}$$
$$= 0.161$$

Social costs due to sabotage and uranium diversion during the operation of CANDU nuclear power plants in Alberta

Derived from Barrager[1976]:

Barrager's estimates are mainly for United States and for LWR. They are listed as follows:

Barrager's[1976, p.49] estimates for US LWR and for whole nuclear fuel cycle (1975 USD)

Sabotage	0.0525	mills/kwh
Diversion	0.01	mills/kwh

For Alberta, nuclear fuel is imported. Social costs due to fuel fabrication and reprocessing are excluded.

For Alberta, the cost due to Sabotage is then

=0.00003+0.05+0.00003+0.00002=0.05 mills/kwh(1975 USD)

the cost due to "Plutonium"

diversion is then

=0.004 + 0.0008 + 0.0002 = 0.005 mills/kwh(1975 USD)

Small amount of plutonium is present in the splent fuel storage bays of the CANDU reactors (about 50 g reported by Dalziel[1981]). The Canadian international relationship with other countries is more moderate than that of the United States. This thesis regards the estimates on sabotage and diversion derived from Barrager to be the upper limits. The expected social costs due to sabotage and diversion for Alberta are assumed to be half of these limits. The cost estimates are then further divided into health and property damages costs. The calculation procedure is similar to the derivation of health and property damage costs from Barrager due to of nuclear power plant accidents from Barrager et al.

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[1] Although plutonium is not extracted for fuel enrichment in Canada, as it is in the United States (CANDU uses natural uranium fuel), some plutonium exist in the spent fuel bundles from CANDU reactors, and trace amount are used for

The results are

costs in M/GweY for Alberta

	human	property damage
Sabotage	0.031	0.451
	(0.018)	(0.260)
Diversion	0.003	0.045
	(0.002)	(0.026)

numbers in brackets are standard deviations

Health cost due to the operation of coal-fired power plants in Alberta

Derived from Mendelsohn [1979]

Using Mendelsohn's [1979, p. 37] cofficients for estimating the number of deaths due to coal-fired power plants in Alberta resulted in probability of negative deaths. The suggested coefficients for the estimates of deaths do not make sense for there should not be positive health effect when the ambient air is polluted. The dose-response function for deaths established by Mendelsohn cannot be applied to the Alberta environment. Information is not enough to pro-rate Mendelsohn's estimates on deaths from New Haven in the United States to that of Alberta. Since they do not make sense and do not enter into the final estimates, the calculation are not shown.

Mendelsohn[1979, p. 37] estimates that the morbidities for a year due to particulates generated by coal fired power plants are

360×10^{-6} cases of Bronchitis per $\mu g/m^3$ per person.
Standard deviation=350×10^{-6}
7×10^{-6} cases of acutes illnesses per $\mu g/m^3$ per person
Standard deviation=2×10^{-6}
But no estimated on NO_x, presumably not significant.

In Alberta, annual particulates concentration is 69.15 $\mu g/m^3$ taken the average of Calgary and Edmonton and SO_x is too low to be expressed in $\mu g/m^3$ (table 4.2).

In 1982, the population in Alberta was 2,317,000 (Statistics Canada, "population" Catalogue No. 91-518.) and the electricity generated from coal was 20616.6 Gwh (ERCB, 1982, p.7). Assuming the 4% contribution of particulates due to coal-fired plant in Edmonton is a representative figure for the whole province (table 4.2).

The number of cases of illnesses

$$= (360+7) \times 10^{-6} \text{ cases per } \mu g/m^3 \text{ per person} \times 69.15\ \mu g/m^3 \times 2.317 \times 10^6 \text{ persons}$$
$$= 58.801 \times 10^3 \text{ cases-year}$$

The health cost due to coal-fired power plants in Alberta

$$= \frac{58.801 \times 10^3 \times 12{,}054 \times 4\%}{20{,}616.6 \times \dfrac{1 \text{ yr}}{365 \times 24 \text{hr}}} = 12.047 \text{ M/GweY}$$

The standard deviation

$$=\sqrt{\left[\left(\frac{12.047}{367}\times 350\right)^2 + \left(\frac{12.047}{367}\times 2\right)^2\right]}$$

$$=11.489$$

Derived from Lees, Dunn, Ersil[1980]

There are two suggested methods. Lees et al[1980, p.46] considered that the total annual health cost due to air-pollution is equivalent to 0.705% of the annual Gross Domestic Product. Using this percentage the total health cost due to air-pollution from all sources in Alberta is 45,338 x 0.705% = 319.663 million 1982 CD. ($45,338 million is taken from Gross Domestic Product in Alberta 1982, page 41).

Lees, et al[1980, p.70] estimated that only 1.24% of the ground level pollution (for all pollutants) was due to coal-fired power plants. Assuming the contribution due to coal-fired power plants in Alberta is also 1.24%. The health cost due to coal-fired power industry only is (1.24% x 319.633)=3.963 million CD. In 1982, the total electricity generated from coal was 20616.6 Gweh. Then the health cost due to coal-fired power industry is

$$\frac{3.963 \text{ million CD} \times 365 \times 24 \text{ h}}{20{,}616.6 \text{ Gweh} \cdot \text{Y}} = [illegible]684 \text{ M/GweY}$$

The second method (Lees, et al [illegible]) suggested 9% of the total provincial health care cost is due to air pollution from all sources.

the heal[illegible]cost per GweY [illegible]rm coal-fired power plants

$$= \frac{1.24\% \times \$1{,}924{,}934{,}000 \times \dfrac{110.8}{100.00} \times 9\%}{20{,}616.6 \text{ Gweh} \times \dfrac{1 \text{ Y}}{365 \times [illegible] \text{ h}}}$$

$$= 1.011 \text{ M/GweY}$$

Note: $1,924,934,000 is the health care expense for Alberta in 1981 taken from Statistics Canada no.68-205. 1982 health care expense is not available at the time of estimation. Therefore it is estimated by the Canadian CPI.

Since these methods are independent and there is no clear indication of which one is better than the other, they are treated to be equally likely and the values in between these estimates are assumed to be uniformly distributed.

therefore the expected health costs

$= (1.684+1.011)/2 = 1.348$ M/GweY

the standard deviation

$= \sqrt{[(1.684-1.011)^2/12]}$

$= 0.194$ M/GweY

Derived from Hill[1977]

Since there is no transportation of coal from the coal mine through the public railway lines to the power plants in Alberta, the health costs due to transportation are excluded from Hill's[1977, p 5.40, 5.41] estimates. The Alberta estimates for health costs become

	for 1000 Mwe plant-year deaths	Injury days
Occupational		
processing	0.0	0.0
transport	0.0	0.0
conversion	0.01 → 0.03	150
Public		
Conversion	0.0	0.0 → 39,800
transportation &waste disposal	0.0	0.0

The health cost due to operation of coal-fired power plant at capacity factor of 0.8

$= [(0.01 \rightarrow 0.03) \times 913{,}000.00$
$+ (0.0 \rightarrow 39{,}800) \times 118.85$
$+ 150 \times 186.91]/(1.0 \times .80)$
$= 0.034 \rightarrow 5.969$ M/GweY

The expected health costs due to coal-fired power plants is $(0.034 + 5.969)/2 = 3.002$ M/GweY and the standard deviation of this expected value is $\sqrt{(5.969 - 0.034)^2/12} = 1.713$

Derived from Barrager et al [1976]

Barrager[1976, p.15] estimated the health cost per lb of sulphur is 9.5 to 33.2 cents (1975 USD) and mentioned that the health cost is highly dependent on the rate of sulphation. Barrager's estimates are based on 0.1 to 1% per hour rate of sulphation. A range of .1 to .5% per hour rate of sulphation is estimated for Ontario (Hill, 1977, p.4.2). Assuming the rate of sulphation in Alberta is equal to rate of sulphation in Ontario, the health cost per lb of sulphur found in coal is 9.5 to 21.35 cents (by linear interpolation). Using the assumptions for Alberta coal-fired power plants suggested by Foulkes[1982, page II-5] i.e.

1. 0.3% sulphur coal
2. 1,547,300 ton per year per unit of .371 Gwe at 0.8 capacity factor.
3. sulphur emitted to air after 35% sulphur removal

The sulphur emitted

$$= 1{,}547{,}300 \text{ tons} \times .3\% \times 65\% /(0.371 \times 0.8)$$

$$= 10.166 \text{ thousands tons per GweY}$$

The health cost due to sulphur

$$= 10.166 \frac{\text{tons}}{\text{GweY}} \times \frac{2205 \text{ lbs}}{\text{tons}} \times (.095 \rightarrow 0.2135) \times \frac{287.1}{161.2} \times \frac{1 \text{ CD}}{.8071 \text{ USD}}$$

$$= 4.7 \rightarrow 10.561 \text{ M/GweY}$$

Barrager estimated that the health costs due to NO_2 is 2 cents (1975 USD) per lb emitted from the stack (Barrager, 1976, p.17). On the average one power unit emits 10.69 thousand tons of NO_2 to the air (Hill, 1977, p.4.7). By the above calculation procedure the health cost due to NO_2 is 3.510 M/GweY. Barrager et al stressed that health cost due to particulates was already included in sulphur dioxide and nitrogen dioxide.

The health costs due to coal-fired power plants

$$= (4.70 \rightarrow 10.561) + 3.510 \text{ M/GweY}$$

$$= (8.21 \rightarrow 14.071) \text{ M/GweY}$$

Assuming the estimates is evenly distributed between the range of this health costs, the expected health costs is the mean of 8.21 and 14.071 i.e. 11.141 M/GweY and the standard deviation is 1.692 M/GweY. These health cost estimates are large when compared with others cost estimates. The sulphur dioxide level in Alberta is barely measurable but far below the national air quality standard, and this cost estimate is used anyway.

Derived from Inhaber[19[illegible]

The coal in Alber[illegible]as sulphur content of 0.3% to .5% (Foulkes, 1977, p. II-5, and Rahama, 1982, p 69). With the assumption of using scrubbers for the new power plants the pollution level of sulphur dioxide would be in the region of, or would not be higher than the existing level which is very low when compared with the pollution levels in Ontario (table 4.2, and Lees et at, 1980, p.41). The lower limits of Inhaber's estimates are considered to be the representative figures for health costs due to coal-fired power plant in Alberta.

For one MweY (Inhaber, 1978, p.59)

	Inhaber's estimates	Alberta estimates
Occupational	0.0	0.0
Public		
deaths	0.016 → 0.047	0.016
disabilities	94 → 280	94.00

A disability is equivalent to from 1 to 5 days lost (Inhaber, 1978, p. 61).

Therefore total man-days lost for one MweY in Alberta
$= (0.016 \times 6000 + 94 \times 1) = 190$ MDL

The health cost due to coal-fired power plants in Alberta $= [190 \times 118.85 \times 1000] \times 10^{-6}$
$= 22.582$ M/GweY

Since the lower values of Inhaber's estimates are used and Inhaber's study is Canadian orientated (although not Alberta) 22.582 M/GweY is regarded as one of the cost estimates.

Summary on the health cost estimates due to the operation of coal-fired power plants:

The expected health cost after taken the average of all the estimates.
$=(1.348+3.002+11.141+22.582+12.047)/5 = 10.024$ M/GweY

The standard deviation of the expected health cost

$$=\sqrt{[(0.194)^2/5 + (10.24 - 1.348)^2/5 + (1.713)^2/5 + (10.24 - 3.002)^2/5 + (1.692)^2/5 + (10.24 - 11.141)^2/5 + (0.000)^2/5 + (10.24 - 22.582)^2/5 + (11.489)^2/5 + (10.24 - 12.047)^2/5]}$$

$= 9.227$

Health cost due to surface coal mining in Alberta:

Derived from Hill[1977]

The Council on Environmental Quality quoted by Hill[1977, p.5.38] estimated .308 deaths and 499 work-days lost for 1000 Mwe plant-year. This is due to surface mining and for occupational only. Assuming the social impact on health due to surface mining in Alberta is same as that estimated by The Council on Environmental Quality, and assuming the cost for a work-day lost is same for an injury day, the health cost due to surface mining in Alberta is

$$[0.308 \times 913{,}000 + 499 \times 118.85] \times 10^{-6} / .75 = 0.455 \text{ M/GweY}$$

Derived from Barrager et al[1976]

Barrager estimated health cost due to surface mining is 0.02 mills/kwh(1975 USD) (Barrager et al, 1976, p.21). This cost estimate is for Appalachia location. Assuming this estimate can be applied to surface mining in Alberta, and following the same conversion procedure as health cost due to normal operation of power plant, the health cost due to surface mining in Alberta is 0.380 M/GweY.

Derived from Inhaber[1978]

	Inhaber's[1978, p.59] estimates on gathering and handling of coal Man-days lost
occupational	8.2 → 21
public	8.4 → 84
totals	16.6 → 105

These estimates are for all types of mining. Surface mining is the coal mining method used in Alberta and is considered to be the safest method (Inhaber, 1978, p.61). The health cost is expected to be at the lower end.
The health cost due to surface mining for coal in Alberta
= 16.6x118.85x1000=1.973M/GweY

Summary on the health cost estimates due to surface mining in Alberta

There are two estimates. The expected health cost is 0.936 M/GweY and the standard deviation of this expected value is 0.734.

The social cost due to air pollution from coal-fired power plants in Alberta on building materials:

Derived from Mendelsohn [1979]:

Particulates and nitrogen dioxide are the major pollutants due to coal-fired power plants in Alberta (table 4.2). Mendelsohn does not have estimate on the damages due to NO_2, presumably not significant. Mendelsohn[1979, p.37] estimated that the social cost due to particulates on building materials is 19 mills per $\mu g/m^3$/person (1978 USD) and standard deviation of this estimate is 51. With the Alberta population of 2.317 million in 1982 and using the average particulates pollution levels between Calgary and Edmonton, and assuming coal-fired power plants contribute 4% of the ambient particulates (table 4.2) the material damage cost in Alberta due to particulates

$$=0.019 \frac{\text{USD}}{\mu g/m^3 \text{ person}} \times 69.15 \mu g/m^3 \times 4\% \times 2317000 \text{ persons}$$

$$\times \frac{287.1}{195.4} \times \frac{1 \text{ CD}}{.8071 \text{ USD}} = 0.221 \text{ million CD in year 1982}$$

$$\text{or } = \frac{0.221 \text{ Million CD} \times 365 \times 24 \text{ h}}{20616.6 \text{ Gweh} \times \text{Y}} = 0.094 \text{ M/GweY}$$

Where 20616.6 Gweh is electricity generated by coal in 1982.

$$\text{Its standard deviation} = \frac{0.094 \text{ M/GweY}}{19} \times 51$$

$$= 0.252 \text{ M/GweY}$$

Derived from Acres[1980]

Information is not sufficiently complete for application of the equations used by Acres in estimating the social costs on material damages for Alberta. In Alberta, only particulates exceed the air qualities standard of 60 $\mu g/m^3$ (table 4.2). The Alberta cost estimates on building materials due to air-pollution is then pro-rated by damage potentials.

The damage potential due to particulates
= exceedance factor of particulates
x severity factor of particulates on building materials
x exposure factor of building materials in certain area

Note: damage potential due to all pollutants is the summation of the damage potentials for each pollutant
exposure factor consists of number of units exposed to pollution and duration of exposure to pollution

$$\text{exceedance factor}^{+} = \frac{\text{recorded} - \text{standard}^{*}}{\text{standard}}$$

* in pollution levels,
\+ (Ontario Research Foundation, 1980, p.132) based on air standard of 60 $\mu g/m^3$ for particulates
the values of severity and exposure factors are listed in the report written by Ontario Research Foundation[1980, p 154, 155].

Acres estimated the social cost on the building materials due to particulates generated from the 4 power stations in southern tip of Ontario was 97,618 '78 dollar (Acres, 1980, p.24, 25, 32). Total electricity generated was 28,338 (Arces, 1980, p.29) and 20616.6 Gweh for Toronto area and Alberta respectively (from coal only).

Lakeview and Hearn power stations are located at the edge of Toronto where population is highest (Acres, 1980, p.21). If the average pollution level for particulates is taken, this averaged value will be lower than the Air Quality Standard. This implies that no damage on building materials. Conversely, there must be some damages where pollution is higher than the standard. The exceedance factor for Ontario is assumed to be reprersented by Toronto. Similarly the Alberta exceedance factor is represented by the average value of Edmonton and Calgary.

	Toronto	Edmonton & Calgary
particulates $\mu g/m^3$	71.082	69.150
	(ORF, 1980. P.32)[+]	(table 4.2)
severity factor particulates on materials	0.560 (ORF, 1980, p.154)	0.560
exposure factor of particulates on materials per person++	0.0017	0.0016
population million	3.270 (Acres, 1978, p.21)	2.317 (Stat. Can. 91-518)
damage potential	575.000	316.600

+ ORF is Ontario Research Foundation
++ this is the average exposure factor taken from the nearest U.S. cities and normalized to per person basis.

The property damage due to particulates generated by coal-fired power plants in Alberta

$$= 97618 \text{ '78 CD} \times \frac{316.6}{575.0} \times \frac{110.8}{74.1} \times \frac{365 \times 24 \text{ h/Yr}}{20616.6 \text{ Gweh}}$$

=0.034 M/GweY

Derived from Hill [1977]

Hill estimated the building materials damages due to air-pollution contributed by coal-fired power plant is in the order of 1$ per year per capita of population served by the plant (Hill, 1977, p.6.13). With the assumption of 1000 Mwe plant-year serving the electricity need of 1,000,000 people, the building material cost is 1 million 1977 dollars per 1000 Mwe plant-year for Ontario, or 2.173 M/GweY in 1982 CD after the dollar value is converted by Canadian CPI and normalized to per GweY basis. Using the same damage potential ratio as in social cost estimates on building materials derived from Acres, (i.e. 316.6/575), the building material damage cost due to air-pollution by coal-fired power plant is in the order of 1.195 M/GweY.

Summary on the social cost due to air pollution from coal-fired power plants in Alberta on building materials

Following the same calculation procedure as that of health costs the expected social cost on building materials is 0.441 M/GweY and its standard deviation is 0.553.

The social cost due to air-pollution from coal-fired power plants in Alberta on textiles:

The study done by Ontario Research Foundation [1980, p.168, 176] reported that the social cost due to air-pollution from coal-fired power plants in Ontario was in the range of 0 to 10 million 1978 CD for the year 1978. Three different methods were conducted.

In the first method, Ontario Research Foundation pro-rated the social cost estimated by Salvin in 1970 due to air pollutants from all sources to Ontario estimate by ratio of damage potentials between Ontario and the United States.

In Alberta, only the pollution level of particulates is above the air quality standard (table 4.2) and the social cost on textiles is, therefore, mainly due to particulates. In 1970, Salvin estimated that annual maximum social cost on textiles in United States due to particulates from all sources was $1,194 million per year (Ontario Research Foundation, 1980, p.158, 170). Since Salvin's cost estimate is for particulates only, the social cost due to particulates from coal-fired power plants in Alberta is obtained by using the ratio of damage potential of particulates between Alberta and the United States and pro-rating Salvin's estimate to that of Alberta.

$$\$1,194\ M/Y \times \frac{2.317}{205} \times \frac{69.15 - 60}{120 - 60} \times \frac{287.1}{116.3} \times \frac{1}{.8071} \times 4\%$$

$$= 0.126\ M\ CD/Y$$

note: assuming the explosure factors per person for both Alberta and the United States are the same.

then normalized into per GweY

$$\text{i.e}\quad 0.126 \times \frac{365 \times 24}{20,616} = 0.054\ M/GweY$$

where

2.317 is the Alberta population in million in 1980

205 is the U.S. population in million in 1970 (Ontario Research Foundation, 1980, p.168)

$120 \mu g/m^3$ is particulates level in U.S. (Ontario Research Foundation, 1980, p.151)

4% is the contribution of particulates by coal-fired power plants in Edmonton, and is assumed to be the representative figure for Alberta. (table 4.2)

Since it is the maximum value, the expected costs is 0.054/2=0.027 M/GweY.

In the second method, the cost estimate of $12.5 per capita per unit of exceedance of particulates per year is used. This cost was estimated by Michelson and Tourin in 1966 and was quoted by Ontarion Research Foundation[1980, p172].

The social cost due to partiuclates from coal-fired power plants on textiles in Alberta is

$$\frac{\$12.5}{\text{person} \times \mu g/m^3} \times 2{,}317{,}000 \text{ persons} \times \frac{69.15-60}{60}$$

$$\times\ 4\% \times 2 \times \frac{110.8}{74.1} \times \frac{365 \times 24}{20{,}616} = 0.224 \text{ M/GweY}$$

where 2 is the factor used by the Ontario Research Foundation to adjust the dollar value from 1966 to 1978 due to inflation.

A study done by Ontario Research Foundation suggested one third of $12 per capita per year estimated by Liu & Yu is the appropriate figure for social cost due to particulates. Using this cost estimate, social cost due to particulates from coal-fired power plants in Alberta on textiles is

$$\frac{\$\ 4}{\text{Y} \times \text{person}} \times 2{,}317{,}000 \text{ persons} \times 2 \times \frac{110.8}{74.1} \times 4\%$$

$$\times \frac{365 \times 24 \text{ h/Y}}{20{,}616 \text{ Gweh}} = 0.472 \text{ M/GweY}$$

The cost estimate ranges from 0.224 to 0.472 M/GweY.

In the third method, Salvin's assumptions were modified by Ontario Research Foundation to represent the local conditions for example the cost for professional laundering and cleaning in the southern part of Ontario. The cost estimate is 9.25 million 1978 CD. If the textiles cleaning activities are assumed to be the same for both Alberta and Ontario, the social costs due to air-pollution on textiles can be pro-rated from 9.25 to that of Alberta cost estimates by the ratio of damage potentials between Alberta and Ontario. This ratio is same as the one used in estimating social cost due to particulates on building materials.

$$\text{i.e.} \quad 9.25 \times \frac{316.6}{575.0} = 5.1 \text{ Million 1978 CD / year}$$

This cost estimate is then further normalized into per GweY basis, and the dollar value is converted to 1982 CD by Canadian CPI. Since coal-fired power plants in Alberta produced 20,616 Gweh in 1982. The social costs due to the air-pollution from coal-fired power plant in Alberta on textiles is

$$5.1 \times 4\% \times \frac{110.8}{74.1} \times \frac{365 \times 24 \text{ h/Y}}{20{,}616 \text{ Gweh}} = 0.130 \text{ M/GweY}$$

The cost estimate is from 0 to 0.130 M/GweY. Since 9.25 is considered by Ontario Research Foundation to be the upper limit, the expected cost estimate is 0.130/2=0.065 M/GweY and its standard deviation is 0.038.

Summary on the social cost estimates due to air-pollution from coal-fired power plants in Alberta on textiles:

Ontario Research Foundation regarded the estimates from the second method were too high and unreasonable. They were discarded. Similarly the Alberta cost estimates by the second method is still too high and they are discarded accordingly. The estimates from first and third method are similar. The expected social costs on textiles in Alberta is 0.065 M/GweY and has standard deviation of 0.038. It is derived from the estimates which is considered by Ontario Research Foundation to be the reasonable estimates for Ontario.

The social cost due to air pollution from coal-fired power plants in Alberta on vegetation and animals:

Derived from Mendelsohn [1980]

In Alberta particulates and nitrogen dioxide are the pollutants from the coal-fired power plants. (table 4.2) Mendelsohn estimated that the vegetation loss due to particulates was 0.1 dollars (1978 USD) per ton of emission and with a standard deviation of 2 (no cost estimates due to NO_2, Mendelshon, 1980, p. 37). Foulkes[1982, p. II-5] estimated that ash content for Alberta coal is 19%. With an annual consumption of 1,547,300 tons for a power unit of .371 Gwe,

the annual ash produced per unit of .371 Gwe
= 1,547,300 x 19% = 294,000 tons / year / units

From Rahnama[1982, page 70] 2 to 3 million tons for every 35 millions tons of ash go to the air in the median size of 2 to 3 micron after abatement.

Therefore the particulates emitted per GweY

$$= \frac{294{,}000 \text{ tons /year/unit}}{.371 \times 0.8 \text{ Gwe/unit}} \times \frac{2.5}{35} = 70{,}755 \text{ tons/GweY}$$

The cost estimates on vegetation based on 0.1 USD 1978 per tons of particulates emitted

$$= 0.1 \times 70{,}755 \times \frac{287.1}{195.4} \times \frac{1}{0.8071}$$

$$= 0.013 \text{ M/GweY}$$

$$\text{The standard deviation} = 0.013 \times \frac{2}{0.1}$$

$$= 0.26 \text{ M/GweY}$$

The social costs due to coal-fired power stations in Alberta on land and water:

The social costs due to coal-fired power stations on land and water, apart from acid rain, are mainly due to surface mining. Barrager[1976, p.27] had these cost estimates. That is 0.10 mills/kwh and 0.04 mills/kwh (1975 USD) for land and water respectively. In terms of 1982 CD, the cost estimates are 1.933 and 0.744 M/GweY on land and water respectively (conversion similar to that of the cost estimate on health derived from Barrager). These cost estimates for Alberta are considered to be high by this thesis when compared with other social cost estimates. The expected cost estimates would be half of them, that is 0.967 and .387 M/GweY for land and water respectively. The standard deviations of the expected cost estimates are 0.568 and 0.223 for land and water respectively.

A.5.3 Consumer Price Index (All items)

Year	Edmonton 1981=100	U.S.A. 1967=100
1965	34.2	64.5
66	35.3	67.2
67	36.8	100.0
68	38.4	104.2
69	40.0	109.8
1970	41.1	116.3
71	42.2	121.3
72	43.8	125.3
73	46.6	133.1
74	51.3	147.7
75	56.9	161.2
76	61.4	170.5
77	68.0	181.5
78	74.1	195.4
79	80.7	217.4
1980	88.9	246.8
81	100.0	272.4
82	110.8	287.1

Source:
U.S. Bureau of Labour Statistics,
Monthly Labour Review
Alberta Statistical Review Annual 1974, 1977, 1982

A.5.4 U.S. Dollar vs Canadian Dollar in '82

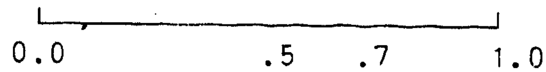
Month	U.S. to Canadian Dollar
Feb	0.8123
Mar	0.8149
Apl	0.8183
May	0.8039
Jun	0.7748
Jly	0.7985
Aug	0.8069
Sep	0.8090
Oct	0.8160
Nov	0.8091
Dec	0.8138
Average	0.8071

Source:Bank of Canada Review, Bank of Canada '84

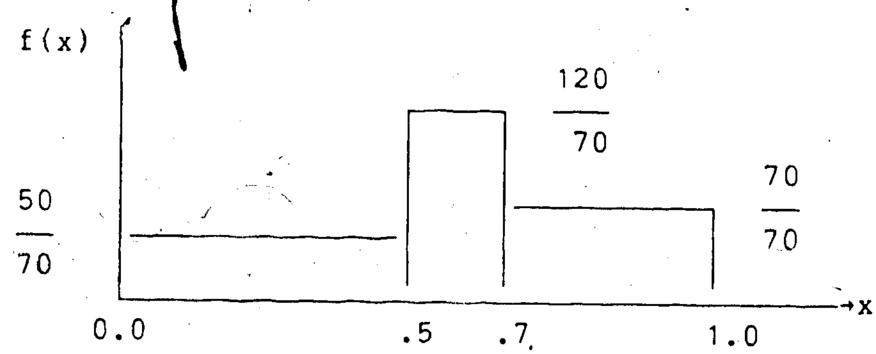
Appendix six

Suppose there are two estimates A and B

One method of combining those two estimates without considering any weighting to them is to take the extreme values, i.e. the range of estimate is 0.0 to 1.0.



The over-lapping portion 0.5 and 0.7 should have higher probability. One other method is to assume that the estimates are independent and equally likely, the combined probability density function, PDF, becomes



This method takes into consideration of the fact that both initial estimates agree for a particular range of values and also considers the variance of the initial estimates. A distribution is, therefore, able to describe the estimate better than a range of value does especially when there are more than two estimates.

Suppose there are N independent estimates each of which is represented by a probability density function PDF, f_n having mean v_n and variance σ_n^2. Assume $f_o(x)$ is the combined probability density function for these estimates. The mean of f_o, v_o is the summation of $w_n v_n$ from n=1 to n=N, where w_n is the weighting factor assigned to nth estimate and summation of w_n from n=1 to n=N is equal to 1.

The proof of combined variance var(v) is

$$
\begin{aligned}
\bar{v} &= \Sigma\ w_x \bar{v}_x \\
E[v^2] &= \Sigma\ w_x E[v_x^2] \\
var(v) &= \Sigma\ w_x E[v_x^2] - \bar{v}^2 \\
&= \Sigma\ w_x E[v_x^2] - \Sigma\ w_x \bar{v}_x^2 \\
&\quad + \Sigma\ w_x \bar{v}_x^2 - 2\bar{v}^2 + \bar{v} \\
&= \Sigma\ w_x Var(v_x) \\
&= \Sigma\ w_x \bar{v}^2 - 2\bar{v}\ \Sigma\ w_x \bar{v}_x + \Sigma w_x \bar{v}_x \\
&= \sum_x w_x (var(v_x) + (\bar{v} - \bar{v}_x)^2)
\end{aligned}
$$