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COSTS

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NUCLEAR POWER SYMPOSIUM

NUCLEAR POWER PLANT COSTS

by

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1. INTRODUCTION

In this presentation, I will be outlining the general content of a cost estimate for a CANDU-PHW nuclear power plant, giving some current examples of actual estimates, and comparing these to fossil-fired plants and light water reactors.

Even though this is a paper on costs, I should remind you that costs are not everything in the selection of a reactor type. For example, the dependence on the U. S. for long-term supplies of enriched uranium as opposed to use of indigenous natural uranium can be quite a deterrent to some nations when considering a light-water reactor purchase.

I shall be delighted to try and field your questions at the conclusion of the lecture.

2. GENERAL MAKEUP OF CAPITAL COST ESTIMATE - CANDU PHW

Direct costs, in our definition, include equipment, installation, buildings and structures, site improvements and nuclear inventories (heavy water and fuel). These currently account for about 55% of the total capital cost of a nuclear generating station, as indicated in Figure 1. Generally, these are more easily estimated and more easily controlled than the indirects.

The makeup of the Direct Costs segment of the pie is shown in Figure 2.

Property costs have not been included and the site is assumed to be flat and with suitable foundation conditions. Thus the "site and buildings" section should be considered a minimum percentage. The points of interest are the relatively high value of the heavy water inventory and the very small value of capitalized fuel.

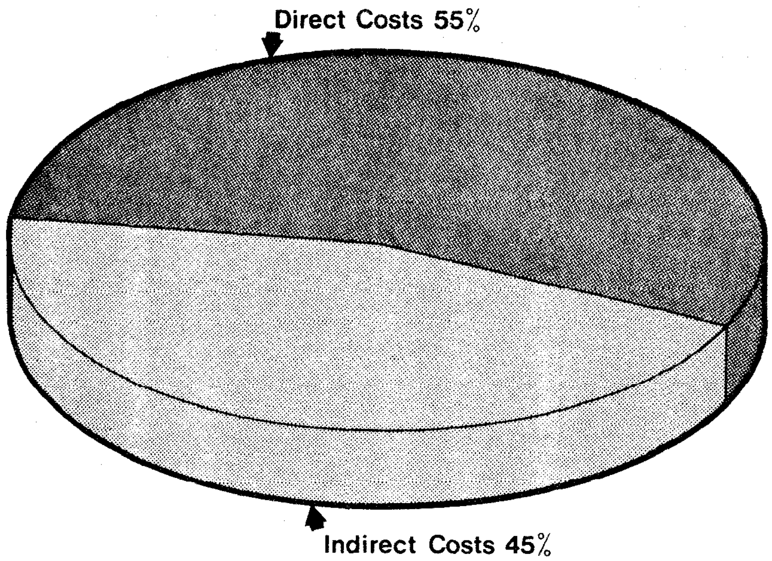


Figure 1 CANDU Capital Cost

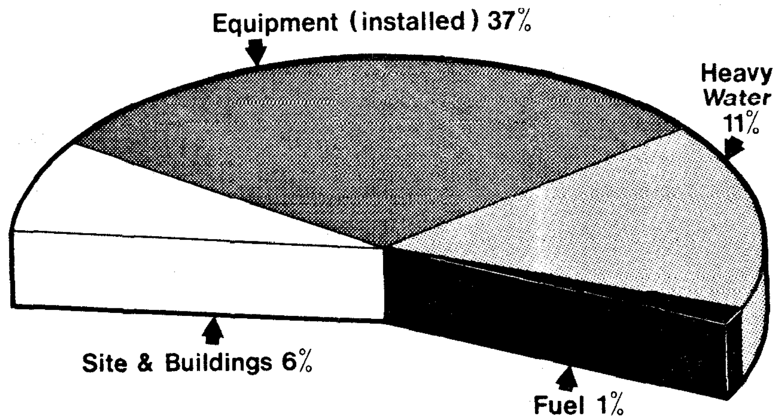


Figure 2 CANDU Direct Costs (55% of total capital)

Figure 3 shows the breakdown of the Indirect Costs into engineering, construction overheads, commissioning and interest during construction. These are very approximate, and will vary considerably depending, for example, on whether we are considering single-unit or multi-unit plants.

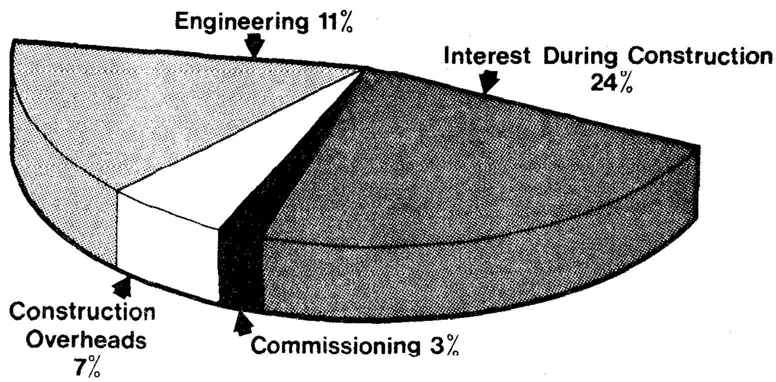


Figure 3 CANDU Indirect Costs (45% of total capital)

There is another way to cut up this Cost pie; by consultant/customer responsibility, for instance. Figure 4 shows a breakdown into a nuclear steam plant (NSP) and the conventional, or balance of plant (BOP), customer's costs (e.g., switchyard, commissioning, staff training), nuclear inventories (D_2O and fuel) and interest. The NSP and BOP portions include related buildings, engineering, construction and commissioning assistance.

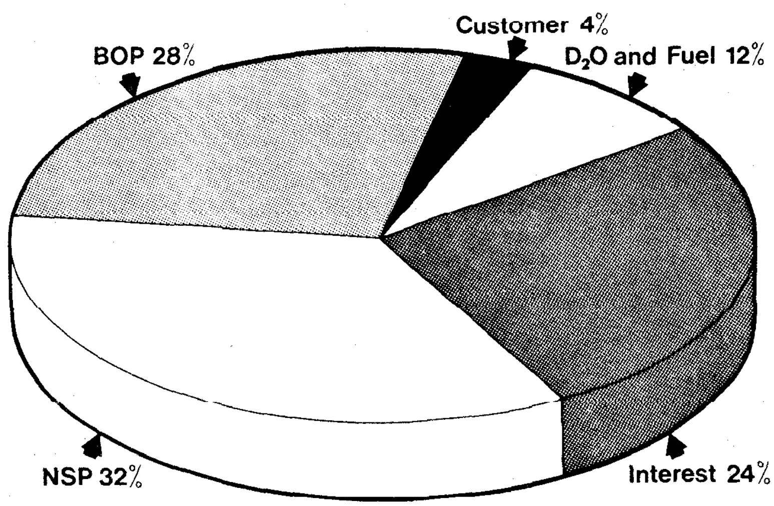


Figure 4 CANDU Capital Cost

The following discussion of cost components is based on the total directs/indirects approach, and not the alternative breakdown into NSP and BOP.

3. DIRECT COSTS FOR 2 x 600 MW CANDU-PHW

A typical single-digit breakdown of the direct costs for a CANDU station consisting of two 600 MW units is given in Figure 5. Site improvements in this table include finish grading, drainage, landscaping, roadways, etc., but not property cost, clearing and rough grading. Inclusion of the latter items could double the cost under division 1.

MILLIONS OF DOLLARS (1972)	
1. *Site Improvements*	2
2. Buildings & Structures	38
3. Reactor, Boiler & Auxiliaries	75
4. Turbine-Generator & Auxiliaries	67
5. Electric Power Systems	15
6. Instrumentation & Control	13
7. Common Processes & Services	20
Total Plant	230
Inventories: Heavy Water	65
Fuel (1/2 charge)	6
GRAND TOTAL - DIRECTS	301

TYPICAL DIRECT COST BREAKDOWN
2 x 600 MWe (net) CANDU-PHW

Figure 5

The Buildings, Reactor and Turbine sections are complete and self-explanatory. Electric Power Systems includes all internal power supplies and distribution as well as output and station service transformers; the switchyard is excluded. Division 6 includes all process instrumentation in the plant as well as communication systems and control and monitoring computers. Included in Division 7 are such "common" systems as pumphouse equipment, service water and circulating water systems, sewage and drainage, heating and ventilation, compressed air, material handling equipment, and radiation protection and waste management systems. Equipment costs are as-installed costs.

Of the $170 million equipment and material costs included in the direct costs of Figure 5, some $130 million (76%) would be spent in Canada at the present time. The imported content is made up mostly of turbine-generator components, carbon steel pipe and heat exchanger tubing, which are not wholly available in this country. All major components of the nuclear steam plant are fabricated in Canada, with the one exception of Zircaloy pressure tubes which are worth about $3 million for a two-unit plant.

4. INDIRECT COSTS

4.1 Engineering

For jobs undertaken in conjunction with Canadian utilities, the engineering manhours spent on the project have been split almost 50-50 between the nuclear plant (AECL) and the "conventional" work (utility). The nuclear plant engineering effort is larger than that for conventional fossil boiler mostly because of the detailed reactor design undertaken. Reactor vessels, fuel channels, control devices and fuel changing equipment are all detailed by AECL such that the manufacturers are required to fabricate only and not to perform detail design as they would do for boilers and pumps. Also, prototype testing and a portion of basic development work are included.

Included in the general heading of "Engineering" in the 11% portion of the pie of Figure 3 is project management and quality control. A strong project team involving both AECL and the utility is required to get these very large projects built on time and within estimate. They must be experienced in and have available modern management tools providing information feedback, cost control, scheduling, material control, etc.

4.2 Construction Overheads

Construction overhead costs include construction material (non-permanent), temporary structures and shops, shop operation and warehousing, supervision, field engineering and planning, accounting, etc. Experience has shown that this is a most difficult item to estimate in advance. It depends to a large extent on the construction organization set up and the division of work between design office and field and between manufacturers' shops and field. Construction overheads can run as high as 10% of project costs, depending on such things as how far down the line of supervision the men charge to overhead instead of to the capital equipment account.

4.3 Commissioning

Commissioning includes the costs of training operating crews, preparing commissioning and operating manuals, commissioning the systems and equipment (including initial fuel loading and the filling and testing of heavy water systems), and operation and maintenance up to the official in-service date, which may be some months after "first steam to turbine". A credit is sometimes taken for power produced prior to in-service date and this can amount to several million dollars. However, this has not been taken into account herein.

4.4 Interest During Construction

At 24% of the total project cost, this item, interest during construction, obviously plays a large part in the economics of a project. During the period 1968-70 when interest rates were rising rapidly, it played havoc with the cost of nuclear plants. It seems to have settled down now to between 8 and 9% for Canadian utility borrowings and the figures herein are based on 9% for the short term. The current emphasis on shortening of construction time is obvious.

The process of calculation of interest at the time of estimate preparation is similar to that used on any large project. Cash flow curves are drawn up for engineering, capital equipment and field work, and the interest calculated on the composite curve, compounded annually. Typical curves are shown in Figure 6 for a 72-month project.

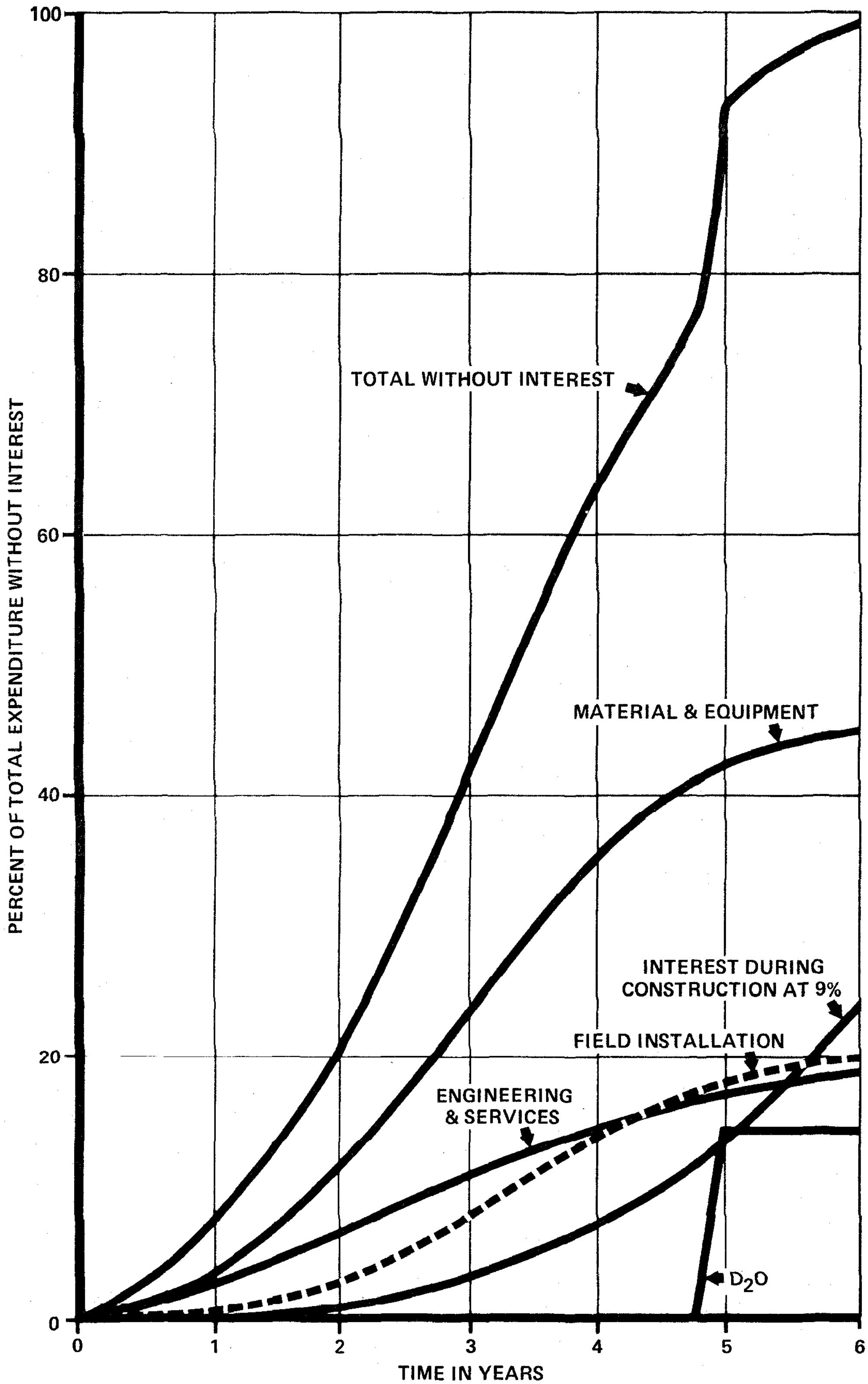


Figure 6 Single Unit 600 MWe CANDU-PHW Plant Cash Flow

4.5 Breakdown of Indirect Costs for 2 x 600 MW CANDU-PHW

A typical breakdown into the headings described above, for a two-unit 1200 MW nuclear plant, is given in Figure 7. It should be noted that escalation has not been mentioned thus far. The costs in Figures 5 and 7 are in constant 1972 dollars with no allowance for escalation. *Recent experience and current forecasts would predict about $64 million* escalation allowance on a project of this size and duration, based on average annual escalation rates of 5%, 7% and 8% on material, engineering and field labour respectively. Contingency allowances have been built into both the direct and indirect costs quoted above.

MILLIONS OF DOLLARS (1972)	
Engineering	46
Construction Overheads	29
Commissioning	12
Interest During Construction	122
Total Indirects	209

TYPICAL INDIRECT COST BREAKDOWN
2 x 600 MWe (net) CANDU-PHW

Figure 7

5. ENERGY COSTS FOR 2 x 600 MW CANDU

In order to determine unit energy costs for a plant coming into service in 1980, say, a number of assumptions have to be made after the current (1972 dollars) capital estimate is completed. The following would be typical of the AECL approach:

(1) Escalation up to the scheduled in-service date is included in the capital cost:

Directs	$\$301 \times 10^6$
Indirects	209
Escalation	64
Total	$\$574 \times 10^6$

(2) Plant life 30 years with sinking fund financing at long-term interest rate of 8%. ∴ Fixed charges 8.88%.

(3) Load factor 0.8

(4) Net output 1208 MWe

(5) Fuel cost $55/kgU

(6) Fuel burnup 211 MWh(thermal)/kgU (8,800 MWd/tonneU)

(7) Station efficiency 0.286

(8) Station operating and maintenance staff -

Professionals	30 @ $24,000 p.a.
Technicians	55 @ $16,000 p.a.
Trades	75 @ $15,000 p.a.
Miscellaneous	40 @ $13,000 p.a.

(9) Insurance $240,000 p.a.

(10) Purchased materials and services $1,050,000 p.a.

(11) Heavy water upkeep $550,000 p.a. *

(12) Interest on fuel inventory 8%.

The unit energy cost is calculated to be 7.56 mills/kWh for this hypothetical station, composed of capital charges, fuelling and operating and maintenance factors as shown in Figure 8.

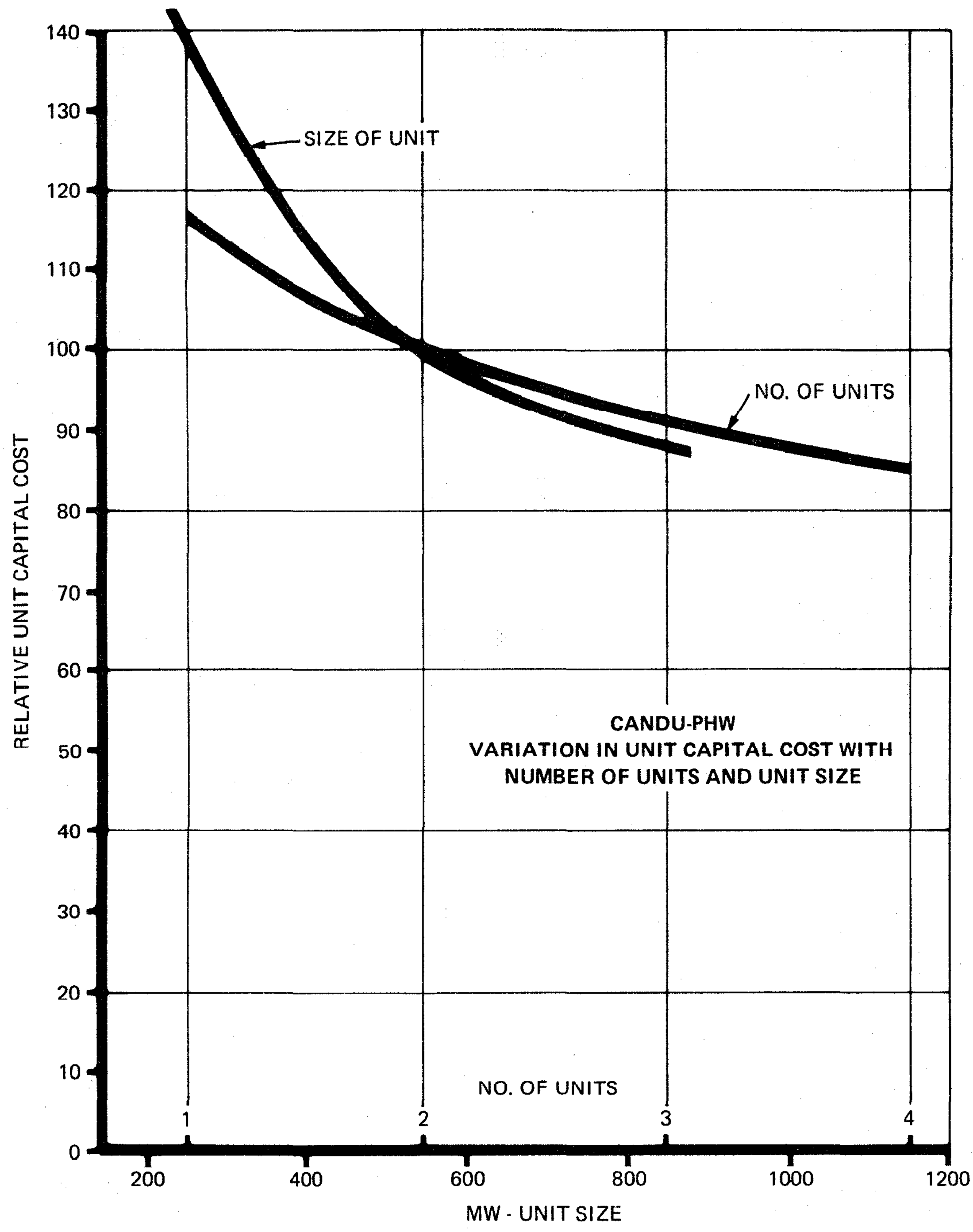
Mills/kWh (1980)

Capital Charges	6.01
Fuelling	0.91
O & M	0.64
Total	7.56

UNIT ENERGY COSTS
2 x 600 MWe CANDU-PHW

Figure 8

* Recent experience at Pickering would indicate that this number could be halved in future estimates.



RELATIVE UNIT CAPITAL COST
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
SIZE OF UNIT
NO. OF UNITS
CANDU-PHW
VARIATION IN UNIT CAPITAL COST WITH
NUMBER OF UNITS AND UNIT SIZE
NO. OF UNITS
1
2
3
4
200
400
600
800
1000
1200
MW - UNIT SIZE

Figure 9

6. EFFECT OF STATION SIZE ON COSTS

There are two aspects of station size which can contribute to substantial energy cost savings. One is larger unit size and the other is multi-unit stations.

Larger units tend to spread the indirects such as construction overheads and engineering over a bigger base, thus leading to reduced capital requirements in terms of dollars per kW. Heavy water quantity per kW also decreases with size. Reduced UEC is due to this capital reduction and also to lower unit cost of operations manpower. Multi-unit stations have similar advantages and, in addition, they reduce direct costs through spreading the manufacturers' overheads, tooling, etc., over higher production quantities.

Figure 9 represents a summary of several studies carried out by AECL over the last few years, and in a "broad brush" fashion shows the relationship between unit capital cost and size and number of units. The size-cost curve has not been taken farther than 750 MW, as definitive design and cost studies have not been completed yet for larger units. Any projection to 1200 MW at this stage would be purely conjectural extrapolation. An exact curve, of course, would not be smooth, as certain designs can accommodate "stretch" very economically, whereas at some stage in the process of increasing size a change in basic design arrangement is required which could put a backward "zig" into the curve. For example, one might have to go from four to six boilers per reactor because of practical limitations on boiler size, or from a small reactor having no neutron flux instability problem to a larger one requiring a zone control system.

The unit quantity versus cost curve covers the existing range from single-unit plants up to 4-unit plants like Pickering and Bruce and is based on studies for reactor unit sizes in the range 500 to 750 MW.

7. COMPARISON OF CANDU WITH FOSSIL-FIRED PLANTS

Current oil- and coal-fired stations are being built at about $250/kW for the two-unit 1200 MW size for service in 1980. With sulphur content of about 2%, coal laid down in Ontario is worth 53¢/MBtu today and rising rapidly. If coal by 1980 costs 60¢/MBtu, a conservative estimate, then energy costs are 8.96 mills/kWh, as given in Figure 10. Oil in Ontario comes to about the same energy cost if not higher. These estimates are based on 80% load factor. With the high fuelling component of cost, fossil plants will probably be operated at lower load factors, which will increase unit energy costs. It looks as if nuclear is here to stay, relative to fossil fuel, if the capital can be found to build the stations.

Mills/kWh

	CANDU	COAL-FIRED PLANT
Capital Charges	6.01	3.17
Fuelling	0.91	5.34
O&M	0.64	0.45
TOTAL U.E.C.	7.56	8.96

COMPARATIVE UNIT ENERGY COST
2 x 600 MW PLANT

Figure 10

8. COMPARISON OF CANDU WITH PWR AND BWR

Any comparison between published costs or estimates of American light water reactors and the CANDU system can be very misleading because of unstated differences in -

(i) financing terms - interest rates and compounding interval, depreciation methods.

(ii) extent of supply - are all utility costs included, e.g. training and commissioning, switchyard, site, environmental studies, etc. ?

(iii) fuel - is first charge capitalized or not?

(iv) overheads - are full utility overheads such as system planning, supply services, management, etc., included?

(v) escalation - 1972 dollars unescalated, or is escalation to the in-service date included?

(vi) site - provided fully developed or not even cleared?

The comparison I am making in this paper is not guaranteed to be free of all these anomalies, but so far as I have been able to determine from an interpretation of current publications and from Canadian and American utilities, who have studied the situation in some depth, the numbers in Figure 11 constitute a fair analysis of the competition within the Canadian utility operational environment today.

MILLIONS OF DOLLARS		
	CANDU-PHW	LWR
Directs (installed plant)	230	230
Interest during construction	122	95
Remainder of Indirects	87	84
SUBTOTAL	439	409
Inventories: Heavy Water	65	-
Fuel Charge	12	48
TOTAL (1972 Dollars)	516	457
Escalation to 1980 in-service	64	52
GRAND TOTAL	$580 x 10^6	$509 x 10^6
UNIT CAPITAL COST	$480/kW	$421/kW

Note: Project schedule 72 months for PHW; 66 months for LWR

Figure 11 Comparative Estimates 2 x 600 MW Plant

Costs obtained from American sources indicate not much basic price difference between the BWR and PWR, so I have averaged out information for these two types and called them simply LWR (light water reactor). The costs obtained were for various sizes of units and stations, and the curves of Figure 9 extrapolated where necessary, were used to bring the LWR costs to a 2 x 600 MW station size.

It can be seen that the basic cost of the plant, equipment, buildings and installation is no different for the LWR than for the PHW. The differences are in inventories (heavy water and fuel) and interest and escalation (due to schedule length). The light water reactors are currently being offered overseas on a 60-month schedule though schedules in the U.S. are longer, whereas we have offered 72 months for turnkey-type jobs. The cost comparison herein has been made on the basis of 66 months for LWR and 72 months for PHW. The reasons for higher fuel costs in the LWR are enrichment, the handling of enriched UO_2 powder and higher fabrication costs associated with the long small-diameter elements.

Figure 12 shows the unit energy costs resulting from these two comparable plants. In this table, the first column is as already described, except that the entire fuel charge is capitalized and the interest on fuel inventory has been put into fuelling UEC instead of O&M in order to line up with U.S. practice. For the LWR, the capital charges have been calculated in the same way and at the same rates as for the PHW.

The LWR fuelling cost is based on published figures, adjusted to delete reprocessing costs and plutonium credit in order to make it comparable to CANDU conditions.

For the O&M cost for the LWR, I have assumed a slightly smaller staff (six fewer people) as a concession to heavy water conservation costs. The assumed O&M cost (0.56 mills/kWh) is conservatively less than numbers being estimated by some American utilities today, when cost of contracted-out maintenance or "maintenance pool" operation is included, and somewhat more than figures quoted by nuclear plant suppliers for U.S. conditions.

Mills/kWh

	CANDU-PHW	LWR
Capital Charges	6.09	5.33
Fuelling	0.95	1.78
O&M	0.60	0.56
TOTAL	7.64	7.67

Note: All initial fuel capitalized.
Project schedule 72 months for PHW, 66 months for LWR.

COMPARATIVE UNIT ENERGY COST
2 x 600 MW PLANT

Figure 12

The total energy cost picture, then, as shown in Figure 12, is pretty well a saw-off between LWR and PHW in Canada. It is therefore a question of future trends in costs which are important.

9. TRENDS IN COSTS FOR CANDU VS. LWR

9.1 Production Runs Vs. One-Off

The Canadian costs quoted herein are based on a progression of "one-off" design and manufacturing efforts. The LWR is now established as production-line units. When Canadian nuclear requirements build up to the extent that two, three or four stations can be built with essentially the same NSSS (nuclear steam supply system), the PHW costs will come down. A study just completed has shown that a repetition of a 4-unit CANDU station with minimal changes due to site characteristics, switchyard connections, etc., would show a 12% reduction in cost. The engineering effort would be halved, and experienced manufacturers and construction and commissioning crews will reduce schedule and cost. Presumably, the American PWR's and BWR's have already benefitted to a considerable degree from repetition of designs.

9.2 Schedules

Ontario Hydro have analysed a typical LWR project, compared it to their own experience in building CANDU-PHW's, and find no basic reason why there should be a significant difference in project schedules. AECL is taking a hard look at this aspect too, as the savings are considerable. Figure 13 indicates the variation in interest and escalation with different schedule durations. Shorter schedules may be achieved by designing for fewer components or with repeat designs. (The third unit at Pickering was placed in full service 63 months after authorization.) If one assumes that both the PHW and the LWR can be built on 60-month schedules, the UEC becomes 7.11 mills/kWh and 7.45 mills/kWh respectively for 2 x 600 MW plants.

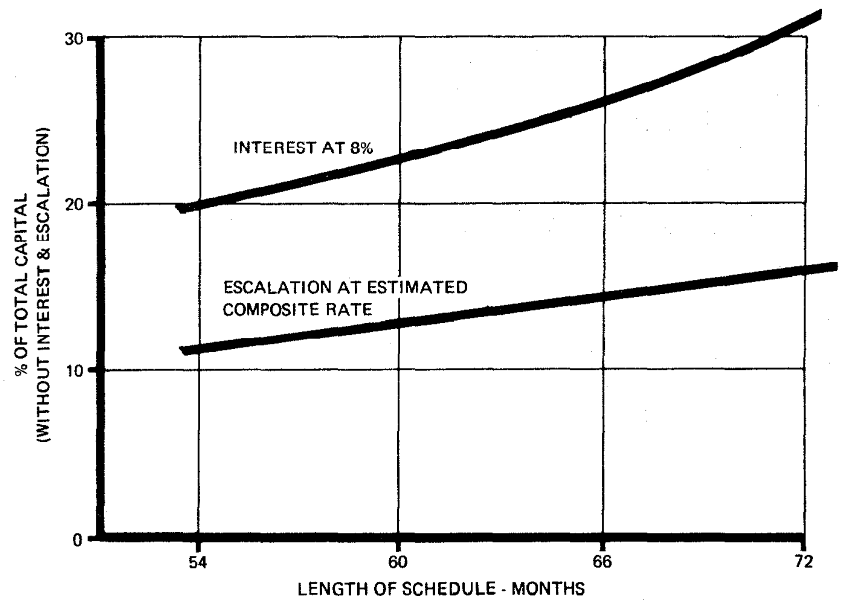


Figure 13 Variation of Interest and Escalation With Project Schedule for CANDU

9.3 Heavy Water

The cost of heavy water, as has been said already, is a major contributor to the capital investment in a CANDU station. With Canadian production now getting established and research proceeding on cheaper methods than the GS process now used, the price of this item should not increase as fast as prices in general over the long term.

9.4 Fuel

Since fuelling costs form such a small percentage of the energy cost for the CANDU, any future increase in uranium prices will not hit CANDU as hard as it will the LWR.

10. SUMMARY

There is no doubt that the economics show that nuclear power is here to stay, in areas where thermal power sources are required. Current costs show a saw-off between American-style PWR's and BWR's and the CANDU-PHW under the financing conditions that apply to publicly-owned utilities in Canada. Current trends suggest that the cost of the heavy water reactors should fall relative to the light water reactors.