Nuclear energy: facing the future

by H. J. Laue*

When the International Atomic Energy Agency was established on 29 July 1957, 15 years after the feasibility of producing energy from uranium had first been demonstrated, three nuclear power plants with a capacity of 105 MWe were in operation in two IAEA Member States. By 29 July 1982, 277 power reactors in 24 countries, with a total capacity of 157 500 MWe, will provide around 9% of the world's electricity.

These numbers clearly show how, within 25 years, nuclear power has become a reliable and economic source of energy. Its development is based on immense scientific and technical research and development programmes which analysed possible failures, their likely effects, and how they could be prevented by effective safety devices, more seriously and more carefully than has been done for comparable energy technologies. Since the introduction of the first nuclear power plants in the 1950s more than ten different concepts have been developed and some of them tested. Today four reactor types have found large-scale application: the pressurized water reactor; the boiling water reactor; the heavy-water, natural-uranium reactor; and the gas-cooled reactor. The annual growth of nuclear capacity and electricity generation throughout the world over the past 25 years is shown in Figure 1.

As more nuclear power plants came into operation and as practical experience with them increased, there have been significant changes in the detailed design to produce more economic and reliable plants, which could meet more rigorous safety regulations, discharge less radioactivity to the environment, and be less sensitive to human errors and equipment failures. It seemed that all requirements had been satisfied for nuclear power to fulfill its major role in the future energy mix. Moreover, with the timely introduction of fast breeder reactors and high-temperature reactors nuclear energy would be able to make a permanent contribution to the world's energy problems, providing a substitute for oil.

A harsh reality

However, the reality did not keep step with technical and economic development. Over the past twelve years there have been drastic revisions in nuclear power forecasts. Projections of installed capacity for the period up the year 2000, as reported in the IAEA's Annual Reports, are shown in Figure 2. There has been a steady decline in the projections for the short-term (1975 and 1980) and since 1975, a dramatic decrease in the projections for the longer term (1990 and 2000). Even with the oil crisis of the mid-1970s and the various national programmes to switch from oil to other energy sources, the capacity projections made in the late 1970s for 1990 and 2000 plummeted. The projections for 1990 and 2000 published in the 1980 Annual Report were one-third to one-fifth of those published in the 1973–1974 Annual Reports. This decline is in spite of the fact that the price of oil has increased by a factor of at least seven during those six years and that hydrocarbons were widely realized to be in short supply. Although the 1990 capacity projections show signs of "bottoming out", some recent studies indicate that the actual turnout in 2000 could be as much as 20% lower than the projection reported by the Agency in 1980.

The reasons for this drastic reduction are many*

First of all, there was the economic situation: the more efficient use of energy, the relative decrease of highly energy-intensive productions, and the economic recession in industrialized countries led to a much slower increase in demand for electricity. Consequently, new orders for nuclear power plants did not materialize in some countries.

In addition, the introduction of nuclear power on a large scale was curtailed through a lack of public confidence, arising from concern about reactor safety and the disposal of nuclear waste, and from unbalanced public perception of various risks. As a result, many countries hesitated to take long-term decisions on nuclear power because of their political implications.

Finally, as the International Nuclear Fuel Cycle Evaluation Study (INFCE) concluded, there is the possibility that civilian nuclear facilities could be misused to produce nuclear weapons (although this is not the usual or most efficient route). This possibility became a major concern of the public and the governments in some supplier countries, and has hindered the further development or introduction of nuclear power in both developed and developing countries.

* Mr Laue is Director of the Agency's Division of Nuclear Power.

* See *Nuclear power development – the challenge of the 1980s* by Sigvard Eklund in IAEA Bulletin Vol.23 No.3 (September 1981).

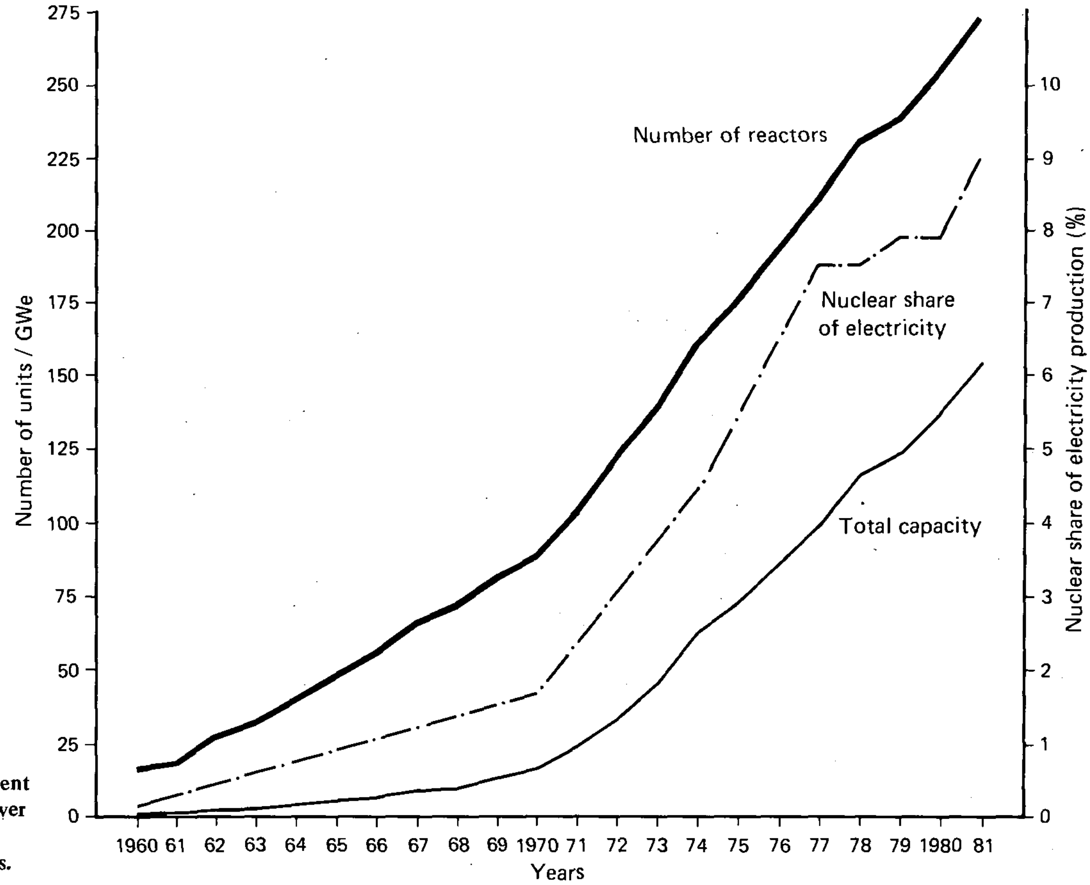

Figure 1.
The development of nuclear power in IAEA Member States.

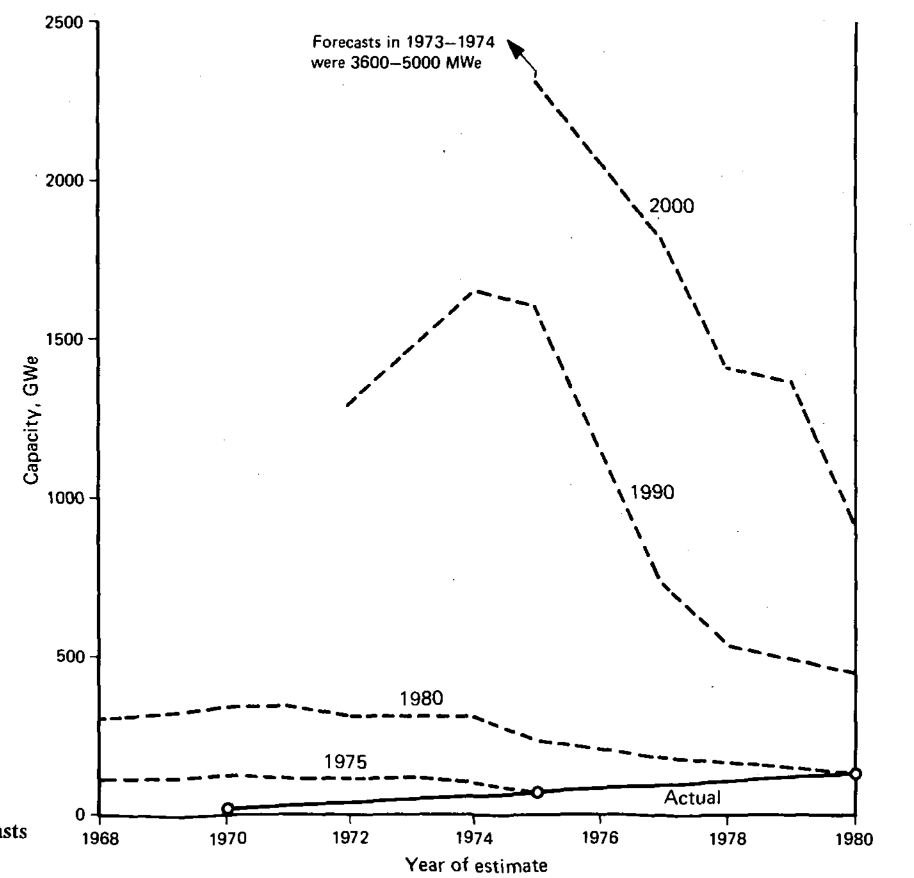

Figure 2.
History of nuclear power forecasts (from IAEA Annual Reports).

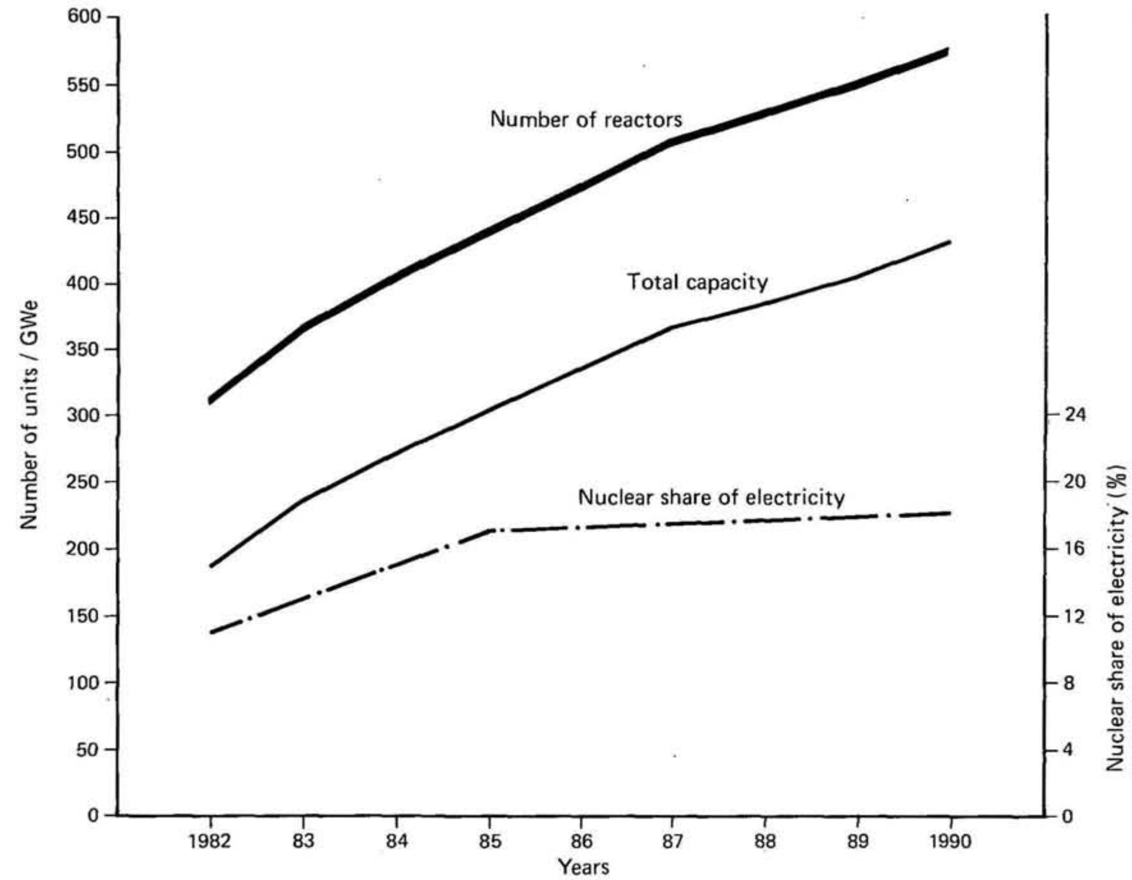

Figure 3. Projected growth of nuclear power in IAEA Member States.

Revised forecasts

Only the nuclear power expansion up to the end of this decade (Figure 3) can be forecasted with some degree of accuracy. The nuclear generating capacity will be approximately 430 GWe by 1990 or around 18% of the total electrical production. Nuclear power therefore cannot be expected to make its "break-through" in the forthcoming decade. The projected 1% increase of the nuclear share of electricity generation between 1985 and 1990 is almost exclusively due to political and economic uncertainties, increasingly complicated and stricter regulatory procedures, and to the lack of standardization of plants and major components. Undoubtedly, the nuclear industry in many countries will suffer at the beginning of the next decade, as a result of this situation.

Among the 33 countries with nuclear power plants in operation by 1990, there will be only ten developing countries. Their 38 power plants represent a total capacity of 24 000 MWe and will provide less than 5% of the total electricity generated in all developing countries, compared to 20% which nuclear power will provide for the industrialized countries. (This estimate is based on figures for power reactors in operation and under construction or committed for start of construction within the next two to three years.)

Estimate of world-wide nuclear generating capacity by main country groups up to the turn of the century as presented in the IAEA's Annual Report for 1981 are given in Table 1. Estimates of total electrical generation and of the nuclear contribution are given in Table 2. On the assumption that nuclear power plants will continue to provide mainly base-load electricity, the tables show that a worldwide 23% share of nuclear electricity generation at the turn of the century can only be reached if the reliability of nuclear power plants is improved.

Many nearly complete or operating nuclear power plants have been beset by financial, management, licensing, and technical problems. The number of such plants has grown to around thirty worldwide, corresponding to a total capacity of 27 000 MWe. Of these plants seventeen have never operated or were stopped indefinitely when between 30 and 100% complete: they include Busher in Iran and Zwentendorf in Austria. During the first half of 1982 alone, 13 US plants joined this category, primarily because of mismanagement, financial troubles, and reduced need for electric power; political uncertainty also played a part. Seven plants worldwide have been inoperable for at least two consecutive years for repair, backfitting and licensing reasons, and several are at present limited

Table 1. Estimates of total and nuclear electricity generating capacity by main country groups (GWe)

Country group	1981 Total	1981 Nuclear	1981 %	1990 Total	1990 Nuclear	1990 %	2000 (projected) Total	2000 (projected) Nuclear	2000 (projected) %
OECD North America	748	63	8	1063	145	14	1405	185–235	15
OECD Europe	468	54	12	734	150	20	1100	225–315	24
OECD Pacific	193	15	8	340	31	9	510	90–130	22
CPE Europe[1]	404	18	4	746	79	11	1200	160–240	17
Asia[2]	152	3.7	2	402	16	4	1040	45–80	6
Latin America	107	0.3	0.3	183	6.9	4	345	20–45	9
Africa and Middle East	67	–	–	122	3.3	2	270	15–30	8
World total[3]	2139	154	7	3600	430	12	5870	740–1075	15
Market-economy industrialized countries[4]	1410	132	9	2170	328	16	3060	500–680	20
CPE Europe[3]	404	18	4	750	79	11	1200	160–240	13
Developing countries outside CPE Europe[2,3]	325	4	1	680	24	4	1610	80–155	7

The nuclear capacity figures for 1990 are based on plants already in operation and under contruction, or committed for a start of construction within the next two-three years; the total capacity figures for 1990, and both nuclear and total capacity projections for 2000, are averages of high and low estimates.

[1] European countries with centrally planned economies, including Yugoslavia.

[2] Including the Republic of China (Taiwan).

[3] Capacity figures for 1990 and 2000 are rounded.

[4] Includes the OECD country groups, Israel, and South Africa.

to less than half-power due to serious steam-generator problems.

Reliability, outages, and energy loss

The information contained in the IAEA Power Reactor Information System (PRIS), together with detailed knowledge of recent problems, could be used to evaluate the causes of prolonged outages or the loss of productivity with a view to improving the reliability of nuclear power plants. The nuclear power industry has accumulated more than 22.8 million hours, or 2600 years, of operating experience to date. The Agency's Power Reactor Information System now covers more than 14.9 million hours or 1700 years, about two-thirds of the total experience gained so far. The system contains performance indices and energy production data for the period 1963 to 1980. In addition, the system's outage file contains information on about 9000 full and partial outages, affecting about 3.3 million hours or 380 years of plant operation from 1971 to 1980.

Table 2. Estimates of total and nuclear electricity generation by main country groups (TWh)

Country group	1981 Total	1981 Nuclear	1981 %	1990 Total	1990 Nuclear	1990 %	2000 Total	2000 Nuclear	2000 %
Market-economy industrialized countries	5662	667	12	8 600	2000	23	12 100	3600	30
CPE Europe	1955	104	5	3 600	485	13	5 700	1200	21
Developing countries outside CPE Europe	1134	22	2	2 800	150	5	6 800	700	10
World total	8751	793	9	15 000	2600	18	24 600	5600	23

Figures for 2000 are averages of high and low estimates.

Table 3. Unavailability against reference load factor of 80.0%

Year	Load factor %	Unavailability factor (UF) %	Planned UF %	Unplanned UF %	Energy lost TWhe	Number of plants
1960	40.0	60.0	–	–	–0.141	1
1961	33.1	66.8	–	–	–1.034	2
1962	68.4	31.5	–	–	–0.425	4
1963	54.1	45.8	–	–	–3.306	9
1964	56.1	43.8	–	–	–5.136	17
1965	57.2	42.7	–	–	–6.168	22
1966	63.0	36.9	–	–	–8.057	25
1967	66.1	33.8	–	–	–7.312	30
1968	61.9	37.1	–	–	–13.301	35
1969	49.9	50.0	–	–	–31.713	40
1970	60.5	40.8	–	–	–21.637	47
1971	64.0	36.1	–	–	–22.143	58
1972	62.9	37.4	–	–	–33.210	69
1973	61.4	32.5	14.9	12.4	–47.181	94
1974	61.8	32.9	16.2	16.5	–52.773	95
1975	61.1	37.9	15.3	22.8	–85.027	116
1976	61.8	37.5	16.4	23.2	–101.776	130
1977	64.0	35.7	16.3	20.8	–104.385	144
1978	67.1	32.4	17.3	15.2	–96.268	153
1979	60.2	38.7	24.0	15.1	–165.470	167
1980	62.3	37.1	27.0	10.7	–160.039	184
Average 1960–1980	58.9%			Total TWhe:	966.502	
Average 1970–1980	62.5%					

Table 4. Unplanned full reactor outages 1971 to 1980

Reason for outage	Energy lost GWhe	%	Time list Hours	%
Reactor and accessories	10 917.9	2.0	25 763.0	2.4
Fuel	8 313.3	1.5	18 947.7	1.7
Reactor control system & instrumentation	27 736.2	5.1	57 074.0	5.2
Nuclear auxiliary and emergency systems	15 277.1	2.8	33 395.6	3.1
Main heat removal system	79 030.9	14.4	151 084.9	13.9
Steam generators	59 379.2	10.9	144 179.7	13.2
Feedwater, condenser and circulating water systems	28 772.4	5.3	47 832.0	4.4
Turbine generator system	89 616.6	16.4	155 833.0	14.3
Electrical power and supply system	21 905.7	4.0	38 420.0	3.5
Miscellaneous	13 227.7	2.4	31 803.6	2.9
Operating error	9 008.7	1.6	16 317.6	1.5
Refuelling	2 964.1	0.5	3 943.4	0.4
Refuelling: maintenance & repair	18 056.0	3.3	31 067.1	2.9
Maintenance and repair	56 747.2	10.4	152 447.2	14.0
Testing of plant systems/components	4 800.1	0.9	10 614.6	1.0
Training and licensing	49.4	0	91.0	0
Regulatory limitations	42 077.1	7.7	56 495.1	5.2
Other	59 077.1	10.8	113 721.2	10.4
Total	546 956.7		1 089 030.7	

Table 5. Unplanned full outages for PWRs > 100 MWe

Reason for outage	Year 1977–78 Energy lost GWhe	Hours	Year 1979–80 Energy lost GWhe	Hours
Reactor control system and instrumentation	3 273.4	4354.5	8 755.9	10 587.6
Unplanned maintenance	6 280.1	8422.6	12 122.1	15 623.6
Regulatory limitations	5 972.4	5646.1	25 757.5	30 530.7
Total	15 525.9		46 635.5	

One can illustrate the economic importance of plant reliability the following way. Assuming a reference load factor of 80%, which nuclear power plants in several countries have clearly shown to be feasible, the actual average load factor between 1960 and 1980 of only 58.9% represents total loss within the last 20 years of 966.5 TWhe*, or 26.6% of the total electricity produced by these nuclear power plants. The data on load factors, taken from PRIS, is shown in Table 3. Including also an estimate for the outage data which is not compiled in PRIS, the total loss of energy over 20 years may have been in the order of 1500 TWhe. This corresponds to twenty times the nuclear electricity produced in the USSR in 1980. (This comparison does not include plants with outages longer than one year, e.g. TMI-1 and TMI-2 after the 1979 accident.)

Table 4 summarizes the loss of energy between 1971 and 1980 due to unplanned full reactor outages, resulting in 547 TWhe or 16% of the electricity generated by these plants. Most unplanned outages were caused by failures of conventional components: e.g. turbine generator system (16.4%); main heat-removal system (14.4%); steam generators (10.9%); but also unplanned maintenance and repair in general (10.4%). Regulatory limitations, 7.7% or 42 TWhe lost production, correspond to the total nuclear electricity generated in 1980 in the Federal Republic of Germany. In almost all cases these outages did not give rise to safety problems. The effect of regulatory limitations can also be shown by comparing the loss of energy of all PWRs two years before (15.5 TWhe) and two years after (46.6 TWhe) the Three Mile Island accident. (The comparison in Table 5 excludes the reactor itself, which failed on 28 March 1979.) It should be noted, however, that during this period there was an increase in nuclear capacity of PWRs by a factor of 1.2, which partly accounts for this three-fold increase in the calculated energy loss.

The forthcoming IAEA International Conference on Nuclear Power Experience will review in depth the operating experience of nuclear power plants and the lessons to be learned for future improvements in the reliability and therefore the economics of nuclear power. The reliability of nuclear power in recent years has been reduced because of efforts to make it safer still. Thus, the primary motives for deciding to introduce nuclear power, reliability and economics, have not received the attention which is necessary to keep nuclear power a viable option. There is no question that nuclear power plants are safe and can be made safer, as the IAEA International Conference held in Stockholm in 1980 concluded.

* TWhe = 10^9 KWhe = 10^6 MWhe = 10^3 GWhe.

Standardize for the future

What can be done to halt the decline in the fortunes of nuclear power which has been chronicled in this article? How can public confidence be regained, the reliability and economics of nuclear power be improved, and its viability as an energy option restored?

The most important economic challenge is to reduce drastically the lead and construction times for nuclear power plants and so reduce their cost, without jeopardizing high safety standards. The average construction time of all nuclear power plants now operating was 67.6 months (5.6 years), whereas the expected average construction time of nuclear power plants now under construction will be more than 100 months (approx 8.5 years). In the Federal Republic of Germany, for example, one year's delay in the construction of a 1300 MWe nuclear power plant results in additional expenses of approximately US $90 millions in financing costs only. Standardization of plant and major components is the principal solution and must be undertaken jointly by the licensing authorities, utilities, and suppliers, on a national or even international scale. For projects to last ten years or more is unnecessary and unacceptable. The procedure current in a number of countries of constantly adjusting the technical concept and design of an individual plant during construction improves the safety only slightly but dramatically increases the costs. A clear definition of the basic criteria for safe design and effective project management are better than constantly changing requirements by the licensing authorities. It cannot be emphasized too strongly that any technical concept can only absorb a certain number of changes without prejudicing the fundamental safety principles. Thus, safety must be built into the original concept and design, for this is the most effective way to engineer safety into the construction and operation of the nuclear power plant. The experience of France and the USSR should be more widely used by other countries. Such principles are even more important for the export of nuclear power plants to developing countries where reference plants are of crucial importance for the first introduction of nuclear power.

Competitiveness and availability

New nuclear power plants will be ordered only if they can produce electricity competitively with other generating systems. Competitiveness will be the major challenge of the future, for it is now generally acknowledged that the environmental and safety risks of nuclear power are low. This judgement is borne out by the increasing operating experience and by research programmes: first experimental results indicate that the release of radioactivity from a major nuclear accident — and, therefore, the number of direct casualties — might be a factor of 100 lower than has been estimated by the different theoretical risk studies.

Commercial efficiency and cost-effectiveness is directly related to the availability of the plant. The average load-factor of around 60% for all nuclear power plants, most of them on base-load operation, can be improved, especially as in some countries long-term load-factors of over 80% have been achieved. Long-term unplanned outages can be avoided by better quality assurance and control, more conservative design, and international standardization of major components. Simplified operating procedures have to be developed taking account of all aspects of the man-machine interface, and a higher degree of inherent safety of major systems has to be achieved. The worldwide operating experience should be more comprehensively evaluated and the important trends and lessons learned communicated more effectively between licensing authorities, utilities, and suppliers. More international co-operation is essential, and the IAEA has an important role to play. The economic consequences of a major incident for an individual utility or a small country could be unacceptable and have to be minimized. Such major incidents cannot be excluded in the future.

Finally, decommissioning and final disposal of radioactive waste have to be financially assured during the operation of plants. In Sweden and Finland for example, a certain sum of money has to be set aside per KWhe produced to finance the decommissioning and final disposal of waste.

The future programmes of the IAEA, based on a quarter century's experience in the peaceful use of nuclear power, will address these priority questions, assist the developing Member States in using this important source of energy more extensively than in the IAEA's first 25 years. Unless these challenges are accepted, the viability of nuclear power for the future supply of energy cannot be assured either in industrialized or developing countries.