UNITED NATIONS

GENERAL ASSEMBLY

Distr.
GENERAL

A/CONF.108/PC/24
3 July 1985

ORIGINAL: ENGLISH

PREPARATORY COMMITTEE FOR THE UNITED NATIONS CONFERENCE FOR THE PROMOTION OF INTERNATIONAL CO-OPERATION IN THE PEACEFUL USES OF NUCLEAR ENERGY
Sixth session
Vienna, 21 October-1 November 1985
Item 3 (a) of the provisional agenda

PREPARATIONS FOR THE CONFERENCE AND DOCUMENTATION
REPORT OF THE SECRETARY-GENERAL

Environmental implications of expanded utilization of nuclear energy

Contribution by the United Nations Environment Programme to the documentation for the Conference

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INTRODUCTION

1. The importance of energy for national development is well established. It is evident, for example, from the strong correlation, among different countries, between the amount of energy consumed per capita and the per capita gross national product. Electricity plays a crucial role in this relationship, for it is especially suited to serve the needs of industrial development, urbanization, and communication - sectors which are particularly important for national development. The suitability of nuclear power as a source of electricity for developing countries depends on how well it can be integrated into the production system which it must serve and into the environment on which it impinges.

2. The emphasis in this paper will be on the environmental implications of the expanded utilization of nuclear energy, particularly in developing countries. However, since the environmental, technical, social and economic aspects are in many cases strongly interrelated, it is unavoidable to touch upon some of these items.

3. The suitability of nuclear power as a source of energy depends on the following: the efficiency with which nuclear power provides the electricity needed by the system of production; the efficiency with which capital is used in the generation of nuclear power, which in turn depends in part on the next-mentioned factors; and the severity of potential environmental and safety hazards and the cost of controlling them.

4. Nuclear power plants belong to a class of machines that convert heat energy into motion, which represents work. In such machines, thermodynamic limitations require that about two thirds of the energy used to generate the motion is released to the environment in the form of heat at a lower temperature than the heat that drives the machine. The remaining energy appears as motion, which in the case of power plants is converted with nearly 100 per cent efficiency into electricity.

5. In a nuclear power plant, heat is derived from nuclear reactions in which fissionable elements, such as uranium and plutonium, are split. A small part of their nuclear matter is converted to radiant energy, which is rapidly transformed into heat. The process also generates an array of intensely radioactive elements. The heat generated by the fission process is used to produce steam, which drives a conventional turbine generator. The heat represented by the spent steam is released to the environment through a cooling system.

6. Nuclear power plants are part of a more complex system, which includes: mining and refining of uranium ore; isotopic enrichment of the refined uranium; fabrication of reactor fuel; plant operation; temporary storage of spent fuel; reprocessing of spent fuel (which yields new reactor fuel); permanent storage of radioactive wastes; and decommissioning of obsolete plants. In most countries with appreciable nuclear power systems, the "front end" of this sequence, that is, the first five parts, has been established and is functioning. However, efforts to establish the rest of the sequence have been less successful. The difficulties inherent in dealing with the "back end", especially reprocessing and waste disposal, and the costs which are likely to be encountered in the effort, are in part responsible for present uncertainties about the future of nuclear power. In the United States of America, several attempts to operate plants for reprocessing spent fuel from commercial nuclear reactors and recovering useful fissionable fuel from it were not successful, and there are at present no such plants in operation.

Techniques for dealing with high-level wastes have been developed, but the necessary facilities do not yet exist. In other countries, notably France and the United Kingdom, the entire cycle has been established, but disposal of waste remains a problem. No full-scale commercial nuclear power plants have been decommissioned as yet (in the sense of permanently dealing with residual radioactivity).

7. At the end of 1983 the nuclear component represented more than forty per cent of the installed generating capacity in some developed countries, including Belgium, Finland and France, but current predictions do no suggest that such a figure might be applicable on a global scale by the year 2000.

8. In developing countries, several factors militate against establishing the full nuclear cycle. Their electric power systems are relatively small; the average number of nuclear power plants per developing country anticipated in 1995 is less than four. It is not economic in such a small system to establish facilities for refining and fabricating fuel or for reprocessing. Finally, all present large-scale commercial nuclear power plant builders are in developed countries. Despite these diseconomies, several developing countries, notably Argentina, India and Pakistan, have established the full nuclear cycle, or are in the process of doing so.

9. Hence, we may assume that in developing countries a nuclear power system, if established, would have the following characteristics: the power plant would be largely constructed by a foreign company but using local labour and resources insofar as possible; it would use imported fuel assemblies; spent fuel would be stored temporarily at the power plant site; and when permanent sites for storing high-level wastes are available, the spent fuel would be shipped for permanent storage and reprocessing. The issue at hand, then, is whether such a simplified system will meet the needs and capabilities of developing countries, taking into account the economic, social and environmental aspects.

I. ENVIRONMENTAL IMPLICATIONS OF NUCLEAR ENERGY

10. Certain of the environmental effects of a nuclear power plant are common to all means of converting the energy inherent in a fuel into electricity, notably the use of land to construct the plant and of air or water to receive the waste heat that is generated along with electricity. Other potential environmental hazards are unique to nuclear power plants, in particular those derived from their production of intensely radioactive materials. Finally, nuclear power plants are free of at least two environmental consequences of the use of fossil fuels to generate electricity - acid rain and increased atmospheric CO_2.

11. Given the practical constraints on the nuclear power systems that might be established in developing countries, the following potential environmental impacts need to be considered: the hazards associated with the release of radioactive materials during operation of the nuclear power plants; the hazards associated with waste management, in particular, the handling, storing and transport of spent fuel; the hazards associated with potential nuclear power plant accidents, which may release massive amounts of radioactive material; the impact of the release of waste heat from the power plant to the environment. Other environmental effects that may be associated with nuclear power, such as the ecological effects of road-building to the site and construction accidents, are common to all construction projects and will not be considered here.

A. Emissions, residuals and health hazards at normal operating conditions

12. United Nations Environment Programme (UNEP) has compiled a table summarizing the emissions, residuals and health hazards of the different stages of the nuclear cycle.*

13. In general, the most intense environmental hazards from the normal operation of a nuclear power system occur in those activities which, in general, would not occur in developing countries, namely, mining and reprocessing of radioactive waste.** Such facilities can contribute significantly to environmental radiation and affect the health of exposed populations. It has been established that uranium miners experience a significantly enhanced death rate due to cancer resulting from occupational exposure to radiation. Recent evidence suggests that cancer incidence may be elevated in the areas near reprocessing and nuclear weapons plants in the United States.

14. A number of comprehensive assessments have been made of the environmental hazards - chiefly an enhanced incidence of cancer and genetic defects - associated with exposure to radiation from natural and man-made sources. These provide estimates of the contribution from nuclear power to the radiation dose that people receive from other sources. An example of such an estimate is shown in table 1.

15. Table 2 shows that the part of the total nuclear power system that can be reasonably established in developing countries would deliver to plant workers about 57 per cent and to the public (based on United States conditons), about 11 per cent of the radioactive exposure due to the entire sequence. The relative impact of the radiation from the entire nuclear system can be judged by comparing it with the total exposure of the general population to radiation from natural sources such as cosmic rays and radioactive rocks. Radiation due to different processes involved in the production of 1 GW of nuclear power (the size of a typical large plant) represents about 0.03 per cent of the dose from natural sources of radiation. It is also evident from table 1 that nearly all of this exposure, in the restricted conditions of developing countries, is due to plant operation. The remaining activities - fuel storage and transport - would contribute negligibly to the total dosage.

16. Certain qualifications should be kept in mind in relation to the foregoing data. First, they refer to normal practice. Radioactive emissions from nuclear power plants may increase sharply during certain equipment failures and will therefore depend on the frequency of such failures. Second, values for emissions from nuclear power plants such as those cited in table 1 are based on relatively few evaluations and do not necessarily reflect current operating conditions. Finally, the estimates of biological effect due to such low levels of radiation are by no means certain, and emerging epidemiological data may support revisions in the direction of increased sensitivity. These

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*This table is available from the Secretariat for reference.

**With the exception of a few cases such as Brazil and Zaire, where the mining stage is present.

Table 1. Levels of radioactive exposure by radiation source

Source	Exposure (man·rem per person per year)
Cosmic radiation	40.0
Terrestrial sources	62.0
Medical exposure	73.0
Global nuclear weapons fallout	4.0
Nuclear power (normal operations)	0.003
Occupational	0.8
Miscellaneous	2.0
Total	181.803

Source: United Nations Environment Programme, "The environmental impacts of production and use of energy", report to the Executive Director, UNEP Energy Report Series (Nairobi, 1979).

considerations suggest that the values at present accepted regarding the radiation effects of normally operating nuclear power plants may be somewhat too low. On the other hand, it should be noted that developing countries that undertake to operate nuclear power plants will generally have fewer of them than developed countries, thereby reducing the resultant exposure to radiation. While, apart from mining or reprocessing, the potential environmental impact from normal operation of the nuclear power system appears to be small relative to other exposures to radiation, the environmental impact arising from abnormal conditions may be very large.

17. All power plants that use fuel must discharge a large part of the fuel energy into the environment as waste heat. The waste heat generated by a nuclear power plant is discharged, as in the case of fossil fuel plants, into cooling water, from which heat is dissipated to the environment. The amount of heat is generally larger in the case of a nuclear plant because of the lower thermal efficiency and the large size of the nuclear unit. In addition, unlike fossil plants almost no heat is discharged through the chimney of nuclear plants. A typical 1,000 MW nuclear power plant will raise the temperature of the cooling water 10°C and discharge about 2,000 MW thermal energy to the water body.

18. Such thermal pollution can affect the ecological balance of aquatic systems. It is possible to recover most of the heat normally discarded by a power plant by designing it as a congenerator. In this case, the recovered heat is conducted to a heat-requiring entity, such as a factory or residences. Since heat cannot be readily transported over long distances, the users must be located near the power plant. In the case of a nuclear power plant, this requirement may raise problems with respect to safety.

Table 2. Normalized collective effective dose-equivalent commitments

Fuel cycle component	Workers (man·rem per TW(e)·h)	Local and regional population a/ (man·rem per TW(e)·h)		Global: 10 years	Global: 10^2 years	Global: 10^4 years
				man·rem per TW(e)·h delivered over specified		
Mining and milling (including mill tailings)	11	6		2.9	28.5	2 850
Fuel fabrication	11	0.023		(--)	(--)	(--)
Reactor operation, including decommissioning	114	48	Tritium	0.17	0.23	0.23
			Kr-85	10	22	22
Reprocessing, including decommissioning	114	11	C-14	34	114	798
			I-129	(--)	0.23	2.3
				44	137	822
Transport	0.011	0.034		(--)	(--)	(--)
Waste disposal	Small	(--)		(--) b/	(--)	(--)
Nuclear research	57					
Total	307	65		48	171	3 650
Corresponding detriment in terms of cancer mortality per TW(e)·h	3.4	0.57		0.46	17	36.5

Source: United Nations Environment Programme, "Comparative data on the emissions, residuals and health hazards of energy sources", UNEP Energy Report Series (Nairobi, 1985); 1982 report of the United Nations Scientific Committee on the Effects of Atomic Radiation.

Notes: TW(e)·h indicates terawatt hours of electrical energy.
A dash (--) indicates that the amount is nil or negligible.

a/ The values given for the exposure of workers and the local and regional population are complete collective dose-equivalent commitments. For local and regional populations these values result from the "first pass" of released radionuclides over the territory, before they become globally dispersed.

b/ It is assumed that proper disposal methods are applied so as to ensure waste isolation over the time period indicated.

B. Low-probability high-consequence accidents

19. Two classes of abnormal conditions need to be recognized. One class is represented by localized equipment failures, such as a defective valve or a pipe break that allows radioactive liquid or gas to escape from the plant. Such defects do not affect the reactor proper and do not release the intensely radioactive spent fuel within it. The releases of radioactivity from such events are regarded as low-level and, subject to the qualifications cited above, they can be expected to contribute to a limited extent to overall exposure to radiation.

20. The second class of abnormal conditions leads to very much greater hazards. These are events that involve the rupture of the reactor containment vessel and the release of its intensely radioactive contents to the environment. A rupture might occur as a result of external factors, such as an earthquake or an airplane crash. This type of accident has not yet occurred. Rupture of the reactor containment vessel may also result from failure of the plant equipment itself, for example, breakdown of the cooling system and the consequent meltdown of the fuel assembly, which could then penetrate the reactor containment vessel. Such an accident has not yet occurred, but was closely approached at the Three Mile Island nuclear power plant at Harrisburg, Pennsylvania in 1979. While complete meltdown did not occur and the reactor containment vessel was not breached, the fuel assembly was seriously disrupted and a large volume of intensely radioactive water was released into the vessel; some relatively low-level radioactivity also escaped into the environment.

21. A series of United States studies have attempted to estimate the consequences of a "worst-case" accident in which the reactor containment is breached. Estimates of the numbers of people who are likely to be killed in such an accident range from 3,300 to 100,000, and property damage from 0.1 to 300 billion dollars. In addition, such an accident would cause cancers and genetic defects in an even larger number of people. These catastrophic effects are related to the fact that most United States nuclear power plants tend to be near relatively populated areas, containing in the order of 50,000-100,000 people within a radius of 16 km, and of the order of several million people within a radius of 80 km. In a "worst-case" accident, fatalities are likely to occur within 32 km of the plant, and injuries within 80 km of it.

22. Estimates of the probability that a worst-case accident will actually occur are even more variable than the estimates of fatalities and damage. While the Wash-1400 report estimated that such an accident could occur with a probability of one in a billion per reactor-year, when the Sandia study applied the estimates to actual plants, the probabilities ranged from 1 in 8,333 to 1 in 100,000. Given the number of nuclear power plants in the United States, a probability of about 1 in 10,000 per reactor-year implies that there is a 23.5 per cent chance that such an accident will occur by the year 2000. Because of the enormous consequences of such an accident, it is prudent to take steps to minimize them, if possible. In the United States, the Nuclear Regulatory Commission now requires that each nuclear power plant establish a test scheme capable of evacuating the nearby population from the area in the event of a major accident. Similar recommendations have been made by the International Atomic Energy Agency (IAEA).

C. Measures to control environmental and safety problems

1. Design

23. Some Governments have reacted to the potential hazards of nuclear power plants by requiring extensive control measures that greatly affect their design, construction and operation. In the United States, many control measures were introduced following the publication in November 1965 of a report by the Advisory Committee on Reactor Safeguards of the Nuclear Regulatory Commission, which called for "incorporating stricter design standards" in nuclear reactors. In response, a number of design changes were introduced during the 1970s, all of them aimed at improving plant safety, especially by reducing potential releases of radioactivity. They include improving the resistance against natural disasters, fire protection measures and more rigorous construction requirements. Similar changes were introduced to improve protection against floods and tornadoes.

24. These changes have caused a sharp increase in their cost. Thus, according to Komanoff's analysis, plants completed in 1971 cost $366 per kilowatt (in fixed 1979 dollars), those completed in 1978 cost $887 per kilowatt, and those projected for completion in 1988 will cost $1,374 per kilowatt (Komanoff [1]). The most recent plant to be completed, at Shoreham, Long Island, was estimated in 1970 to cost $225 million, or $440 million in 1979 dollars; on completion it cost about $3 billion, or about $2,800 per kilowatt in 1979 dollars. Since these costs include the real interest paid on the capital loans during the period of construction, they depend on the length of that period. One reason for the increased construction costs is that the time of construction has also increased significantly. In the United States, plants completed in 1971 required an average of 5.5 years to construct; plants completed in 1978 required 6.5 years; plants projected for completion in 1988 will require 8.1 years. Total lead times (including preconstruction activities) were six years during the 1970s and are now seven to nine years. These changes have increased the capital costs of nuclear power plants, for they extend the period during which capital must be borrowed and interest costs incurred. This effect has been aggravated by the recently high rates of interest.

2. Radioactive waste management

25. In normal operations, nuclear power plants in developing countries will need to manage radioactive waste arising from routine maintenance and repairs (such as contaminated tools and clothing) and from certain operations (such as processing water contained in spent fuel storage tanks). In addition, the highly radioactive spent fuel must be removed from the reactor, stored for at least several years, and finally, after being sealed in a special shipping cask, transported to a point of embarkation for shipment abroad for reprocessing.

26. Each step in the nuclear system generates some environmental radiation; the amounts are discussed in a detailed study by the United Nations Environmental Programme (UNEP [2,3]). Management of radioactive wastes is governed by their level of radiation and their content of transuranic radioactive elements (TRU), with atomic number greater than 92. After each year of operation, about one quarter to one third of the reactor fuel must be replaced; in a typical 1,000 MW nuclear power plant, this amounts to about 30 tonnes per year. The spent fuel is intensely radioactive and contains a high proportion of TRU. It is encased in an impervious metal cladding which, if intact, prevents dissemination of the fuel material during handling. After being removed

from the reactor core, the spent fuel is transferred to an adjacent storage pool.

27. The radioactivity of stored fuel falls to about 1 per cent of its original level in two years, and to about 0.3 per cent in five years. It is then regarded as suitable for shipment. For this purpose, the fuel elements are enclosed in heavy shielded casks, weighing about 23 tonnes each, which are carried to their destination by truck or rail. About 60 truck shipments are required for the spent fuel produced by a 1,000 MW plant per year. Additional waste management problems may arise if accidents occur in manipulating spent fuel and in shipping the loaded casks.

3. Operating procedures

28. In practice, environmental protection during the operation of nuclear power plants requires a series of activities, notably monitoring, training, management, regulation and analysis.

(a) Monitoring

29. Detailed radiation monitoring is essential to carry out all protective measures. Continuous monitoring of various plant sectors and components is built into the design of the nuclear power plant. However, to provide protection against public exposure, it is also necessary to monitor the external environment (air and bodies of water) and key elements of the ecosystem (for example, fish, crops and milk). Since public protection can only be achieved by reducing contact with the source, it is totally dependent on such monitoring.

(b) Training

30. As already indicated, a major part of the radiation exposure from nuclear power plants is the result of abnormal operations, in particular malfunctions and their repair. The most effective means of protection from such radiation is prevention, by minimizing the frequency of malfunctions and the intensity of their consequences. Here the competence of the relevant personnel plays a crucial role, a fact that has become particularly evident since the accident at the Three Mile Island nuclear power plant. A recent review of the qualifications of nuclear power plant personnel stated the following: "Analysis of the Three Mile Island accident put in question the competence of operators to deal with unusual plant situations which they had not experienced before" (Harley and Spitalnik [4]). This viewpoint has led to a significant intensification of training programmes, especially for plant operators. Because of the complexity of plant controls, and the importance of rapid responses to unusual situations, recent training programmes have been based on simulators and computer-based operator aids. Thus, training of nuclear plant personnel, es- pecially with respect to the prevention and control of malfunctions, and therefore of radiation exposure, is becoming heavily dependent on sophisticated technology.

(c) Management, regulation and analysis

31. Since protection against the radiation hazards inherent in the operation of nuclear power facilities depends on proper design and construction and on effective operation, especially in response to unusual events, competent management is an essential element of protection. Management must govern the exceedingly complex construction programme, the choice and training of personnel, and the response to government regulations. Management must be capable

of responding to changing requirements, especially with respect to safety and protection. The effectiveness of management in environmental protection is closely related to the matter of governmental regulation. Government intervention has played a major role in the creation and development of the nuclear power industry, and it has been most prominent with respect to environmental and health hazards.

32. A major regulatory role has been played by radiation exposure standards, for these establish the levels at which protective action must be undertaken. In establishing these standards, Governments are nearly always guided by the recommendations of two major international bodies, the International Committee on Radiation Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The standards are also generally accepted by international organizations, in particular IAEA, the International Labour Organisation (ILO), the World Health Organization (WHO) and the Organisation for Economic Co-operation and Development (OECD). The most recent standards are set forth in ICRP [5], and their application to nuclear power programmes is discussed in detail in Beninson <u>et. al</u>. [6]. These authors suggest that the radiation dose limits recommended by ICRP should not be regarded as a degree of exposure that can be accepted with impunity. They state the following: "It is now generally recognized that the risk from life-long exposure near the ICRP dose limit cannot be considered as insignificant ... in most circumstances it is reasonable to request a higher degree of safety."

33. In practice, the degree to which operational personnel and the general public are protected from radiation generated by nuclear power activities is also governed by the cost of the protective measures. The most recent considerations of ICRP and IAEA propose a cost-benefit approach as a means of determining the degree of protection that is to be sought, for example, by shielding or limiting the time of exposure. The aim is to optimize protection, that is, to find the point at which the cost of achieving a given change in protection is equal to the "cost" of the resulting change in the detriment arising from radiation exposure.

D. Positive environmental aspects of nuclear energy

34. Discussion of nuclear technology often centres on the complexities and potential hazards of the use of nuclear energy for the generation of electricity. The environmental advantages of this fuel cycle and the benefits to be derived from nuclear technology in general are frequently neglected. A full consideration of these advantages and associated benefits is a necessary part of any decision concerning the use of nuclear technology. Comparative studies of the environmental and health effects of different fuel cycles depend upon inputs of varying precision. The value judgements resulting from such studies are helpful in certain specific decision-making situations, but do not readily lend themselves to generalization. Nonetheless, with this reservation in mind, it is reasonable to conclude that there are a number of positive factors associated with the use of the nuclear fuel cycle.

35. The extent of an environmental impact depends to some extent on the quantity and nature of the resources used and on the volume and nature of the wastes produced. In this context, the generation of electricity by the nuclear fission process has the advantage that the 200 tonnes of uranium required to operate a 1 GWe nuclear power plant for one year can be produced with between 10-15 per cent of the man-hours needed to produce the two million tonnes of anthracite coal required for the operation of a coal-fired plant of similar size over a comparable period of time. The occupational mortality and morbidity for different energy cycles under certain conditions are compared in

figure I, the data depending to a great extent on the reference system and the assumptions made in each case. It thus appears probable, although the quantification is subject to many uncertainties, that the nuclear fuel cycle has an advantage over coal in terms of occupational mortality and morbidity over the whole cycle.

36. Many of the positive or beneficial implications of the nuclear fuel cycle are those which depend on the absence of deleterious effects of other fuel cycles. The absence of SO_x and CO_2 emissions, with a consequent reduction of climate perturbations, and the reduction of land utilization are examples of such implications. Figures II and III give comparative data that could be used in an indicative way on emissions of SO_x NO_x in the different fuel cycles.

II. EXPANDED UTILIZATION OF NUCLEAR POWER IN DEVELOPING COUNTRIES

37. The environmental implications of nuclear energy in general were briefly considered in the last chapter. Expanded utilization of nuclear energy in developing countries could have certain environmental implications which need to be given particular attention.

38. In order to determine the suitability of nuclear power plants for developing countries, it is useful to consider the following questions:

(a) What available nuclear power plants are suitable to the country's existing and projected electricity power system?

(b) What is the expected efficiency of the investment in the construction of the nuclear power plant, that is, the construction cost per unit of capacity?

(c) What is the expected operating efficiency of the nuclear power plant, that is, the actual electric output (and its cost) per unit of design capacity of the plant?

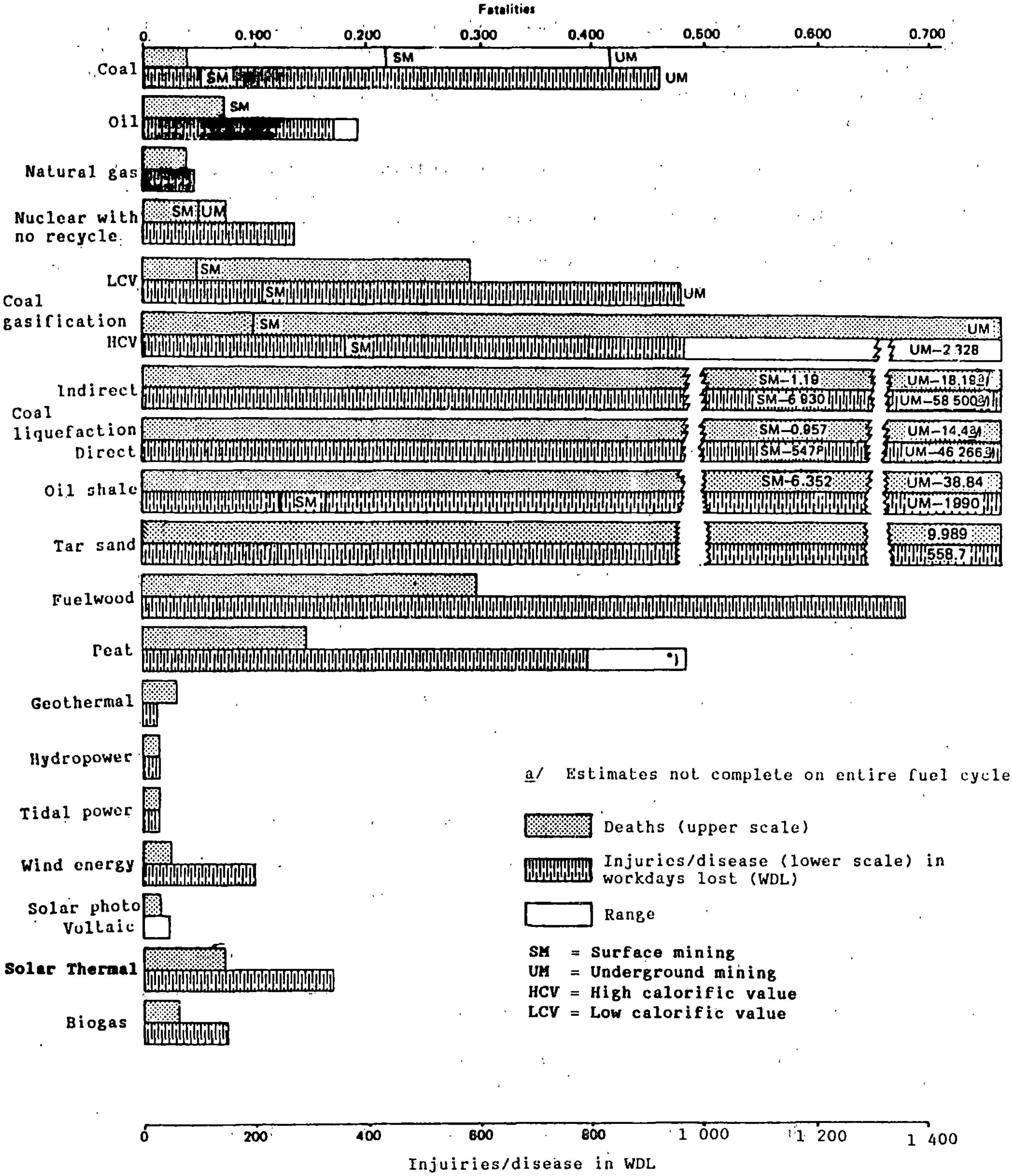
(d) What are the expected environmental problems and what resources are available to minimize them?

(e) What training programmes are needed to provide personnel to construct, operate, and maintain the nuclear power plant and to conduct programmes for environmental protection and safety?

(f) Given the reply to the above questions, what alternative sources of electricity might compete with nuclear power plants?

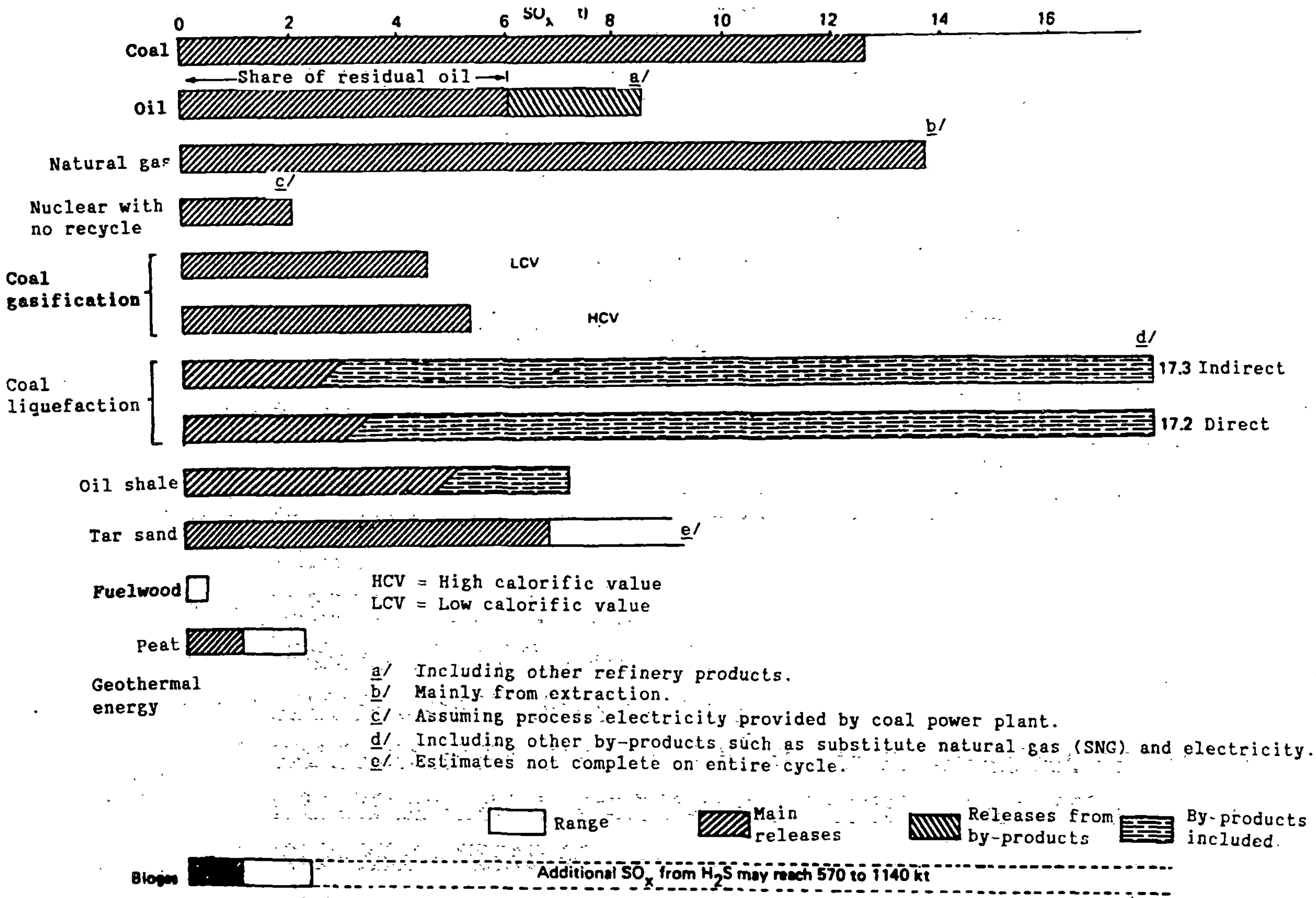
A. <u>The suitability of nuclear power plants to the electric power system of developing countries</u>

39. The size of a generating plant, whether nuclear or fossil-fuelled, that can be effectively added to the electric power system of a country depends on the size of that system. If the capacity of a single plant is too large in relation to the capacity of the entire system, then failure of the plant or a routine shutdown can readily destabilize the operation of the system itself. The generally accepted relationship between these two factors is that no single power plant should be larger in capacity than 15 per cent of the peak load of the system. Since the system must include a 15 per cent reserve capacity,



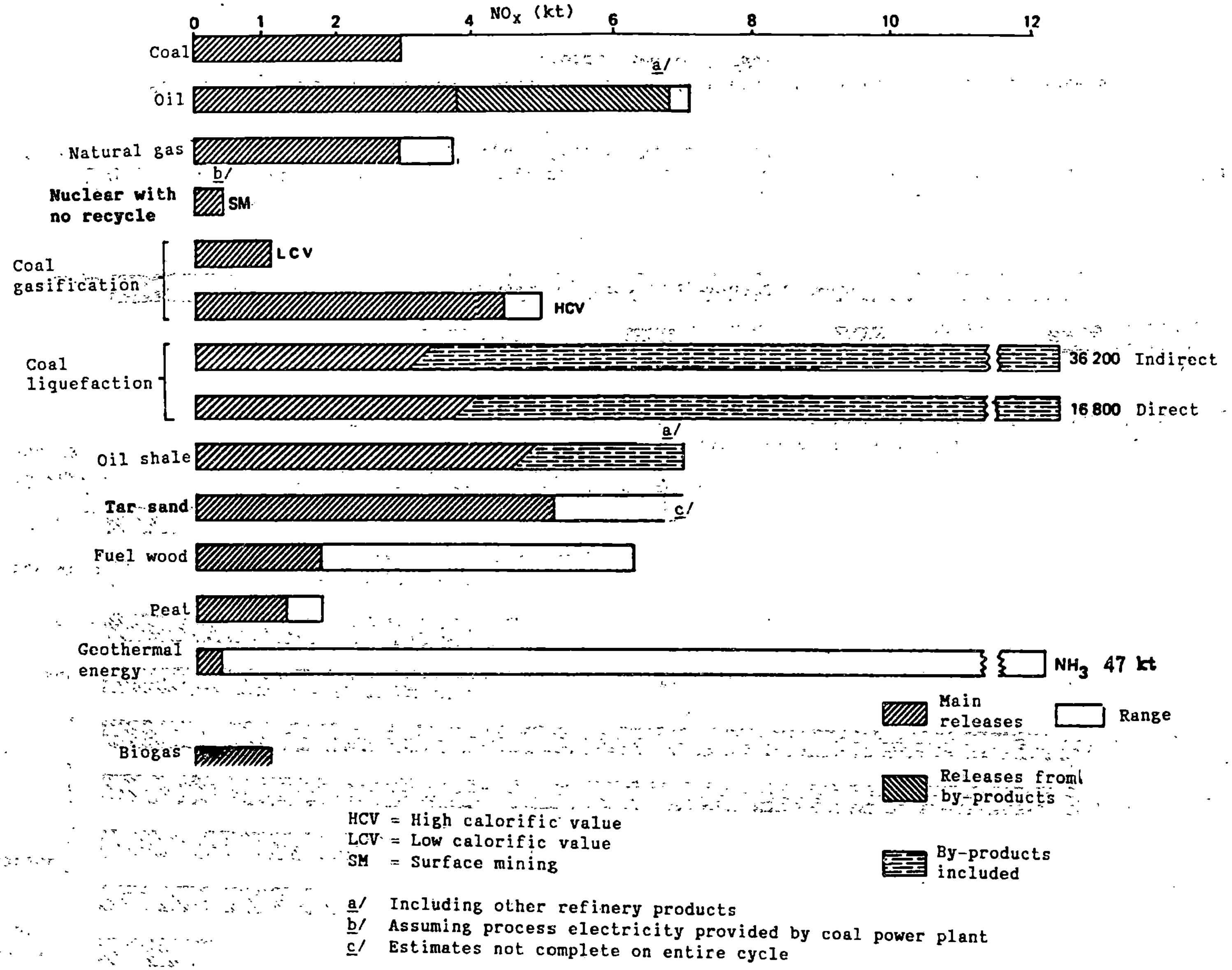
Source: United Nations Environment Programme, "Comparative data on the emissions, residuals and health hazards of energy sources", UNEP Energy Report Series (Nairobi, 1985).

Figure I. Comparison between occupational health hazards of the different cycles for electricity generation (normalized to 1 TW(e)-h)



Source: United Nations Environment Programme, "Comparative data on the emissions, residuals and health hazards of energy sources", UNEP Energy Report Series (Nairobi, 1985).

Figure II. Comparison of SO_x releases from the different cycles for electricity generation **(normalized to 1 TWh)**



Source: United Nations Environment Programme, "Comparative data on the emissions, residuals and health hazards of energy sources", UNEP Energy Report Series (Nairobi, 1985).

Figure III. Comparison of NO_x releases from the different cycles for electricity generation

(normalized to 1 TWh)

this means that no single plant should be larger than 13 per cent of the design capacity of the system.

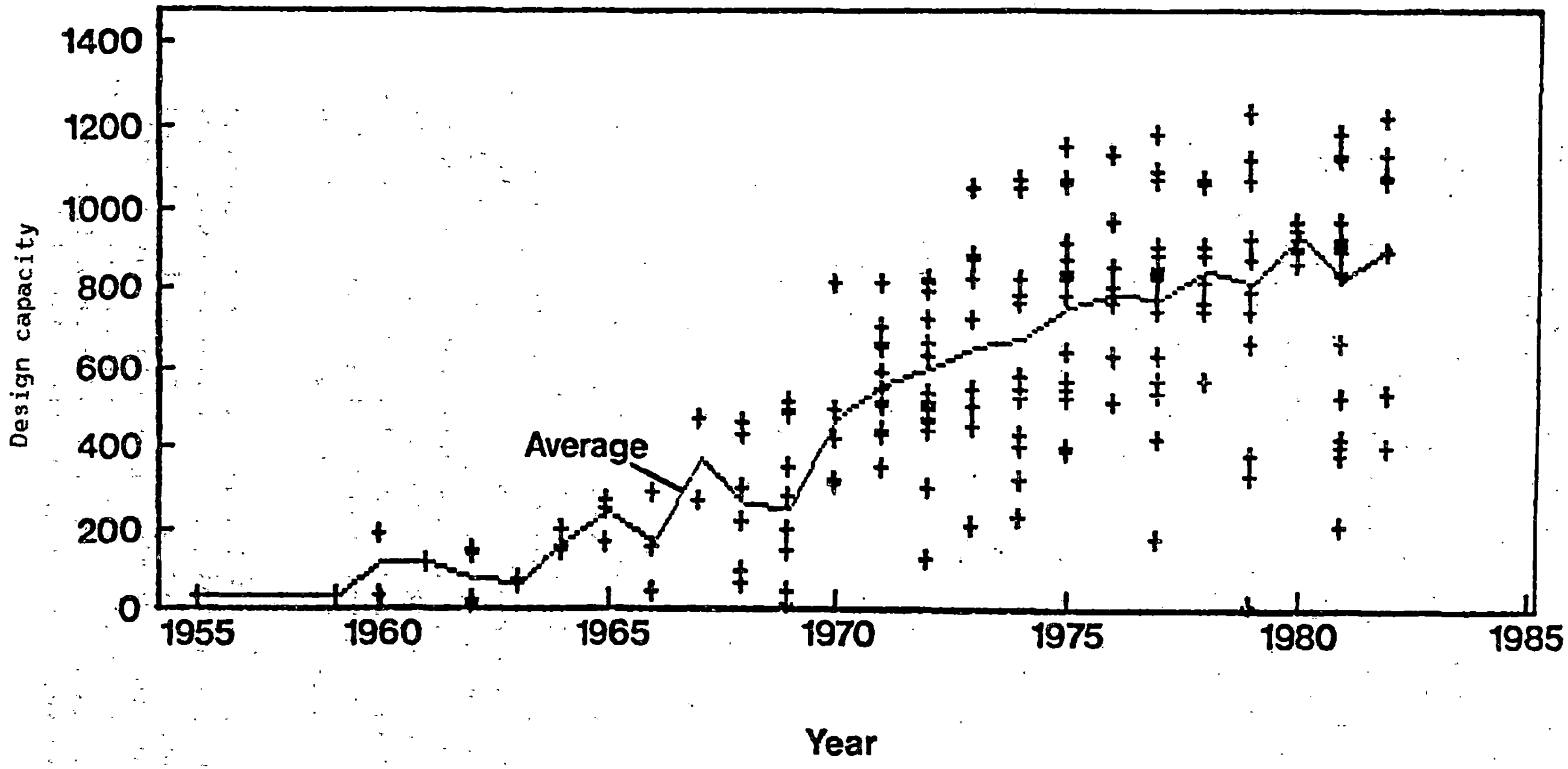
40. Since the electrical power systems of developing countries are necessarily small, this requirement imposes a significant limitation on the size of a power plant that they can accommodate. At present there are no manufacturers that offer to construct a nuclear power plant smaller than 300 MW in capacity, nor are any planning to do so in the immediate future. Another factor which militates against the use of small nuclear power plants is the economy of scale, which implies that the capital cost per unit of capacity falls with increasing capacity. As shown in table 3, the capital cost per kilowatt of capacity of a 200 MW plant is more than twice that of a 1,000 MW plant. This economic factor explains the tendency toward a general increase in the capacity of nuclear power plants. As shown in figure IV, the world-wide average unit capacity of nuclear power plants has increased from about 200 MW in 1965 (year of commercial operation) to about 900 MW in 1982. A similar trend is evident in the size of plants ordered by developing countries, which averaged less than 200 MW between 1960 and 1965, but nearly 800 MW between 1975 and 1980 (see figure V).

Table 3. Ratio of nuclear power plant capital cost at given size in megawatts to cost at 1,000 MW

Plant size	Ratio
100	2.80
200	2.10
400	1.50
600	1.19
800	1.09
1 000	1.00
1 300	0.92

41. Accordingly, it is of interest to examine the relationship between the anticipated total capacity of the electric power systems of developing countries and the capacities of their existing and planned nuclear power plants. The relevant data are presented in a table available from the Secretariat. In this table, data regarding nuclear power plants that are installed, under construction or planned in developing countries are derived from a recent IAEA report supplemented by additional information. The anticipated total power system capacities were computed from the 1980 actual values, based on assumed rates of annual increase in capacity of 9.2 per cent (the average annual rate of increase in overall public, or centralized, power system capacity, in developing countries during the period 1976-1980) and 7.4 per cent (the average for 1979 and 1980).

42. The table shows that a total of 16 nuclear power plants in six developing countries were in operation at the end of 1983, and 21 plants were under construction in nine developing countries. A total of 54 additional plants are planned for completion by 1990-1995 in 20 developing countries. In most of these countries, the actual or planned nuclear power plants conform in size to the requirement imposed by system stability. The table also shows that several developing countries (Bangladesh, Cuba, Kenya and the Libyan Arab

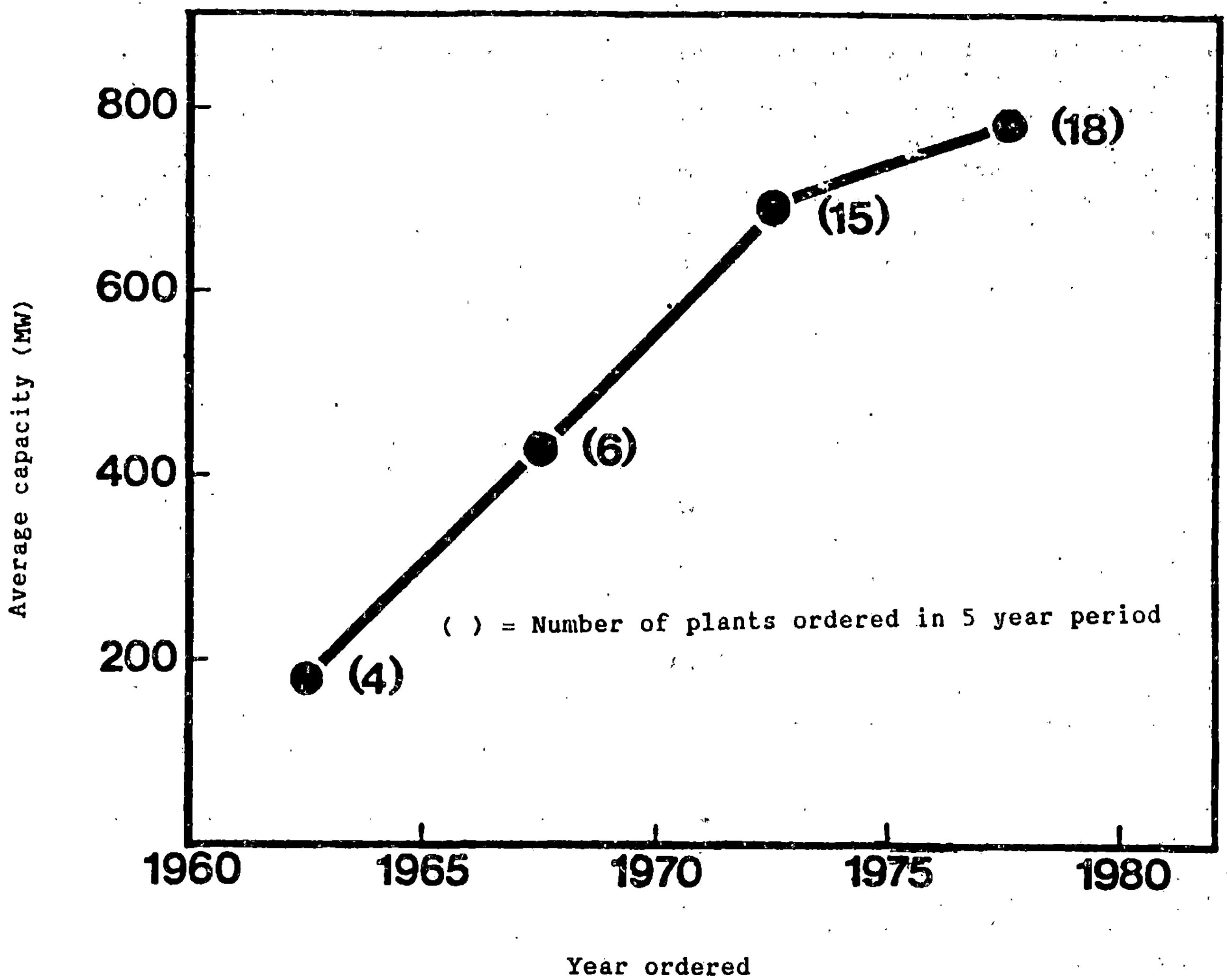


Source: International Atomic Energy Agency, Operating Experience with Nuclear Power Stations in Member States in 1982 (Vienna, 1984).

Notes: No data available for plants in the German Democratic Republic and the Union of Soviet Socialist Republics.

a/ Relative to year in which plant began commercial operation.

Figure IV. Design capacity a/ of 215 nuclear power plants world-wide



Source: J. E. Katz and O. S. Marwah, Nuclear Power in Developing Countries. An Analysis of Decision Making (Lexington, Massachusetts, D. C. Heath and Company, 1982).

Figure V. Average capacity of nuclear power plants in developing countries

Jamahiriya) have been forced to use relatively uneconomic, small nuclear power plants in order to meet the requirements of system stability. It should therefore be noted that considerations of system stability and economy alone restrict the suitability of nuclear power plants in developing countries, and that in several countries that now plan to construct such plants, these constraints have not been observed.

B. Expected efficiency of investment in nuclear power plants

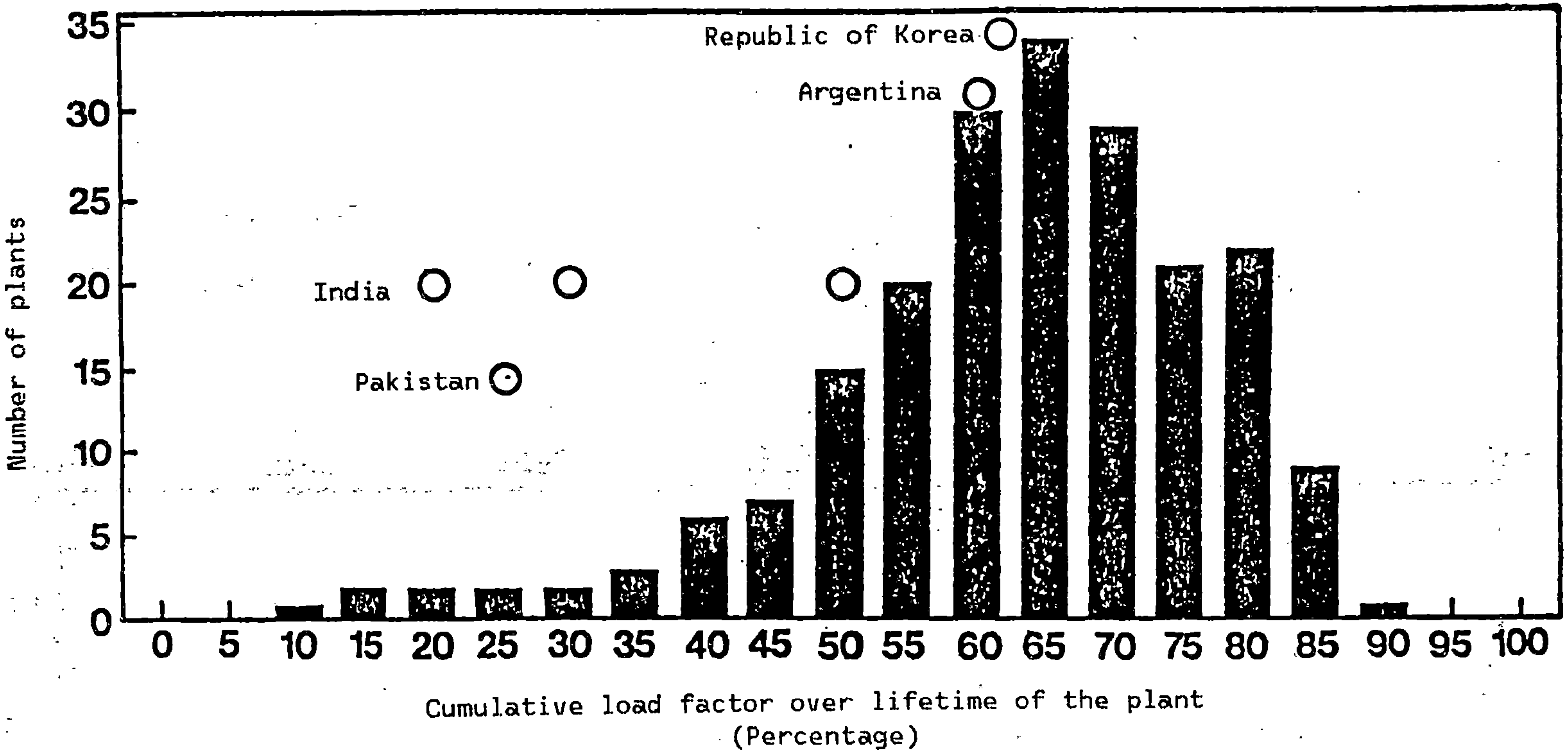
43. Capital costs for nuclear power plants constructed in developing countries can generally be expected to be somewhat greater than they are in the United States. Thus, one study indicates that costs in developing countries are 25 per cent above those in the United States. Similarly, an estimate of the cost of constructing nuclear power plants in the Republic of Korea indicates that they are 15-20 per cent above United States costs. It seems reasonable to expect that capital costs for nuclear power plants will generally be 20-25 per cent greater in developing countries than they are in the country in which they represent the largest source of supply, the United States. Moreover, in view of the remaining unresolved environmental and safety problems, these costs will continue to rise in the immediate future.

44. The overall physical efficiency of a nuclear power plant, the load factor, is another crucial element in its economic suitability for developing countries. IAEA [7] provides such data on the outages of plants operating through 1982. Figure VI describes the frequency distribution of the cumulative load factors, computed for the entire performance of the plant from the date of its first commercial operation through 1982, for 206 plants. While the mean cumulative load factor is 63 per cent, it varies considerably. The distribution is significantly skewed to the low side, about 17 per cent of the plants having cumulative load factors of 50 per cent or less, that is, the amount of electricity actually generated is one half or less than expected from the design capacity of the plants. The relevance of such low efficiencies for developing countries is also indicated in figure VI, which shows that the cumulative load factors for several of the nuclear power plants now operating in developing countries are rather low, lying between 22 per cent and 50 per cent. Nuclear power plants that perform poorly with respect to load factor occur among the most recently built plants. Indeed, as may be seen from figure VII, most of them occur among the most recent plants, and there has been generally no improvement in the average load factor of nuclear power plants, world-wide, in the last 20 years.

45. These considerations suggest that, based on present experience, nuclear power plants in developing countries are likely to operate at an overall economic efficiency that is below the world-wide mean. The capital cost per installed kilowatt is likely to be higher, and the average load factor may well be lower than the world-wide average. As a result, the overall cost of electricity produced by nuclear power plants in developing countries is likely to be higher than costs estimated from experience in developed countries.

C. Environmental control and safety requirements

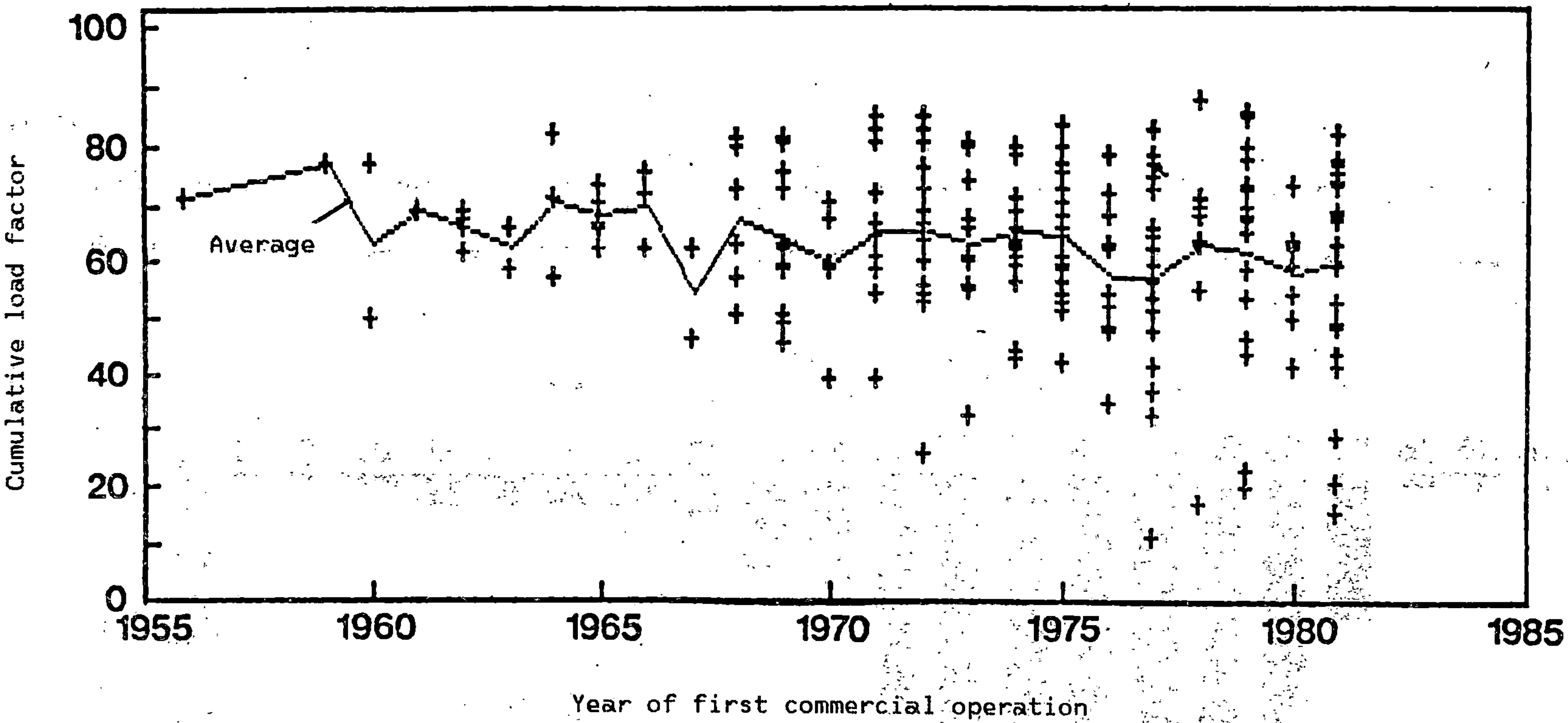
46. As indicated earlier, it is likely that in developing countries, nuclear power plant environmental and safety problems will be associated only with the operation and eventual decommissioning of the plants, storage of spent fuel, and transport of spent fuel to a transfer point for shipping abroad. Suitability therefore depends on the ability of developing countries to meet the requirements for dealing effectively with these problems.



Source: International Atomic Energy Agency, "Nuclear power: status and trends" (Vienna, 1984).

Note: No data available for plants in the German Democratic Republic and the Union of Soviet Socialist Republics.

Figure VI. Performance of 206 nuclear power plants world-wide



Source: International Atomic Energy Agency, "Nuclear power: status and trends" (Vienna, 1984).

Note: No data available for plants in the German Democratic Republic and the Union of Soviet Socialist Republics.

Figure VII. Performance of 215 nuclear power plants world-wide

1. Normal plant operation

47. Monitoring equipment is needed to control radiation exposure of plant workers during routine operations, and more particularly in relation to repair work. Disposal facilities are also required to deal with low-level wastes that the plant may emit, or which may arise from repair work, involving, for example, clothing and tools contaminated with radioactive materials. Such requirements become considerably more stringent in connection with potential major accidents. These may require very rapid assessment of the spread of radiation from the damaged plant and the capability of evacuating the threatened population from the area.

48. Evidence of the difficulties that developing countries have thus far experienced in meeting the foregoing requirements is based on responses to a questionnaire, distributed in 1979 to member countries by the IAEA in co-operation with the Food and Agricultural Organization of the United Nations, ILO, the Office of the United Nations Disaster Relief Co-ordinator and WHO, regarding facilities available for mutual assistance for radiation accidents. Part II of the questionnaire dealt with assistance available within the responding country regarding facilities required for medical treatment, for disposal of contaminated material, and for monitoring radioactive samples. This part of the questionnaire also inquired about preparations for large-scale radiation accidents and the number of training exercises carried out in that connection.

49. The results of the questionnaire show that the facilities required to respond to a serious radiation accident are, in at least some respects, inadequate in all the developing countries that, on the basis of their anticipated electric generating system, might be suitable for nuclear power plants. Of seven classes of required facilities, one country (Thailand) lacked all seven, two countries (Peru and Turkey) lacked five facilities, three countries (Bangladesh, Singapore and Venezuela) lacked four facilities, Colombia and Mexico lacked three facilities, while Chile, India, the Islamic Republic of Iran and Pakistan lacked one facility. A number of countries in the list did not respond to the questionnaire, and Cuba responded only with the following statement: "Facilities and staff in atomic energy are at present limited". Only one country, India, reported that training exercises (two) had been carried out. A number of countries in the list reported that they would need outside aid in the form of added personnel, equipment or specialists. The data suggest that developing countries, including those which are now operating nuclear power plants, are to a significant degree lacking in the facilities needed to respond to a serious radiation accident at a nuclear power plant.

2. Abnormal plant operation

(a) Evacuation from a nuclear accident

50. A serious nuclear power plant accident would require rapid evacuation of the area. In the United States, the operator of each nuclear power plant must demonstrate, by means of test exercises, a capability of carrying out such an evacuation of an area encompassed by a radius of 80 km from the plant site. Such an evacuation must be very rapid, for warning times may be as short as 0.5 hours. In the United States, it has proven to be difficult to establish acceptable evacuation plans. For example, as of April 1985, a major plant in the vicinity of New York City had failed to develop a suitable evacuation plan. One factor that contributes to such difficulties is the population density in the vicinity of the plant. Most developing countries have average

population densities considerably in excess of that in the United States, which suggests that they are likely to have even more difficulty than the United States in such evacuations, should the nuclear plant be located near population areas.

51. Another major factor in evacuating the area around the nuclear power plant is automotive transport, since this is essential if the response is to be sufficiently rapid. Developing countries are seriously deficient in this regard, as compared with the United States. In the United States, there are on average 3.425 seats available in automotive transport per capita. In a number of developing countries, including those with currently operating nuclear power plants, the available transport is only about 0.02 seats per capita or less.

(b) Dispersion of radioactivity

52. For the developing country beginning a programme of nuclear power plant installation, it is naturally tempting to make use of literature and calculations published in developed countries. However, insight into the input assumptions and value judgements not made explicit in such publications is only attained after long scrutiny. Therefore, developing countries are strongly advised not simply to quote the results of calculations made in developed countries of such things as collective dose, but to repeat calculations with careful insertion of input data relevant to their own situation and known conditions. Moreover, in the case of large-scale accidental releases, there are many additional value judgements in calculating collective doses, and these involve assumptions about possible evacuation procedures, including warning times, ability to organize evacuation, and effective speeds of evacuation based upon lognormal velocity distributions.

(c) Aircraft accidents to nuclear power plant

53. On a random basis the probability of a crash at any specific location of an affected area of about 10,000 km^2 is said to be less than 10^{-7}. Moreover, in the Windscale inquiry carried out in the United Kingdom of Great Britain and Northern Ireland, despite the low estimated probability, it was pointed out that the walls of thickness 1.7 m around the cells would provide an adequate margin of safety, since it is assumed that an aircraft engine would just penetrate a wall of 1.1 m thickness. The United States Atomic Energy Commission has evaluated the probability of potentially damaging aircraft impacts per year, at nuclear sites within 8 km of airports, as between 10^{-6} and 10^{-7}. Since the majority of reactors are further away from airports, it is also assumed that the probability for most nuclear power plants is likely to be between 10^{-6} and 10^{-8}. Even if there were an aircraft impact, it is assumed that there would be very little probability of producing a core melt sequence.

54. Bearing in mind the deliberate bombing of hydropower dams during the Second World War, with bombs specially designed to breach the structure, and the more recent Israeli bombing of an Iraqi reactor complex, the probability of deliberate damage to nuclear reactors through the use of aircraft or missiles might be even greater than the risk from the impact of civil aircraft.

D. Personnel and training

55. The construction of a nuclear power plant in a developing country involves the introduction of a technology that is not only new to the country, but that has itself only recently been developed. As a result, it is not easy

to develop personnel with adequate basic and specialized training to deal with the complex operation of a nuclear power plant. It is necessary to find suitable sources of potential trainees, to establish training courses capable of producing the needed personnel, and to provide the ongoing training needed to keep up with technological changes in the field.

56. Personnel involved in nuclear power plant operations must have considerable preceding experience. This may require four to twelve years of education beyond secondary school (Weidlich, 1980). The duration of subsequent specialized training of nuclear power plant personnel varies with the type of position involved. However, the training time for the most exacting positions varies a good deal among developed countries, ranging from 32 to 142 weeks. A developing country for which comparable data are available, Turkey, which has drawn up a plan for introducing nuclear power, proposes much longer periods of training, ranging from 146 to 301 weeks. It would appear that developing countries should expect that the specialized training of nuclear power plant personnel, and inspection, will be lengthy, of the order of three years.

III. ROLE OF INTERNATIONAL CO-OPERATION

57. It can be seen from the foregoing discussion that in order to provide adequate protection from the environmental and health hazards associated with expanded utilization of nuclear power considerable resources of developing countries have to be mobilized. International co-operation is therefore essential, especially in the areas described below.

A. Training

58. By training is meant the development and acquisition of the complete spectrum of personnel needed to construct (in whole or in part), operate and maintain the plant, and, in addition, to know exactly what to do in case of abnormal operation of the plant. Training courses are being organized on bilateral bases and under sponsorship of the IAEA, usually in developed countries. Some of the courses should be conducted on site in developing countries to take into account local conditions and include all sorts of problems which may be met only in developing countries.

59. In addition, training of staff in unusual situations in which they have no previous experience is currently based on simulators and computer-based operator aids. It would be necessary for developing countries to have access to or to acquire such facilities, modify them, if necessary, to suit their local conditions and use them to train their staff when needed.

B. Radioactive waste management

60. Waste management, particularly that of high-level waste, is one of the greatest environmental concerns of nuclear technology. Because spent fuel is highly radioactive and its radioactivity persists for a very long time, it requires permanent isolation from the human environment. This could be provided in deep geological repositories. The search is continuing in different parts of the world for suitable sites and technologies. The principal mechanism for releasing radioactive waste into the biosphere from a sealed geological repository is flowing ground water. To ensure that a candidate site is not vulnerable to such ground-water action, certain forecasting tools and on-site investigations are required. On-site studies will define the physical, chemical and mechanical properties of the host rocks and the effects on it of radiation and heat emitted by the waste. Since the candidate sites could be found

either in developed or developing countries, the selection and the necessary investigations represent another extremely important domain of international co-operation. In this connection, an international agreement on the permanent disposal of radioactive waste to preclude the possibility of its being misplaced would be highly desirable.

C. Major accidents at nuclear facilities

61. Attempts have been made in several studies to estimate the consequences of a worst-case accident in nuclear plants, including both the damage in life and property and the probability of occurrence of such an accident. Almost all these studies are based on data from and conditions prevailing in developed countries. It is important that such studies be repeated using data from developing countries and in accordance with the conditions prevailing there. International co-operation is essential in this respect.

62. It has also been mentioned earlier that sabotage and planned attacks by aircraft or missiles on nuclear power plants could have a higher probability and worst consequences than accidents of civilian aircraft. Methods to prevent such attacks should be sought. This is another important subject for international co-operation. One way to achieve this could be through a treaty to ban all attacks on civilian nuclear facilities.

63. The opportunities for such co-operation and its difficulties can be ascertained from the experience of developing countries that have planned or undertaken nuclear power programmes. Some of these problems were analysed by Fritz [8]. They included the following:

(a) Inadequate understanding of safety issues, particularly by Governments, utilities and industries;

(b) Absence or incompleteness of comprehensive national policy, laws, standards and criteria regulating power plant industry;

(c) Insufficient budget of regulatory agencies and funds for practical training.

64. Brazil has emphasized the value of co-operation regarding scientific and industrial training and regulatory aspects of its nuclear power programme. Its co-operation with the Federal Republic of Germany has involved the establishment of an independent regulatory body and of safety and licensing procedures, the training of several thousand engineers and technicians and the construction of two power plants. The Republic of Korea has also emphasized international co-operation, especially with respect to training. Since 1967 about 2,000 scientists and engineers of the Republic of Korea have participated in IAEA overseas training programmes. The Republic of Korea has now established several government regulatory, safety and licensing organizations.

65. This suggests that a closer examination of the issue may help to define an effective relationship between developing and developed countries in regard to safeguarding against the environmental hazards of nuclear power. The general issue of determining how relations between developing and developed countries can best contribute to the economic and social progress of the former is complex and subject to a wide range of approaches. In the specific case of nuclear power, and in particular the need for environmental protection, the question can be usefully framed in financial terms. Nuclear power is an extremely capital-intensive enterprise and therefore constitutes a heavy drain on the limited financial resources of a developing country.

66. At the same time, as indicated earlier, the chief reason why developing countries experience difficulty with creating the regulatory and safety organizations essential for environmental protection is the lack of sufficient financial resources. Thus, the very considerable financial burden of acquiring the nuclear power facility itself interferes with the development of the necessary protective measures.

67. It would appear, therefore, that the characteristics of an appropriate co-operation between developing and developed countries should be defined by its impact on the financial resources of the former. Thus, for those developing countries that have not yet undertaken a nuclear programme, the issue is whether the programme can be accompanied by a sufficient increment in its general level of development to support the necessary protective measures as well as the construction of the nuclear facility itself. This suggests that the co-operation between developed countries and the developing ones that are capable of introducing nuclear facilities and programmes ought to be governed by the aim of overall economic and social development. Conversely, the danger of inadequate environmental protection arises for a co-operation arrangement that is concerned only with the introduction of nuclear power, and not with the overall development of the recipient nation.

IV. CONCLUSIONS

68. The foregoing considerations justify the following conclusions regarding environmental implications of expanded utilization of nuclear energy, particularly in developing countries:

1. Developing countries seem to have to rely on the ability of the nuclear power industry in developed countries, well into the future, to build plants, reprocess spent fuels and provide specialized services. However, the development of nuclear power has encountered some difficulties in developed countries largely due to environmental and safety aspects inherent in nuclear technology. Accordingly, it is imprudent for developing countries to rely entirely on the nuclear power industry of developed countries in planning how to meet their future needs for electricity. Technical, social, economic and environmental studies should be undertaken to fix the optimum mix of their energy systems;

2. The chief advantage of nuclear power to a developing country is that it might produce electricity more cheaply than alternative means. However, this advantage is disappearing as the effort to reduce the inherent environmental hazards of nuclear power plants has sharply increased their cost relative to alternative technologies. Studies undertaken in developing countries, in co-operation with developed countries or international organizations if possible, should identify the safety measures and level of acceptable risks that correspond to the conditions and sites of nuclear plants in developing countries;

3. Waste management problems associated with the normal operation of nuclear power plants involve special difficulties in developing countries. While in theory (and to some degree in practice in developed countries) the disposition of the relatively low-level wastes that would be encountered in the limited nuclear systems of developing countries is manageable, it requires monitoring and treatment facilities which are not always readily available in developing countries. Measures to remedy this situation should be undertaken. If permanent disposal of radioactive waste is to be provided by developing countries, on-site studies should be undertaken to define the physical,

chemical and mechanical properties of the host bodies. An international agreement on permanent disposal of radioactive waste is highly recommended;

4. The extreme hazards that may arise from a major nuclear power plant accident would be particularly difficult to deal with in developing countries, where the required monitoring, treatment and medical facilities are notably lacking. In addition, the high population density and limited availability of motor transport make the establishment of the necessary evacuation plans extremely difficult in developing countries, if nuclear plants are to be located near urban areas. This in itself should become an important criterion in site selection in developing countries. Nuclear power plants for environmental and safety measures should be located far away (at distances of the order of 50 km or more) from heavily populated urban areas;

5. Nuclear power plants and their attendant facilities require the availability of a wide range of highly specialized personnel, many of whom must be recruited for nuclear training from other technologically advanced industries. Given the industrial pattern in most developing countries, it is difficult to recruit personnel for training without diverting them from other essential services. Developing countries with limited personnel resources tend to assign them preferentially to construction and operation of nuclear power plants, often neglecting essential environmental, safety and regulatory services. Accordingly, emphasis should be given to the importance of establishing regulatory and safety agencies with an adequate budget and trained personnel to look after the essential environmental aspects of nuclear plants;

6. Training of personnel for nuclear power plants and associated facilities requires long lead times, of the order of 12 years or more before the operation of a plant. This requires mobilization of limited resources and personnel over an extended period of time, and tends to strain other sectors of the economy of a developing country. Developing countries should not be encouraged to enter the nuclear era without careful optimization of resources and preparation of trained personnel, particularly on the safety aspects of plant operation;

7. The environmental advantage of nuclear power plants over fossil-fuelled plants, consisting notably in the fact that they do not contribute to such problems as the greenhouse effect or acid rain, is not very pronounced in relation to developing countries. The anticipated nuclear power plant capacity in these countries by 1995 would reduce expected global atmospheric CO_2 concentrations by less than 0.01 per cent. The contribution of electric power production to the more local problem of acid rain might be reduced by 6-8 per cent. An alternative way to reduce the effect of electric power production on these environmental problems would be the introduction of renewable energy sources;

8. International co-operation narrowly directed toward the expanded use of nuclear power in developing countries is not an effective means of contributing to their economic development. In turn, the effort to introduce nuclear power into a developing country with inadequate economic resources may result in inadequate control of the environmental hazards inherent in nuclear power. The indicated solution is to direct international co-operation toward the expanded use of energy sources with minimum environmental impact in whatever forms are most appropriate, in a given developing country, to the development of its economy and the quality of its environment. One approach to ensure that the use of nuclear power by developing countries is governed by their overriding need for economic development is to encompass the process within the programmes of the relevant international agencies broadly devoted to the cost-effective and environmentally benign use of all forms of energy.

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