A New Look at Nuclear Power Costs

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By the middle of 1973, nuclear power forecasts, based on cost estimates and actual contracts for several large stations and for their fuel supplies, indicated a rapid growth of the nuclear share of the energy market, with a possible target of about one-third of the world total energy input by the end of the century. These forecasts generally rested on cost comparisons with fuel oil-fired stations at a time when crude oil was selling in the range of $2 to $3 per barrel.
Less than a year later, the price of crude oil in major exporting areas had quadrupled to a range of $8 to $12 per barrel while domestic prices of oil products as well as of coal and gas had started a rapid rise which national regulations could only temporarily slow down. Any economic observer or indeed any policy maker could not have been blamed for inferring that a 300% increase in the price of the major competitive fuel which showed no sign of foreseeable reversal should lead to a sharp upward revision of nuclear power programmes limited only by the time requirements for expanding plant manufacturing capacity and the nuclear fuel cycle infrastructure. Political considerations of reducing dependence on imported fuels seemed to make the case for nuclear power even stronger. Revised nuclear programmes were indeed mapped out on the basis of these eminently reasonable arguments. Yet, by the end of 1975, the national projections for nuclear power growth have, with the exception of a few countries, receded not only below the targets considered in the first reaction to the oil crisis but even below the levels estimated at a time when availability of oil at one-fourth of its present price was taken for granted for the rest of the century.

The causes of this paradoxical outcome, illustrated in Table 1, are often divided into economic and non-economic categories. Though convenient, this is a somewhat artificial division. Except for the extreme view that "nuclear power is unsafe at any price", most concern so powerfully and often quite rightly voiced over the hazards specific to nuclear plants and their fuel cycles can, in the last analysis, be met by accepting additional costs. Safety of operation, protection of the environment, control of the various phases of the nuclear fuel cycle and especially of its back end have been or can be increased to an extent which brings nuclear risk expectation substantially below comparable risk values which are accepted as routine by-products of life in our industrial society. These measures have involved additional costs which are reflected in recent estimates both directly and indirectly through inclusion of additional safety features, greater engineering manpower costs, longer periods of construction, and increased contingency provisions.

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Nuclear power development demands improved training of the operator personnel. At the Pickering nuclear power stations in Ontario, Canada, a nuclear power plant simulator has been installed. The simulator complex is an exact operating duplicate of the control room for one of the four Pickering generating units. Operators will be trained on the simulator to develop experience in responding to normal, abnormal, and emergency conditions which they might encounter. Photo: CAE ▶

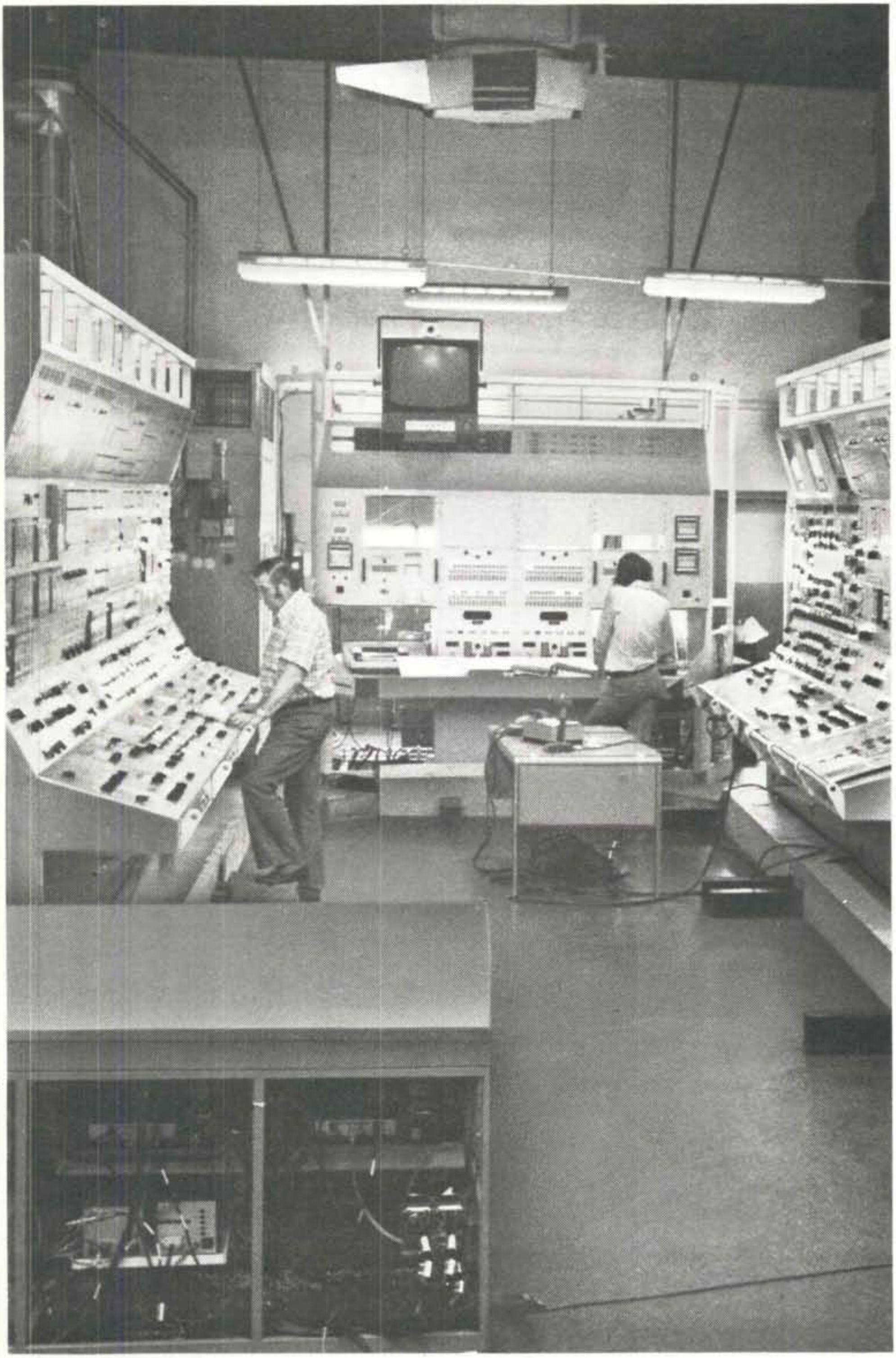

TABLE 1: Development of Estimates[1] of World Nuclear Power Growth[2]
(Installed Capacity — at year end — GWe)

Estimate Date Year	1969	1970	1973	1975	1976
1970	25.6	18	14	–	–
1975	101–125	118	94	71	–
1980	235–330	300	264	179–192	–
1985	–	610	567	475–525	440–450
1990	–	–	1070	875–1000	750–850
2000	–	–	–	2000–2500	1700–2000

1 OECD/NEA — IAEA estimates based on information supplied by member governments.
2 Not including countries with centrally planned economies.

TABLE 2: A Panorama of Capital Costs Estimates of LWR Stations in the 1000 MW(e) Size Range
(Expressed in Current US $ including Escalation)

Date of Estimate	Mid-67	Mid-69	Mid-72	Early 73	Late 74
Date of Operation	Mid-71	Mid-74	End 77	End 77	83
Unit Capital Cost (Current $ per kW(e))	134	200	350	440	720

TABLE 3: Average Estimates of Unit Investment Costs for LWR, Coal and Oil Fired Stations[1] in the 1000–1100 MW(e) Range
(Expressed in US $ of Mid-1974 Purchasing Power (1974 $ per kW(e)))

	LWR	Coal-Fired	Oil-Fired
1969 Estimates	267	235	200
1974 Estimates	500 ± 75	425 ± 40[2]	350 ± 25[2]
Range of Ratios of 1974 to 1969 Estimates	1.59–2.15	1.64–2	1.63–1.88

1 Twin units on the same average site with once-through cooling.
2 With SO_2 removal systems.

CAPITAL COSTS OF NUCLEAR POWER PLANTS IN RETROSPECTIVE

A first glance at the estimates of light-water-cooled and moderated reactor (LWR) investment costs made over the last seven or eight years shows figures spread over such a wide band as to severely shake any trust in the reliability of future figures. Table 2, based on the series of comprehensive studies carried out by the US Atomic Energy Commission (USAEC) over the years, summarizes this somewhat disturbing picture.

Taken at their face value, the unit capital costs of light-water-cooled and moderated reactor plants within the same size range would appear to have been multiplied by a factor of more than five over a span of seven years. If late 1975 estimates were taken into account this cost multiplication factor would approach six. Since neither the cost of equipment nor the amount of construction labour required showed increases of this magnitude, the situation obviously calls for further analysis, the first step of which is a separation of "apparent" increases due to inflation accounting from "real" cost additions arising from unexpected new requirements.

The accounting increases

The figures quoted in Table 2 contain variable amounts of escalation estimated over different periods of time at different rates which hinder considerably any attempt at determining real as opposed to accounting increases in nuclear power plant costs.

However important and necessary an accurate estimate of escalation may be for the manufacturer, the purchasing utility, the banker or the rate maker, its impact on total capital costs must be fully corrected for purposes of intertemporal or interstations economic comparisons. It should be clear that including escalation in total cost estimates is tantamount to measuring a distance between two points with a standard whose length would be shrinking; often irregularly, as one proceeded from the origin to the destination. Thus, the total figure of $720/kW(e) for a station for 1983 operation requiring, say, 7.5 years for construction is obtained by summing a certain number of dollars of 1976 purchasing power with another number of dollars of 1977 purchasing power, etc., all the way to 1983. Clearly this total is incommensurable with that of the payments estimated for an oil-fired station to be commissioned in the same year but whose construction would only start in 1978 or with that of the costs actually incurred for a nuclear station commissioned at a different time, since each total cost would be expressed as a sum of dollars of different values.

Another point of confusion arises from the estimate of interest during construction in periods of inflation. The amount of interest during construction is of course connected with the rate of escalation assumed not only because the progressive payments on which interest is due vary, but also because the rate of interest is itself dependent on the rate of escalation. Clearly funds will not be available on the same terms from either individuals or governments if the expected rate of inflation is, say, 10% or if it is 0. The same argument applies in a more general way to the rate of present worth discount. It is, however, often ignored in cost estimation.

Figure 1, taken from the comprehensive survey of nuclear power costs contained in the USAEC report WASH-1345, illustrates the importance of these points. Escalation for the LWR expected to be in operation in 1983 is of the order of 25% of the total while it was

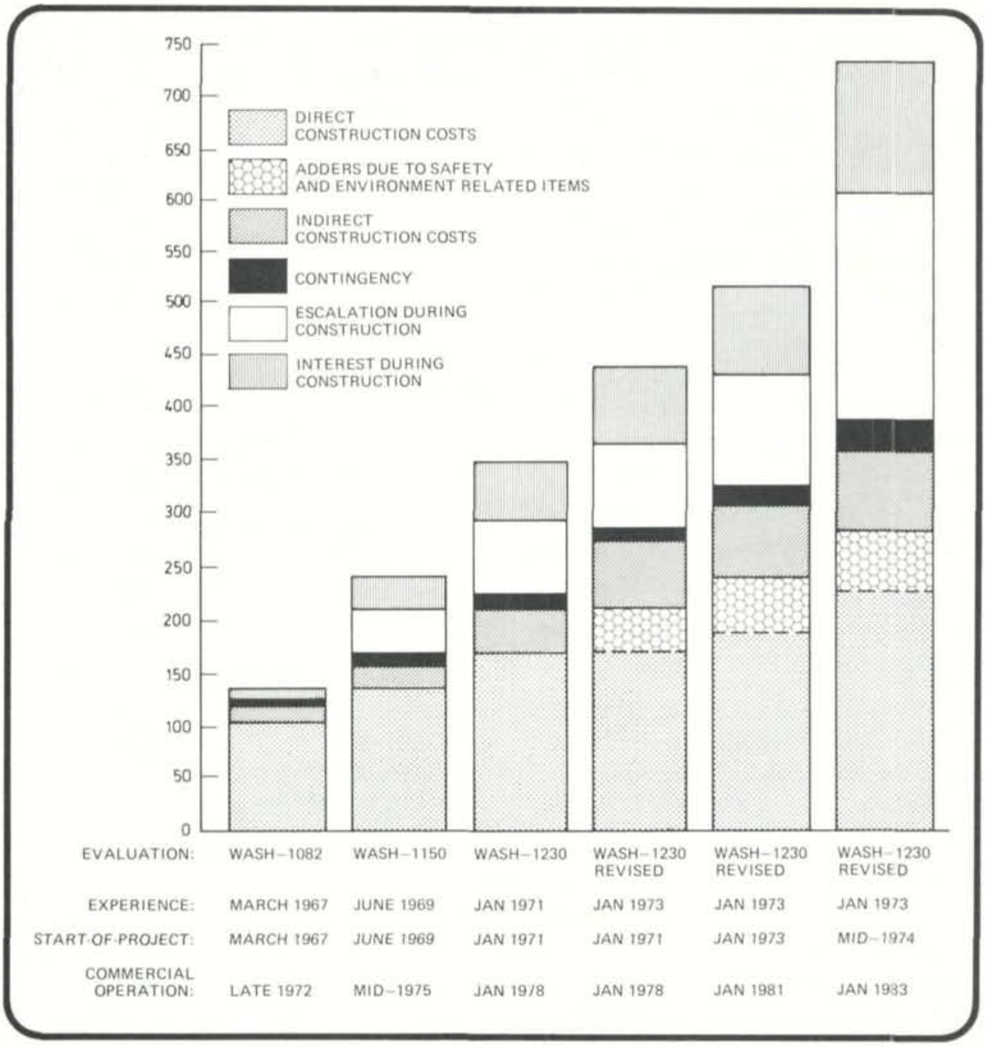

Fig.1. Comparison of nuclear plant cost estimates [total investment cost for 1000-MW(e) units]

an almost insignificant part of the 1967 estimates. But Figure 1 goes only part of the way, since even if the escalation estimates are removed from each total the results obtained are still expressed in monetary units of different purchasing powers ranging from 1967 to 1974.

The "real" cost increases

The next step is to bring all estimates to a common denominator by expressing all costs in terms of a dollar of a particular year. A particular example of such "corrected" economic comparison is shown in Table 3, where escalation has been removed, interest during construction adjusted and estimates made in 1969 and 1974 of the capital costs of nuclear, coal-fired and oil-fired stations in the 1000—1100 MW(e) range have all been expressed in constant dollars of mid-1974 purchasing power. While the figures obtained are unavoidably abstract averages with no relation to a specific case, they do however shed some interesting light on what has actually occurred over the last five years:

1. Estimated nuclear power plant investment costs expressed in constant dollars have increased over the last five years by 60% to 115% and not by 200% as Figure 1 may suggest.
2. Estimated capital costs of fossil fuel stations have also increased over the same period at rates which on the average are only marginally lower than those applying to nuclear stations.
3. The margins of cost uncertainty are somewhat wider for nuclear plants.

The causes of these increases are complex and interlinked. If we leave out the under-estimates connected with aggressive market penetration policies which prevailed essentially in the 1966—69 period, they can be roughly divided into environmental, safety, indirect and contingency cost changes whose detailed discussion is beyond the scope of this paper. However, it may be argued with some strength that environmental and safety considerations account for the bulk of the increases through additional equipment requirements, but especially through large expansion of engineering and construction services, a lengthening of the period of construction and a substantial expansion of contingency allowances.

Table 4, summarizing the 1969 and 1974 estimates for different categories of labour required for nuclear power plant engineering and construction, shows labour ratios falling within the range of the cost ratios of Table 3 and confirms to some extent the validity of the argument about the main causes of the cost rise.

Capital costs differentials of LWR stations

The data of Table 3 can be used to obtain rough estimates of the ranges of unit capital cost differences between large-scale light-water reactors in industrial countries and fossil-fuel-fired stations. Consistency requires one, however, to compare the upper values of estimates for nuclear plants with the upper values of estimates for fossil stations, for it would be somewhat illogical to assume that environmental considerations, which are one of the major causes of possible increases, would apply with special force to one category of power plants and not at all to another. Under these conditions the approximate range of unit capital cost differentials between nuclear and coal appears to be $40 to $110 per kW(e) and that between nuclear and oil $100 to $200 of mid-1974 purchasing power. To be conservative, the maximum differences of $110 against coal and $200 against oil might be retained as a general guideline.

It should be pointed out with particular strength that the above analysis refers only to large-size light-water reactor stations in industrial countries with major ongoing nuclear programmes. Any attempt to extrapolate these figures to estimate the costs of a first nuclear station in a developing nation, for instance, through simple relationships between unit cost und size would be both sterile and misleading. Variability of such fundamental factors as industrial and labour infrastructure site conditions, scope of supply, type of contract and financing terms makes each situation unique and any generalization impossible.

TABLE 4: Past and Present Average Estimates of Labour Requirements for the Construction of a 1000 MW(e) Nuclear Power Plant
(Millions of Manhours)

	1969 Average Estimate	1974 Average Estimate	Ratios of Estimates
I. Construction Labour:	6	11	1.83
II. Professional Services:			
a) Architect Engineering	0.7	1.2	1.71
b) Construction Management	0.7	1.3	1.86

TABLE 5: Estimated Range of Direct Front End Fuel Cycle Costs for a LWR at Equilibrium
(US $ of mid-1974)[1]

	$/kg of fuel	mills/kWh
Uranium and Conversion	339–500	1.41–2.10
Enrichment	296–440	1.23–1.83
Fabrication	120–150	0.5 –0.62
Total Direct	755–1090	3.14–4.55
Indirect Costs	–	1.23–1.80
Total Front End Costs	–	4.37–6.35

[1] 1000 MW(e) Station – thermal efficiency: 33%
fuel enrichment: 0.03
equilibrium burnup: 30,000 MWd/t

TABLE 6: Break-even Prices of Coal and Oil and Plant Site
(mid-74 $ per million kilocalories)

	Coal	Oil
Most Adverse Case for Nuclear Plants	3.76	4.56
Most Favourable Case for Nuclear Plants	1.84	2.35

Note: A present worth discount rate of 10% at constant prices and a 70% load factor were used for these calculations.

NUCLEAR FUEL CYCLE COSTS

During the last three years, the variations of the cost estimates of some of the major components of the nuclear fuel cycle have been even wider than those of nuclear plant investments. Particularly wide margins of uncertainty arise at the back end of the fuel cycle and it appears therefore reasonable to separate the front end costs from reprocessing and recycling.

The front end costs

Uranium. In the three years extending from 1973 to 1976, the price per lb of U_3O_8 has risen dramatically from the \$6 — \$8 range prevailing in the early seventies. The extent of this rise cannot, however, be summarized in a single figure. Neither the spot prices for limited quantities of uranium for 1976 delivery, which reached \$42 per lb at the end of 1975, nor prices paid for actual deliveries during the year under previous contracts, which range over much lower values, nor those accepted under new contracts signed during a period of special stress can be taken as reliable guides for the future.

The most that can be said is that the days of cheap uranium are gone, but that the results of the 1974—1975 price explosion are still to be felt in terms of new discoveries and production in promising areas where prospecting was limited or non-existent during a long period of glut. A reasonable range of future prices would seem to lie between \$20 to \$30 (of mid-1974 purchasing power) per lb of U_3O_8 with escalation in keeping with general inflation.

Enrichment. The present prices of enrichment services supplied by installations built several decades ago are also not indicative of future prices. The present level of \$53 to \$61 per kg of separative work charged by the USA is likely to be substantially exceeded for new installations and a range of \$80 to \$120 mid-1974 dollars with adjustments to keep up with general inflation seems to be indicated.

Fuel fabrication. This cost component has been an island of stability in the past and is likely to remain within a range of \$120—\$150 per kg of fabricated fuel.

Table 5 summarizes the consequences of these estimates for the cost components of 3% enriched uranium fuel and for the fuel component of the generating costs of electricity produced in a LWR station. They cover a relatively wide range of 4.37 to 6.35 mills per kWh. The brackets are even further widened when the back end of the nuclear cycle is taken into account.

The back end costs

The main cost components of the back end of the fuel cycle suffer from such margins of uncertainty as to make the economic analysis of their interaction a somewhat premature exercise. Taking only some of the major cost components, the following broad picture emerges:

Reprocessing. Considering the lack of commercial experience it is not altogether surprising to see estimated costs of reprocessing range all the way from \$150 to \$300 per kg as compared to the early 1972 estimates of \$40 per kg which, even when corrected for inflation, still represents a three- to sixfold rise.

Cost of fabrication of mixed Pu, U fuel elements. These costs have been estimated to fall within a range of $250 to $350 per kg. As a result the cost difference with uranium element fabrication may vary from $100 to $200 per kg.

The **value of the recovered uranium** will depend on the costs assumed for natural uranium and for separative work.

The **value of fissile plutonium** for recycling in light-water reactors will also depend on the above factors but in addition be influenced by the assumed economic penalties for mixed oxide fuel fabrication.

Thus, even in this highly simplified enumeration, we are led to a combination of uncertainties affecting four of the major interacting components: natural uranium, separative work, reprocessing and fabrication penalties. If only two extreme values were retained for each of them, sixteen cases would still have to be examined. For the present purposes it will suffice to state that very approximately the most favourable combination yields a profit of $150 per kg of heavy metal or about 0.631 mills/kWh; the most adverse shows a deficit of more than $100 per kg or more than 0.42 mills/kWh.

Considering the additional unknowns of ultimate waste disposal costs, it would seem reasonable for the present purposes to assume that reprocessing will just about break even and not factor it into the present very summary estimates. This does not in any way reflect upon the fundamental importance of the back end of the nuclear fuel cycle for the development of a mature nuclear industry.

The last point is all the more relevant as the range of estimates of the front end costs does not take into account either the cost of expanded fuel storage facilities at the plant site which will prove necessary if no reprocessing occurs nor the possibility of compulsory reprocessing even if it does not yield an economic benefit. Either eventuality would extend the upper limit of the total fuel cost range close to the 7 mills per kWh mark, while the lower limit might drop to 3.74 mills per kWh under the most favourable assumptions.

TENTATIVE CONCLUSIONS

In spite of the uncertainties emphasized in the previous sections, large-size nuclear power plants still retain a considerable economic edge in most situations. This conclusion follows quite clearly from Table 6, which sets out the break-even fuel costs of coal and oil (i.e. the levels above which nuclear plants begin to enjoy competitive advantages) under the most favourable and the most adverse combinations of assumptions estimated in this survey for nuclear investment and fuel costs.

If we concentrate first on the most adverse case, the levels of $3.76 per 10^6 kilocalories for coal and $4.56 per 10^6 kilocalories for fuel oil (corresponding roughly to $26 and $46 per ton) shown in that table are at present substantially exceeded at most locations and, barring a precipitous drop in oil prices which neither producers nor consumers seem to desire, they are highly unlikely to be reached in the foreseeable future. In the most favourable case the economic advantage of nuclear stations becomes overwhelming even though its exact value can only be determined through an analysis of the specific features of each particular case.

Under these conditions the reasons for the paradox of shrinking nuclear programmes in spite of obvious cost advantages must to a large extent be sought beyond the field of economics. The postponements and cancellations affecting the shorter term plant-ordering policies of the electric utilities of some major nuclear countries like the US might be explained as the result of the 1974–75 recession and by the accompanying stagnation of electric power consumption. Equipment ordered in the late sixties on the basis of an assumed rate of growth of demand of 6% to 7% per year came into operation in 1974 and 1975 when demand was not growing at all. This left several utilities with large reserve margins of spare capacity at a time when capital shortages and sharply increased fossil fuel costs made financing of new installations particularly difficult.

But this is only a partial explanation and the major cause is doubtless to be sought in the compounding of uncertainties. Some of these uncertainties may be approximately quantified as was done in this summary review, but the psychological impact of their accumulation on utility managers and government leaders is not reducible to simple figures. In addition, some major unknowns in the nuclear fuel cycle and the public acceptance fields can simply not be translated into cost equivalents. It is on the clarification of these questions and on their successful resolution rather than on a proliferation of economic comparisons that the future of nuclear power will depend.