Capital Investment Costs of Nuclear Power Plants

by Georg Woite

The estimation of capital investment costs for power plants is one of the most relevant steps in power system planning. The intention of this article is to summarize capital cost experience and estimates in industrialized and developing Member States, and to provide some guidance for cost extrapolation.

Various definitions of capital costs of power plants are currently used by different organizations or for different types of studies. As diverse definitions may lead to "costs" which differ by a factor of two for identical power units, this may cause a major misunderstanding. In this article, capital costs will be reported according to a set of definitions which has been found useful at the IAEA for long-range economic studies of a country's electricity system expansion. In these studies [1–6] the relative merits of different types and sizes of nuclear and conventional power plants for an expanding electricity generation system are compared over an adequate planning period. For this purpose, the capital investment costs of electricity generating units are defined as the total of direct and indirect costs of the complete power unit, including owner's costs, contingencies, and interest during construction. The costs are expressed in monetary units of a reference year, and are referred to the net electric power output of the unit. Costs of the initial fuel loading, heavy water (if applicable), taxes, duties, and escalation are excluded.

Other types of studies, e.g. financial studies, will require the inclusion of items listed above. When the country- or project-specific rules for escalation, taxes and duties are known, such cost estimates can be derived from the costs reported here. In order to further facilitate the comparison of cost experience and estimates from different sources, owner's costs, contingencies and interest during construction are identified separately. Costs excluding these items are called base costs.

CAPITAL COST EXPERIENCE

A first glance at the cost experience and estimates of nuclear power plants (see Tables 1 and 2) shows figures spread over such a wide band as to severely shake any trust in the reliability of future cost estimates. Figure 1, based on the series of comprehensive studies carried out on behalf of USAEC and USERDA since 1967, illustrates this somewhat disturbing picture. Taken at their face value, the unit capital costs of LWR plants within the same size range appear to have been multiplied by a factor of about six over a span of eight years. 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 to do this is a separation of "accounting" increases due to inflation from "real" cost additions arising from new licensing requirements or other reasons. The principal reasons for increasing capital costs are discussed below.

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Table 1: Capital Cost Experience [1]

		1	2	3	4
Plant type		BWR	PHWR	PHWR	PWR
Net electricity output (MWe)		640	320	207	626
Reference date		1963	1968	1976	1975
Site		Oyster Creek	Atucha	Rajasthan II	Angra
Country/Licensing conditions		USA	Argentina/ Fed. Rep. Germany	India	Brazil/ USA
Source		Ref.[9]	Ref.[13]	Ref.[15]	Ref.[13]
Cost in US $ (millions)	Direct			58	271
	Indirect			22	54
	Subtotal (base cost)	60	70	80	325
	Owner's costs	3	10	14	54
	Contingencies, etc.	1	incl.	incl.	incl.
	Interest	4	incl.	30	132
	Total	68[2]	80[2]	124	511
	Total cost in $/kWe net	106[2]	250[2]	600[3]	816

[1] Costs are in U.S $ of reference date. Fuel, heavy water, and escalation are excluded
[2] Costs of the customer.
[3] Exchange rate 9.12 Rs/$.

Regulatory impact: Safety and environmental protection requirements were increased to an extent which could hardly be foreseen in the earlier years of commercial nuclear power. This is particularly visible in the USA where the amounts of many important commodities (e.g. concrete, steel, pipes, cables) had to be practically doubled in order to meet regulatory requirements. The amount of man-hours of construction labour per kWe has increased proportionally. Because of extended schedule and increased complexity of nuclear power plant construction, the indirect costs have grown even more than the direct ones. More temporary structures are required to store, label and protect equipment and construction materials. About twice as many engineers, etc., are required for longer time per project to perform engineering and construction management services. Quality assurance and quality control is another example of substantially increased requirements. The number of

Table 2: Recent Nuclear Plant Cost Estimates[1]

	1	2	3	4	5	6	7	8
Plant type	PWR	PWR	PWR	BWR	PWR	PWR	PHWR	PHWR
Net electricity output (MWe)	600	900	1139	1190	1100	1230	638	1100
Reference date	1976	1976	1976	1976	1976	1977	1976	1976
Site	———	Middletown, USA		———	West USA	Not specified	Ref.[12]	Middle-town
Country/Licensing conditions	USA	USA	USA	USA	USA	Fed. Rep. Germany	Canada	USA
Source	Ref.[16]	Ref.[11][2]	Ref.[10]	Ref.[16]	Ref.[18]	Ref.[14]	Ref.[12]	Ref.[17]
Remarks					High estimate	Turnkey		
Cost in US $ (millions)								
Direct	325	378	421	432			257	491
Indirect	115	136	148	151			115	155
Subtotal (base cost)	440	514	569	583	655	820	372	646
Owner's costs[3]	50	60	65	65	70	80	50	70
Contingencies, etc.[3]	35	40	45	45	50	incl.	30	50
Interest[3]	170	196	220	222	250	250	145	245
Total	695	810	900	915	1025	1150	598	1011
Total Cost in $/kWe net	1158	900	790	770	930	935[4]	937	920

1 Costs are in U.S $ of reference date Fuel, heavy water, and escalation are excluded.
2 Updated by IAEA staff.
3 Estimated by IAEA staff if not specified.
4 Exchange rate 2 2 DM/$.

standards applicable to the design and construction of a nuclear power plant in the USA grew from about 100 in 1970 to about 1600 in 1976. Analyses of the combined effect of regulatory requirements led to the conclusion that they have increased the capital costs of nuclear power plants by a factor of two since the early years of commercial nuclear power.

Inflation and interest during construction: Annual inflation rates in industrialized countries increased considerably since the early years of nuclear power. They have also led to higher nominal interest rates. Together with extended design and construction periods, this means that both the absolute and relative importance of inflation and interest during construction have increased considerably.

Commercial effects: Before 1970, reactor manufacturers and architect-engineers were willing to undergo substantial commercial risks to enter a new and very promising market. A number of low-priced contracts reportedly led to substantial financial losses of the vendors. After the quadrupling of oil prices in 1973, they found themselves in a much more favourable situation. Consequently, their prices have been rising to a level suitable to cover all their usual commercial risks. More recently, as a result of public opposition, of reduced economic and electricity demand growth, and of financing and other difficulties, the nuclear power programmes of many countries were revised downwards substantially since 1975. Consequently, more competition among manufacturers and architect-engineers can be expected now and in the near future.

CURRENT CAPITAL COST ESTIMATES

Some current capital cost estimates are summarized in Table 2. The estimates in columns 1 to 4 and in 8 are consistent with respect to licensing and economic conditions; they are based on quasi-ideal site conditions. It can be seen that the estimates for 1100–1200 MWe units vary between $770 and $940 per kWe, depending on the scope of supply and economic conditions[1]. Boiling-water reactors are estimated to cost about the same as pressurized-water reactors (col. 3 and 4). Heavy-water reactors are estimated to cost about 15% more than light-water reactors if the same site and licensing criteria are applied (col. 3 and 8). However, if Canadian licensing criteria of 1976 are applied to a 600 MWe CANDU-type HWR, and US licensing criteria of the same year to a PWR of the same size, the CANDU-type HWR is estimated to cost considerably less than the PWR (col. 1 and 7).

Current, but so far unpublished cost estimates for 600 MWe projects indicate total costs[2] of $800 million ($1300/kWe) or more for both light-water and heavy-water reactors.

EXTRAPOLATION OF CAPITAL COST EXPERIENCE

The extrapolation of construction cost experience to future projects, possibly in other countries, is very difficult since there exists a great number of cost-influencing factors, some of which are hardly predictable. However, for approximate estimates needed for nuclear power planning studies, a number of principal cost-influencing factors can be identified.

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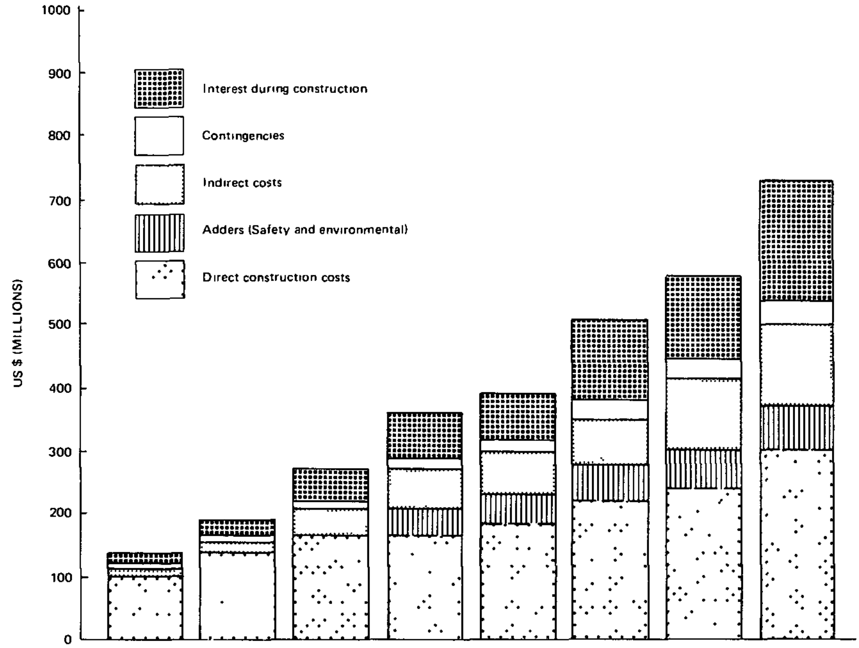
[1] In 1976 US $, including owner's costs, contingencies, and interest during construction, excluding fuel, D_2O *and escalation.*

[2] In 1977 US $, inclusions and exclusions as above.

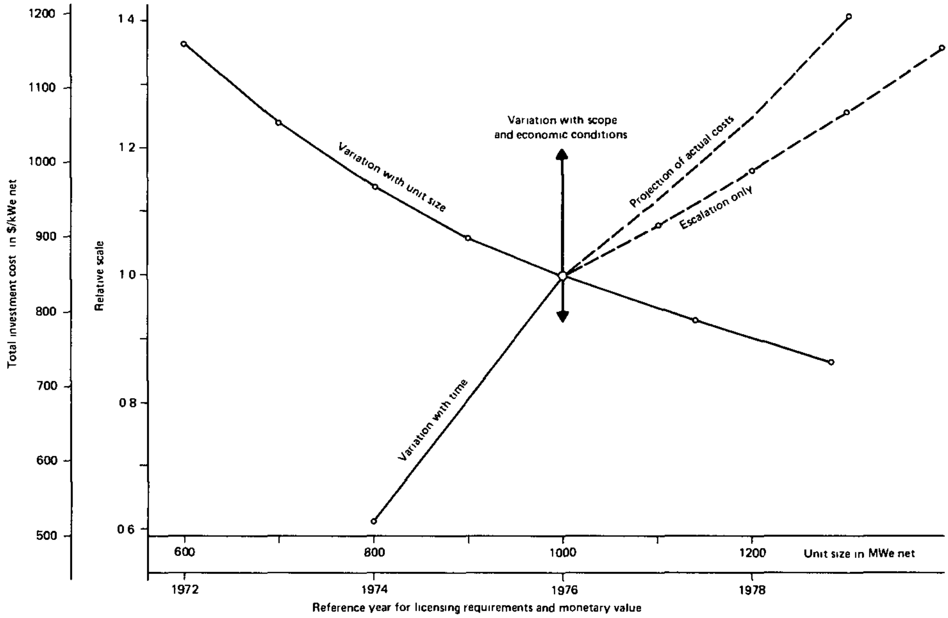
Figure 1: Nuclear Plant Investment Cost Estimates[1] for Single 1000 MWe Light-water Reactor Plants



EVALUATION	WASH 1082	WASH 1150	WASH 1230	WASH 1230 REVISED	WASH 1230 REVISED	WASH 1230 REVISED	WASH 1345 REVISED	WASH 1345 REVISED
EXPERIENCE	3/67	6/69	1/71	1/73	1/73	1/73	1/74	1/75
START-OF PROJECT	3/67	6/69	1/71	1/73	1/73	MID 74	1/75	MID 1976
COMMERCIAL OPERATION	LATE 1972	MID 1975	JAN 1978	JAN 1978	JAN 1981	JAN 1983	JAN 1985	MID 1986

[1] In US $ at start of project Sources Refs [7 8 11]

Figure 2: Variation of nuclear power plant cost with time and unit size[1]



[1] The reference value corresponds to the total investment costs excluding fuel and escalation of a 1000 MWe net PWR (USA) under quasi ideal site conditions

Table 3: Scaling exponents[1] for nuclear power plant costs

No.	Account	Cost models 1971–1975	Cost models 1976–1977
21	Structures	0.4	0.2
22	Reactor plant	0.6	
	Nuclear Steam Supply System		0.3
	Balance of reactor plant		0.41
23	Turbine plant	0.8	0.75
24	Electric plant	0.6	0.37
25	Miscellaneous	0.3	0.2
	Base cost	0.6	0.45

[1] Scaling exponents **N** are used to extrapolate given costs C_o (in millions of dollars) of a unit size S_o (in MWe) to a different unit size **S** by

$$\frac{C}{C_o} = \left[\frac{S}{S_o}\right]^N$$

The scaling should not be applied to unit sizes below 600 MWe.

Unit size: The stringent licensing requirements which are currently applied affect small and medium power reactors more (in relative terms) than they do larger reactors (1000 MWe or more). Before 1976, the base cost of a 600 MWe nuclear unit was estimated to be about 26% less than that of a 1000 MWe unit (or, in other words, the cost in $/kWe was estimated 23% higher for the 600 MWe unit). Since 1976, the base cost of a 600 MWe unit is estimated only about 20% less than that of a 1000 MWe unit, this means that the cost in $/kWe is estimated 33% higher for the 600 MWe unit. This is reflected in scaling models (see Table 3) which show smaller scaling exponents for the 1976/77 cost model than for the earlier one, indicating less variation of costs with unit size. Application of the 1976/77 scaling model leads to a variation of costs with unit size as illustrated in Figure 2.

Time: Construction costs of nuclear power plants are subject to ongoing general inflation and, additionally, to increasing safety and environmental protection requirements. Together with extended construction schedules and higher interest rates, this has led to a very sharp increase in total plant costs in the past few years. The development of licensing criteria is still progressing. However, declining interest rates (in some countries), increasing competition among manufacturers, and (hopefully) standardization should prevent nuclear power plant costs from escalating at such high rates as in the past.

In Figure 2, the 1976 cost reference value is tentatively projected at annual rates of 8% (assumed for general inflation) and 12% (possible combined effect of inflation, licensing criteria, and other factors as discussed above).

Scope of supply: The technical scope of a power plant depends on site conditions, licensing criteria, and technical specifications by the customer. In Table 4, some items are described which may deviate from the standard scope of supply, and tentative cost estimates are provided.

Some potential cost additions will be particularly applicable to developing countries, e.g., the construction or improvement of transportation and unloading facilities, improvement of the telecommunications system, electricity and water supply to the site, and a construction camp (or allowances for transportation of construction workers). Furthermore, utilities in developing countries will generally aim at a higher degree of self-reliance with respect to maintenance and repair than is usual for utilities in industrialized countries. This is logical to avoid long outage times needed for transportation of special tools, testing and inspection equipment, or spare parts which can only be obtained from the manufacturer's country.

Economic conditions: Interest and inflation rates have been discussed above together with other time-depenent factors. Additionally, the prices of land, power plant equipment, construction materials, and wage rates vary from country to country and also from site to site. The effect of these variations may be assessed, for instance, by the use of the computer programs CONCEPT /19/ or ORCOST /20/. These computer programs are available from the IAEA for release to Member States.

It should be noted, however, that potential savings have often been overestimated, particularly for construction labour costs and labour-dependent indirect costs (engineering, construction services, etc). Experience has shown that the effect of low wage rates is largely offset by low labour efficiency. Also, wage rates at nuclear power projects are often higher than the country's average rates. Finally, the work which remains to be performed by foreign specialists will cost substantially more than in their home countries. It is beyond the scope of this article to discuss the implications of other important parameters which may have a decisive influence on the comparative cost analysis of different bids, for instance, the amounts and conditions of loans, exchange rates of local to foreign currency, and the variation of the exchange rates with time.

COMPETITIVENESS OF NUCLEAR POWER

Numerous concerns on the potential risks from nuclear power stations and on their environmental and social impacts have been raised in industrialized countries. Legal questions originating from these concerns were repeatedly answered with additional safety and environmental protection equipment. This development has led, together with other factors, to soaring nuclear power plant investment costs. The prices for uranium and some nuclear fuel cycle services were also increased dramatically. As a consequence, nuclear electricity costs have been rising beyond the rates of general inflation. However, since similar events have taken place in the field of fossil fuels, nuclear base load electricity has still kept an economic margin over fossil-fired base load electricity in most of the industrialized countries. In developing countries, the competitive position of nuclear power is generally weaker than in industrialized countries. Reasons for this are:

- Nuclear power requires a large initial investment which is difficult to raise in most developing countries.
- For reasons of electrical grid stability, the installation of 1000 MWe or larger units is not acceptable in most of the developing countries. The specific investment costs (in $/kWe) for smaller units are higher.
- Nuclear power plants will generally cost more in developing than in industrialized countries.
- Due to less stringent environmental regulations, oil- or coal-fired power plants can be built without SO_x removal systems in many developing countries; their capital investment costs and operating costs will therefore be lower than in industrialized countries where this is not permitted.

Unfortunately, equivalent cost reductions are not possible for nuclear units, since they are designed to meet the licensing requirements of the manufacturer's country. However, big electricity generating units will generally be located not too far from load centres. Regarding the increasing air pollution in these industrialized and densely populated areas of developing countries, it can be assumed that SO_x removal systems will be required in an increasing number of countries for power units of 600 MWe or more. Hence, it would be misleading to assume that the capital cost ratio of nuclear units including all usual safety and environmental protection requirements and of oil- or coal-fired units excluding equivalent provisions would generally characterize the economic competitiveness of nuclear power in developing countries. It will be necessary to evaluate the competitive situation of nuclear and conventional energy resources specifically for every country.

Although commercial competitiveness is a very relevant element in the decision-making for big capital investments, there may be some strategic aspects which could call for the construction of a nuclear power plant even if it is not fully competitive in current economic terms:

- A nuclear power project may help to develop the local industry.
- The prices of competing energy resources are expected to escalate faster.
- A nuclear power project will lessen the dependency on oil imports.

Other strategic aspects may be counter-productive, particularly for developing countries:

- Non-proliferation concerns have caused a number of restrictions for the export of nuclear equipment, materials, and know-how.
- A complete nuclear fuel cycle is beyond the possibilities of most countries; decreasing dependency from oil imports will then correspond to increasing dependency from imports of nuclear fuel and services.

The latter aspects could induce decision-makers to delay the decision for a nuclear power plant even if it would be competitive for base load electricity generation.

CONCLUDING REMARKS

Soaring costs of nuclear power projects far beyond the originally estimated limit have led to great difficulties, to disappointment, controversies, and even to the cancellation of projects. This has happened also among countries and companies with some experience in nuclear technology. It appears to be even more difficult for inexperienced countries and companies

Table 4: Typical cost variations for nuclear power units

A) Variations of technical scope[1]

Account No.	Description of cost items	Cost variation in US $ (millions) Low	High	Example
	Direct Costs			
20	Site evaluation (incl. detailed evaluation of soil structure, measuring of natural radioactivity, fauna, flora, meteorology	3	6	4
21	Opening of the site (water, electricity, access road[2], communication system)	2	10	3
	Site improvement (excavation of rocky ground or foundation on non-solid ground, drainage, etc.)	2	20	5
	Water intake/discharge	–5[3]	20	0
	Flood or wave protection	0	10	2
	Seismic protection[4]	0	20	0
	Protection against tornadoes and gas cloud explosions	–15[3]	0	0
	Additional spent fuel and waste storage	5	10	5
	Provision for subsequent units at the same site	5	10	0
	SUBTOTAL for accounts 20–21[10]			19
22	Protection against aircraft crash	10	15	0
23	Additional bypass system[5] and control equipment for easier operation and maintenance	5	10	5
25	Facilities for inspection and repair of contaminated equipment[6]	2	5	2
	Spare parts[6,7]	2	8	3
	Transportation costs[6]	10	15	10
	SUBTOTAL for direct plant costs (accounts 20–25)			39

Table 4: (continued)

Account No.	Description of cost items	Cost variation in US $ (millions) Low	High	Example
	Indirect Costs			
92	Engineering and construction management services incl. execution supervision and special consultancy[6]	10	20	10
93	Staff training	3	5	5
93	Construction camp[6] (housing and social facilities) incl. maintenance costs for the construction period; or allowances for transportation of workers	5	20	6
93	Other owner's costs (quality assurance by owner, redrawing and translation of documents, general and administrative costs, public information center)	20	35	20
	SUBTOTAL for indirect costs			41
	Expenditures before start of construction			
	Preparatory studies, planning, preliminary engineering by utility or consultants, feasibility studies	2	4	2
	Site survey, pre-selection of sites	1	2	1
	Tendering, bid evaluation, contracting	1	4[8]	3
	Expenditures for facilities outside the power plant			
	Construction or improvement of transportation facilities outside the power plant fence (roads, railroad, harbour)	4	10[9]	10
	Barges, trailers	1	2	2

Table 4: (continued)

Account No.	Description of cost items	Cost variation in US $ (millions) Low	High	Example
	Expenditures for facilities outside the power plant (cont.)			
	Main transformer	3	4	3
	Switchyard	6	10	6
	SUBTOTAL for expenditures before start of construction or outside the power plant fence			27
	TOTAL for variations of technical scope[10]			107
	B) Variations of economic conditions			
20	Land and land rights[11]	– 0.9	5	0
21–25	Equipment costs [12]	0	40	20
21–25	Materials costs[12]	–10	10	0
21–25	Labour costs[13]	–40	0	–10
91–93	Labour-related indirect costs[13]	–20	20	10
	TOTAL for variations of economic conditions			20

[1] Scope variations as compared to Ref. [10] (Basic scope corresponding to early 1976 US licensing requirements and ideal site conditions) The "low" and "high" variations should be understood as typical rather than as absolute minima or maxima. The cost variations are given in early 1977 US $ The apply to 600 MWe nuclear units; many of them to not vary substantially with unit size.
[2] Inside the power plant fence.
[3] For less stringent licensing requirements than currently required in the USA.
[4] Including protection against seismic liquefaction of sandy ground, Seismic protection up to a horizontal acceleration of 0.25 g is included in current US licensing requirements. The "high" cost variation corresponds to protection against 0 4 g.
[5] For 100% steam flow to bypass the turbine
[6] Particularly applicable to developing countries.
[7] Two million dollars are assumed as costs of spare parts for standard US requirements.
[8] Higher costs are likely for a thorough evaluation of a multi-system package-type approach.
[9] Construction of bridges could further increase this cost item.
[10] Subtotals and totals for the low- and high-cost variations are not indicated since they are not likely to occur simultaneously.
[11] One million dollars are assumed as average land costs; the "high" cost variation corresponds to densely-populated areas with high land costs.
[12] Variation of prices for equipment and for construction materials.
[13] Variation of wages, salaries, and overheads; substantial savings in labour-related costs are not likely for a first nuclear project.

to control the costs of a nuclear project unless they buy a standard nuclear unit from an experienced supplier, which means little participation of the local manufacturing and engineering capacity.

Construction and start-up delays are among the most important reasons for higher costs since they increase escalation, interest during construction, and lead to additional costs for replacement electricity supply or to an electric energy deficit (if not at the company level, then at the national economy level). Schedule control by good planning and construction supervision is therefore one of the most relevant means of cost control. It must be supported by timely political decisions and adequate contractual arrangements such as the ones listed below.

— A country embarking on nuclear power should decide early on its policy of the development of the local industry. Since an over-estimate of the domestic industrial capacity, particularly with respect to quality standards, is likely to result in severe difficulties later, it is essential to perform a thorough investigation of local capabilities at an early date.

— An early decision on the priorities of either economically competitive generation of nuclear electricity or transfer of nuclear technology to the local industry is indicated. A contract for a "learning plant" with maximum local participation is likely to have a cost disadvantage as compared to the purchase of a nuclear unit with minimum local participation, and may not result in economically competitive electricity generation, but will (if efficiently organized) lead to strongly increasing local participation in follow-on projects, and thus to an advantage in the long run for countries with a great potential nuclear energy demand.

— A checklist of the required principal decisions on environmental and safety matters and on the development of technical infrastructure should be developed. Delayed decisions on regulatory requirements, on a higher voltage level of the transmission system, or on the development of the land-based and water-based traffic system can hold up a nuclear project considerably.

— It is essential to decide which codes and standards shall be applicable to a nuclear power project. The ideal case is that only one supplier country is involved in a nuclear power project, and that its codes and standards are the same as in the recipient country. This will facilitate contributions by the local mechanical and electrical industry.

— Maximum use should be made of standardized design of nuclear power units. Deviations will generally be costly; if one or the other system is omitted, not much money may be saved, and safety and performance of the resulting modified design may be questionable.

— It is vital to define a reference plant for every nuclear project. Reference should be made to the design and to the safety analysis report. Other "software" as for instance the construction schedule and the project organization should also be adopted as far as they are applicable to the conditions in the recipient country.

— The scope of supply should be defined as exactly as possible in the technical contract. Spare parts, special tools for inspection and maintenance, nuclear fuel services, etc. should be included from the beginning. Scope changes are likely to cost more when they are contracted later.

The Agency is prepared to guide Member States with respect to the planning and implementation of nuclear power projects. It has issued Guide books [21, 22] and is holding international nuclear power training courses and regional seminars. Advisory missions and technical assistance to individual Member States are carried out where this is requested. These missions may help in estimating the costs of nuclear projects, and in keeping their costs and schedule under control.

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