Decommissioning of Nuclear Power Facilities

April 1990
DECOMMISSIONING
OF
NUCLEAR POWER FACILITIES

by

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with

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EMTIE
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ABSTRACT

To provide background information for power sector reviews, information on decommissioning of nuclear power plant is summarized and the main issues are outlined in the report. The proposed options for decommissioning, i.e., (a) continued surveillance and maintenance; (b) entombment; and (c) dismantling and disposal of the radioactive components, are presented. Experience acquired to date and its applicability to future decommissioning projects is discussed. The report covers regulatory aspects and the efforts of the International Atomic Energy Agency (IAEA) to assist member states, particularly developing countries, in instituting a regulatory framework and relevant standards. Estimates of decommissioning cost vary considerably but, with a discounting factor, this cost represents an increase of a few percent on the total cost of generation. Financial arrangements to provide adequate funds for decommissioning are also examined with emphasis on needed arrangements in developing countries. The linkage of decommissioning to the larger problem of radioactive waste management and the attendant risks accruing from the potential lack of resolution of this issue is emphasized.
### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGR</td>
<td>ADVANCED GAS-COOLED REACTOR</td>
</tr>
<tr>
<td>BWR</td>
<td>BOILING WATER REACTOR</td>
</tr>
<tr>
<td>DOE</td>
<td>DEPARTMENT OF ENERGY (USA)</td>
</tr>
<tr>
<td>EPA</td>
<td>US ENVIRONMENTAL PROTECTION AGENCY (USA)</td>
</tr>
<tr>
<td>FRG</td>
<td>FEDERAL REPUBLIC OF GERMANY</td>
</tr>
<tr>
<td>GAO</td>
<td>GENERAL ACCOUNTING OFFICE (USA)</td>
</tr>
<tr>
<td>GCHWR</td>
<td>GAS-COOLED, HEAVY-WATER-MODERATED REACTOR</td>
</tr>
<tr>
<td>GCR</td>
<td>GAS-COOLED REACTOR</td>
</tr>
<tr>
<td>HTGR</td>
<td>HIGH-TEMPERATURE GAS-COOLED REACTOR</td>
</tr>
<tr>
<td>HWR</td>
<td>HEAVY WATER REACTOR</td>
</tr>
<tr>
<td>IAEA</td>
<td>INTERNATIONAL ATOMIC ENERGY AGENCY</td>
</tr>
<tr>
<td>IEA</td>
<td>INTERNATIONAL ENERGY AGENCY, AN ARM OF THE ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT (OECD)</td>
</tr>
<tr>
<td>kWh</td>
<td>KILOWATT-HOUR</td>
</tr>
<tr>
<td>LMFBR</td>
<td>LIQUID-METAL FAST BREEDER REACTOR</td>
</tr>
<tr>
<td>LWR</td>
<td>LIGHT WATER REACTOR</td>
</tr>
<tr>
<td>MW</td>
<td>MEGAWATTS</td>
</tr>
<tr>
<td>MWe</td>
<td>MEGAWATTS-ELECTRIC</td>
</tr>
<tr>
<td>MWt</td>
<td>MEGAWATTS-THERMAL</td>
</tr>
<tr>
<td>NEA</td>
<td>NUCLEAR ENERGY AGENCY, AN ARM OF THE ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT (OECD)</td>
</tr>
<tr>
<td>NRC</td>
<td>NUCLEAR REGULATORY COMMISSION (USA)</td>
</tr>
</tbody>
</table>
PHWR  PRESSURIZED HEAVY WATER REACTOR
PWR  PRESSURIZED WATER REACTOR
TMI  THREE MILE ISLAND
UK  UNITED KINGDOM
USA  UNITED STATES OF AMERICA
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EXECUTIVE SUMMARY

In the context of electricity sector or time-slice lending, the World Bank often conducts reviews of power systems of borrowing countries in which nuclear power is a significant component. In such cases, it is necessary for Bank staff to be informed on various aspects of nuclear power and of the nuclear fuel cycle. One aspect of nuclear power plants is the decommissioning of the plant at the end of its useful life, which presents special problems over and above those of taking conventional industrial plants out of service. This study was commissioned by the World Bank as a brief on the alternative strategies for nuclear plant decommissioning, the experience to date, regulatory aspects, and the present and future estimated costs.

Three alternative strategies are available for the decommissioning of nuclear power plants: continuing surveillance and maintenance (which defers final decommissioning); entombment; and dismantling and disposal of the radioactive components. The latter option, which entails removing and disposing of all fuel and radioactive fluids and subsequently all contaminated structural materials and equipment, is the preferred strategy in most industrialized countries.

Experience to date has clearly demonstrated that decommissioning of large nuclear facilities is feasible. Most of this experience has been with research and relatively small-size demonstration reactors, but some of the earliest commercial power reactors are also now being decommissioned. Experience in maintenance and repair of existing reactors has also led to the development of techniques applicable to decommissioning, particularly in the area of radiation protection. It should be noted that the radiological consequences of decommissioning activities are considered low and well within accepted international standards of radiation protection.

Many of the national nuclear safety authorities are in the process of developing health and safety standards for decommissioning that will identify the extent to which the materials and equipment in a plant, and the site itself, must be decontaminated before they may be released for unrestricted use. The International Atomic Energy Agency is developing international guidance to be used by such organizations in setting the standards. Regulations also have been or will be issued in several countries requiring plant owners to ensure that sufficient funds will be available in the future for safe plant decommissioning.

Estimates of the future costs of decommissioning large nuclear power plants vary substantially, as discussed in the report. In the US, for example, estimates of the cost of decommissioning a single 1000-megawatt reactor unit range from about $100 million to over $300 million. In spite of this uncertainty, however, it is generally believed that decommissioning costs will have a small effect, perhaps a few percent increase, on the costs of generating electricity by nuclear power.
Financial arrangements for decommissioning that are in effect in various industrialized countries include prepayment (e.g., by an annual fee), external sinking funds, surety methods and insurance. Such provisions should be made well in advance of decommissioning -- preferably before a plant begins its initial operation -- to ensure that the necessary funds will be available to take the plant out of service in a safe manner at the end of its useful life.

Since plant decommissioning involves handling, packaging and disposal of radioactive materials, it is inextricably interwined with the broader and more complicated issue of radioactive waste management and disposal (on which a separate paper has been prepared as part of the series on nuclear power issues). The problem may become particularly acute at decommissioning time if large quantities of spent fuel accumulate at reactor site (either in water pools or in dry caskets) for lack of a central spent fuel repository site(s) which would allow gradual removal of spent fuel from the plant. Moreover, some of the radioactive components and other materials to be removed at decommissioning would have (at least in some scenarios described in the main report) to be shipped to a high level waste repository. Public controversy and opposition has rendered agreement on the siting of such repositories highly problematic in many countries with active nuclear programs. For example, in the US, in spite of the political consensus expressed in the Nuclear Waste Policy Act of 1982 as amended in 1987, the issue is far from resolution with strong opposition from local and state authorities at the candidate site, at Yucca Mountain, Nevada. Thus, although decommissioning is methodologically treated as a problem separate from waste management, its consideration within the broader context of radioactive waste disposal and its difficulties with public acceptance must not be overlooked.
1.0 INTRODUCTION

Taking a plant out of service for good at the end of its useful life is a common industrial activity and most normal industrial facilities can be readily dismantled at the end of their useful lives. Special procedures have to be adopted for nuclear plants, however, to place them in a condition that provides adequate protection for the health and safety of the decommissioning workers, the public, and the environment from the radioactivity present in such plants, all within the regulatory requirements of the authority in whose jurisdiction that plant exits. This process, known in the nuclear industry as decommissioning, presents problems of a unique nature among industrial plants. The ultimate goal of decommissioning is the cleanup of a facility and site so that the operating license can be terminated and the facility and site can be released for unrestricted use.

All radioactive materials, such as those present in a nuclear facility, that must be removed in decommissioning, decay over time into stable, non-radioactive materials. The length of time for such decay can vary from a few days to thousands of years and is specific to each radioactive element. Some materials remain chemically toxic even after radioactivity has decayed.

Different types of nuclear facilities require different decommissioning approaches. For example, reprocessing plants, which handle large quantities of highly radioactive materials in solution, present decommissioning problems which are different from those encountered in the decommissioning of nuclear power reactors. This report will focus on the decommissioning of the latter since commercial fuel reprocessing facilities exist only in a few industrial countries and are unlikely to be established in most developing countries. The report will, moreover, concentrate on Light Water Reactors (LWR), which consist primarily of Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), since these are the dominant types of reactor at present and in the foreseeable future in developing countries (the International Atomic Energy Agency has reported that there were 428 nuclear reactors operating worldwide at the end of 1988, about 75% of which are LWRs).

There are three ways in which the materials of a nuclear power plant can become radioactive during the operation of the plant. The first arises from the nuclear fuel itself which is only mildly radioactive when it is first placed in the reactor core, but becomes highly radioactive because of the neutronic reaction which takes place when power is produced. This neutronic reaction causes the uranium in the fuel to fissic, producing heat and "fission products" which are highly radioactive. Some of the neutrons produced in the chain reaction, instead of causing fission, are absorbed by uranium and create new elements, such as plutonium, which are themselves fissile and radioactive.

\[\text{For a glossary of terms see Annex IV.}\]
The second source of radioactivity comes from the neutron activation of the structural materials in the reactor. In the same way in which some of the neutrons produced in the reaction are absorbed by the uranium fuel, some are also absorbed by the reactor vessel, components, and adjacent structures and produce radioactive isotopes within the structural materials.

The third source of radioactivity arises when fission products leak through the fuel cladding into the cooling water. Although the cooling water is continuously purified to remove radioactive materials, some deposition of fission products usually occurs on the surfaces of the cooling system.

When the time comes for a nuclear power plant to be decommissioned, the first action is to remove the major source of radioactivity - the remaining nuclear fuel, which is taken out of the reactor and removed from the site for ultimate disposal. The subsequent tasks of decommissioning are the removal of the second and third forms of contamination that remain after the fuel has been removed, which must also be disposed of. Most of the materials in the plant will only hold surface contamination, which can be removed by a variety of methods such as the application of chemical detergents, or by electropolishing (in which an electric current is applied and a current used to remove surface layers of a metal, including deposits on such surfaces). In contrast, those structures nearest to the reactor core which have become neutron-activated will have to be disassembled and removed from the plant for ultimate disposal as radioactive wastes.

There are three main basic engineering options available for taking nuclear facilities out of service - continuing surveillance and maintenance, entombment of the highly active part of the facility, or decommissioning of the plant by dismantling it and disposing of the radioactive portions of the plant as nuclear waste.

It should be noted that it is possible to keep the non-nuclear portion of a plant intact and utilize it with an alternative fuel source. This "conversion" of a plant consists of separating the original nuclear steam supply system from the generating system and disposing of the nuclear system in accordance with one of the three decommissioning options identified above. It may then be possible to repower the existing turbine-generator system with a new steam supply system. Although conversion is not a method of decommissioning a plant, it should be understood that one of the three options identified above would have to be pursued in the event of plant conversion.

At the present time there has been only limited experience in decommissioning nuclear power plants, due to the fact that very few have yet reached the end of their useful lives. However, experience is building up and information from projects such as the Shippingport Decommissioning Project in the United States is becoming widely available. As discussed in Section 3, the information being gained indicates that there are no technical obstacles to the safe decommissioning of nuclear power plants and to the disposal of the contaminated components. Moreover, it is expected that as the time approaches for currently operating power plants to be
decommissioned, industrial organizations will be established to compete for decommissioning business and the disposal of the waste. About 15,000 m$^3$ of waste is estimated to arise from decommissioning a single 1000-MW LWR, accounting for some 40% of the total waste produced in 25 years of operation and decommissioning.

The costs of decommissioning are estimated to be a few percentage points of the total generating costs, as discussed in Section 5.1. The figures show that there is little consistency among different countries even when identical technologies are involved, or even within the same country. This indicates a high degree of uncertainty in the estimates of decommissioning costs.

To ensure the availability of funds for plant decommissioning appropriate financial provisions must be made for them, as discussed in Section 5.2. In some cases it may be practical for utilities to pay decommissioning costs as they are incurred, out of revenues from other plants that are being operated by the utility at the time of decommissioning. However, it is becoming common practice for countries to establish special funds based on revenues earned during the operating life of the plant even though decommissioning may not be necessary for 20-30 years in the future. The latter approach ensures that those who benefitted from the electricity produced by the plant during its useful life pay the costs to decommission the plant.

This report surveys the alternative technologies and strategies available and experience to date in taking nuclear power plants out of service and examines briefly regulatory requirements which are now being introduced by those nations with large nuclear power programs. Finally, it analyzes the estimated costs of decommissioning and the financial strategies available to cover these costs.

Decommissioning of a plant implies the availability of temporary storage facilities and subsequent permanent repositories for low, medium, and high level radioactive wastes, since all the spent fuel, radioactive liquids and possibly other contaminated structural materials would have to be transported and disposed of off-site. The selection of an appropriate site for such disposal has been a difficult task and still remains unresolved in many countries with substantial nuclear power programs. Therefore, the risk of not having available an acceptable method and site for radioactive waste disposal at the time of plant decommissioning must be considered in any decision to proceed with nuclear power development. This issue is addressed in a companion paper under the series on nuclear power.
2.0 ALTERNATIVE TECHNOLOGIES AND STRATEGIES

Thermal electricity generating plants of all types comprise the same main constituents - a furnace, steam generators, heat exchangers, cooling towers and turbo-generators. The part which makes a nuclear power station unique from all other thermal plant types is the "furnace" - or nuclear reactor. It is this part of the facility that requires special decommissioning procedures once a nuclear plant has reached the end of its useful life and arrangements are being made for the site to be released for unrestricted use.

Three alternative strategies can be considered:

1) Continuing surveillance and maintenance;
2) Entombment; or
3) Dismantling and disposal of the radioactive components.

Option 1 does not by itself constitute a complete decommissioning strategy and is only an interim option that could be exercised in order to allow a plant’s residual radioactivity to decay before performing plant decommissioning by either of options 2 and 3. In all cases the fuel is first removed together with radioactive liquids and other contaminated materials in the form of waste. The following paragraphs describe these alternative strategies in more detail.

2.1 CONTINUING SURVEILLANCE AND MAINTENANCE

Surveillance and Maintenance, sometimes called "mothballing", consists of placing the facility in a state of protective storage. In general, the facility may be left intact once all the fuel and the radioactive fluids and waste have been removed from the site. Adequate radiation monitoring, environmental surveillance, and appropriate security procedures must be established to ensure that the health and safety of the public is not endangered under the terms of a license that permits the plant owner only possession of the plant but not its further use.

The plant has to be maintained in good condition to conform to nuclear regulatory requirements at all times. In order to ensure that these regulatory requirements are being met, it is essential that routine inspection and monitoring of radioactivity be carried out in and around the plant. For this purpose, all monitoring equipment must be maintained in good condition at all times.

Long-term surveillance and maintenance cannot be considered either cost-effective or environmentally acceptable since the predominant radionuclides have half
lives in the range of 20 to 50 years and, therefore, their quantities will not diminish significantly during any reasonable time period. Consequently, this strategy is generally viewed as a deferment of the ultimate necessity for decommissioning and the consensus among industry and regulators is that it is not an acceptable permanent solution.

2.2 ENTOMBMENT

Entombment consists of sealing all the highly radioactive or contaminated components remaining after all the fuel and radioactive fluids and wastes have been removed (e.g., the pressure vessel and internals) within a new structure built around the biological shield. This additional structure is required to provide secure containment over the lengthy period of time during which significant quantities of radioactivity remain within the reactor, perhaps as long as 200 years. It also requires an appropriate and continuing surveillance program to be maintained.

Entombment is not normally used as a decommissioning strategy for nuclear power plants and has only been used in those cases where a reactor has suffered extensive damage due to a severe accident which has destroyed much of the system's basic integrity and where other methods of decommissioning are not feasible for many years. An example of this method is the entombment of the No. 4 reactor at Chernobyl in the Soviet Union following the accident in 1986 (the Soviets call this structure the "Sarcophagus"). It is worth noting that the accident at Three Mile Island in the United States damaged only the reactor core and internals and not the pressure vessel or the biological shield. As a consequence, once the removal of the damaged core was completed, the TMI reactor could be totally dismantled like any other reactor.

2.3 DECOMMISSIONING BY DISMANTLING

Dismantling consists of first removing all the fuel, radioactive fluids, and waste, followed by removal of all other materials that have become radioactive during normal plant operations in order to return the site to unrestricted use. Decommissioning of a nuclear power station by dismantling is expected to be carried out in three phases.

2.3.1 Phase 1

This phase consists of defueling and the sealing of mechanical opening systems entering the biological shield. Soon after the reactor is shutdown for the last time, the reactor fuel is removed and transferred to the fuel cooling ponds using specially designed fuel handling equipment and procedures. Following its removal the fuel is transported off-site with other stored fuel, as during normal operation. The rate of defuelling is dependent on the availability of empty fuel racks in the cooling pond, availability of flasks, and transport constraints. During this phase most of the radioactive wastes accumulated on site during the course of the station's operating life are retrieved,
processed and packaged. As a result of this process over 99% of all radioactive inventory, virtually all of it contained within the spent fuel, will have been removed from the site.

No dismantling takes place during this phase, although some decontamination may be carried out, where appropriate, in preparation for plant dismantling.

2.3.2 Phase 2

Phase 2 involves the dismantling of the all plant and buildings outside the reactor biological shield and reinforcement of the shielding. Over 90% of the plant and buildings removed during this phase will be non-radioactive and can be handled as wastes produced during decommissioning of conventional power stations. These plant components include turbine-generators and associated electrical portions of the plant.

The radioactive wastes produced during this phase include those parts of the reactor system outside the biological shield, as well as the fuel handling equipment, fuel storage ponds, and most of the radioactive waste management plant. These wastes are typically characterized by their large volume and low activity, and consist mainly of contaminated steel and concrete. There may also be small quantities of intermediate level waste arising from the decontamination process. Effective safety measures must be applied for the control of contamination during this phase.

This phase is expected to take between 5 and 7 years to complete. After its completion, it is possible, and perhaps reasonable, to defer the next phase to allow further decay of the remaining radioactivity. In this case the remaining reactor structures would be weatherproofed and surrounded by a security fence, leaving the larger part of the site available for redevelopment for other purposes.

2.3.3 Phase 3

Phase 3 consists of complete dismantling and removal of all remaining equipment and structures and the final clearance of the site. This includes removal of the reactor pressure vessel, reactor internals, and the concrete biological shielding. Much of this material will have become radioactive due to neutron activation and surface contamination.

During this phase it is necessary to use remote handling equipment and techniques to dismantle the reactor in pieces that are suitably sized for packaging prior to transport to disposal sites. This is carried out in a contained environment which is ventilated and monitored to prevent the spread of radioactive particulate and gaseous materials produced during the cutting and handling operations.
This phase is expected to take about 5 to 7 years to complete after which the site will be fully cleared and returned to unrestricted use.

2.3.4 Processes

While decommissioning is usually seen in terms of phases, it is also useful to consider it in terms of processes. Decommissioning thus consists of two distinct operations. The first encompasses the engineering operations required at reactor site. The second process consists of the disposal of the radioactive waste generated in the engineering processes. Hence, the decommissioning strategy is closely linked to waste management strategy and policy and thus deeply imbedded in regulatory issues.

2.4 PREFERRED STRATEGY

Currently the strategy which appears to be preferred in most countries is to decommission the nuclear plant by dismantling it, disposing of the radioactive components as nuclear waste, and returning the site to a condition suitable for further use, such as the construction of another power plant. The last of the three phases of plant dismantling would be the most complex and most expensive of the three phases. Phase 3 may follow immediately after phase 2 or may be delayed. Countries will probably differ in their strategy of implementing phase 3.

The following table provides a summary of the decommissioning methods described in Sections 2.1, 2.2, and 2.3.
Table 1
Summary of Decommissioning Methods

<table>
<thead>
<tr>
<th>Decommissioning Method</th>
<th>Action</th>
</tr>
</thead>
</table>
| **Surveillance and Maintenance** | Fuel and radioactive fluids removed and transported off-site with radioactive waste.  
Plant kept in good order to meet nuclear regulatory requirements. 
Plant and environment continuously surveyed.  
Equipment for monitoring radioactivity maintained in good order at all times.  |
| Entombment                    | Fuel and radioactive fluids removed and transported off-site.  
The remaining structure and radioactive components including the biological shield are entombed in an integral structure capable of maintaining its integrity for as long as 100 years or more. |
| Dismantling                   | **Phase 1:** Fuel and radioactive fluids removed and transported off site with radioactive waste.  
**Phase 2:** dismantling of the non-radioactive plant such as turbo-generators, control gear, etc., and removal off site. Decontamination and removal off site of parts of the reactor system outside the biological shield.  
**Phase 3:** Dismantling and removal of all remaining equipment and structures and final clearance of the site. Remote handling techniques used for dismantling and packaging of radioactive components. |

The following Sections describe experience of decommissioning to-date, regulatory considerations, the cost estimates for plant decommissioning, and the financial strategies for covering these costs.
3.0 DECOMMISSIONING EXPERIENCE

Most world experience to date in decommissioning of nuclear facilities has been with research and relatively small size demonstration reactors. This experience has demonstrated the feasibility of decommissioning to each of the three stages identified in Section 2. A summary of the number of reactors which have been decommissioned to date or are in the process of being decommissioned is provided in Table 3.1.

Table 3.1
Summary of Worldwide Reactor Decommissioning Experience

<table>
<thead>
<tr>
<th>Country</th>
<th>Total No. Projects</th>
<th>Reactor Types</th>
<th>Most Advanced Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>13</td>
<td>PWR, BWR, HWR, HTGCR</td>
<td>Shippingport 72 MWe PWR</td>
</tr>
<tr>
<td>France</td>
<td>9</td>
<td>GCR, HWR, LWR LMFBR</td>
<td>Marcoule G1, G2 &amp; G3 100 MWe GCR</td>
</tr>
<tr>
<td>FRG</td>
<td>8</td>
<td>BWR, PWR, HWR GCHWR</td>
<td>Niederbach 100 MWe GCR</td>
</tr>
<tr>
<td>Canada</td>
<td>3</td>
<td>PHWR</td>
<td>Gentilly-1 250 MWe PHWR</td>
</tr>
<tr>
<td>UK</td>
<td>2</td>
<td>AGR, GCR</td>
<td>Windscale 33 MWe AGR</td>
</tr>
<tr>
<td>Sweden</td>
<td>1</td>
<td>PHWR</td>
<td>Agesta 80 MWe PHWR</td>
</tr>
<tr>
<td>Japan</td>
<td>1</td>
<td>BW..</td>
<td>JPDR 125 MWe BWR</td>
</tr>
</tbody>
</table>

Limited experience has also been gained in the decommissioning of fuel cycle facilities, such as reprocessing plants.

\*\*\* For further details, see Annexes I and II.
\*\*\* See Abbreviations for explanation of acronyms.
3.1 EARLY EXPERIENCE WITH SMALL FACILITIES AND APPLICABILITY OF OPERATING REACTOR EXPERIENCE TO NUCLEAR DECOMMISSIONING

Early experience in decommissioning of research and demonstration reactors has been found applicable and useful in the decommissioning of larger projects such as the Shippingport Station, the first commercial power reactor built as a joint venture by Duquesne Power Company and the US Atomic Energy Commission in 1957 in Shippingport, Pennsylvania. Similarly, the experience gained in the decommissioning of early commercial power stations like Shippingport, Dresden in Illinois, and Humboldt Bay in California is expected to be of significant value in the decommissioning of the later and much larger commercial plants built in the 1960s and 1970s, which will be ready for decommissioning in the late 1990s and the 2000s.

Since the mid-1980s, no serious technical problems have been found that will prevent the safe decommissioning of any nuclear facility, although, as discussed in Section 3.3, it is necessary to improve the relevant techniques in order to reduce costs and occupational radiation exposure.

In addition to past experience with decommissioning of small research and demonstration reactors, the need for scheduled maintenance and repairs at operating power plants has led to the development of techniques which are also applicable to decommissioning, with benefits accruing particularly in the area of radiation protection. For example, it has been necessary to repair or replace steam generators in several reactors, which has involved decontamination, pipe disconnection, lifting and removal of the old components and replacement with new ones, all of which have been done in relatively high radiation fields. Furthermore, a range of in-reactor inspection and repair techniques has been developed, including visual inspection of rooms and components, radiation field measurements, weld inspection, a variety of cleaning and cutting methods, and other machining procedures.

The experience of small-scale decommissioning, maintenance and repair at existing reactors, and post-accident decommissioning (see Section 3.4) is being used in the planning of major decommissioning projects now under way or planned (as described in Annexes I and II). These projects, which consist primarily of the older commercial power plants, will provide a further basis for the decommissioning of the large units now operating in the world.

Experience based on smaller facilities is helpful in planning the decommissioning of modern large plants since it provides a basis for (a) planning the composition and size of the crews needed and (b) projecting the needed levels of effort and materials for activities such as pipe cutting, vessel segmentation and concrete demolition. Such experience is also useful in the estimation of costs, schedules, occupational exposure and waste volume in future decommissioning projects.
Nevertheless, there is still a lack of experience with large plants and it is quite possible that unexpected problems could arise. Consequently, there are still uncertainties about the real costs of decommissioning. The fact that large commercial plants have longer operating periods and higher power levels than the small, older plants would tend to increase decommissioning costs per megawatt relative to these older plants, since the newer plants have higher radiation levels due to heavier contamination of the surfaces and higher induced radioactivity of the metallic components. On the other hand, it should be noted that in most decommissioning work undertaken to date, it has not been a priority to keep costs low, but rather to learn decommissioning techniques and to develop the necessary equipment, whereas a primary objective of future projects would be to minimize cost taking advantage of equipment developed and techniques learned in previous projects.

3.2 EXPERIENCE WITH SHIPPINGPORT

The US nuclear industry has decommissioned several small, often experimental reactors and one commercial reactor. Decommissioning technology has been safely and successfully demonstrated at the Elk River project (58 MW thermal) and the Sodium Reactor Experiment (30 MW thermal). More recently the US Department of Energy extensively documented decommissioning of the commercial-scale Shippingport nuclear power station (236 MW thermal) in Pennsylvania, USA completed in 1989. Physical decommissioning of this facility began in September 1985 and was completed in 1989. Although Shippingport was a pressurized water reactor (PWR), its decommissioning is atypical of the large number of existing PWRs. The plant was used as a prototype for testing various nuclear fuel cycles (such as one employing thorium fuel rather than uranium) and thus has different kinds of contamination from other PWRs. Nonetheless, the experience is relevant in terms of developing and demonstrating the engineering techniques necessary for decommissioning all kinds of nuclear reactors.

Steel components from the reactor core that had become radioactive through irradiation during operation of the plant were transferred out of the reactor pressure vessel in 1986. At the same time, a number of other activities were conducted, including asbestos removal, system draining, electrical deactivation, and external surface decontamination. Removal of radioactive primary system piping was completed in February 1988. Radioactive solid waste has been shipped to the US Department of Energy's Hanford Reservation in Washington State for burial. As of April 1988, nearly 200 truck shipments and one large rail shipment had been made, containing about 7,000 cubic meters of low-level waste. The Shippingport reactor pressure vessel has also now been transported by barge to Hanford and buried.

The total Shippingport Decommissioning Project is estimated to cost $98.3 million. Although the Shippingport Station had a generating capacity of only 72 MWe, which is quite small compared to the larger unit sizes in the range of 1100 - 1300 MWe
adopted in the 1970s and 1980s by reactor manufacturers and utilities, its physical size was actually comparable to that of the larger nuclear plants with these higher power ratings. The total volume of its containment building was about 30,000 cubic meters, compared to about 60,000 cubic meters for a typical large PWR; and its reactor pressure vessel was about 12.5 meters high by 5.5 meters diameter, compared to 13 meters high by 4.5 meters diameter for a typical large PWR. Thus, the experience at Shippingport is considered representative of the larger-scale decommissioning projects of the future. Furthermore, regardless of the differences in scale, the main objective of the Shippingport Decommissioning Project has been to develop and demonstrate project management techniques as well as decommissioning technology and capabilities.

Experience of decommissioning other types of reactor, such as the gas-cooled system, is being obtained from the decommissioning of the Windscale Advanced Gas-Cooled Reactor prototype in the United Kingdom. This work was started some two or three years ago and the experience being gained will be used by the Central Electricity Generating Board (CEGB) which recently announced that it had retired from service and would decommission the Berkeley and Bradwell generating stations, two of the early gas-cooled reactor systems. Similarly, work on decommissioning of smaller, older commercial reactors is starting in other countries - principally France, the U.K., and the Federal Republic of Germany.

3.3 FURTHER TECHNOLOGY DEVELOPMENT NEEDS

Further technology development is considered necessary in four principal areas:

- Disassembly of nuclear power plants will entail segmentation of reactor vessels and internals to reduce these components down to transportable sizes, and work is required to improve the capability to do this remotely as well as to demolish heavily-reinforced concrete structures.

- Methods for achieving complete decontamination of surfaces are being developed so that structures can be either recovered or disposed of as regular solid waste, thus reducing the volume of waste requiring disposal in a low-level waste repository.

- Techniques for reducing the volume of radioactive waste produced in decommissioning are desired, including space-efficient packaging of piping and components, compaction, incineration, and melting and casting of metallic components into ingots.

- Finally, improved methods for rapidly determining radioactivity levels over large volumes of decommissioning wastes are desired.
3.4 DECOMMISSIONING EXPERIENCE FOLLOWING ACCIDENTS

There are two examples where reactors had to be rendered safe following severe accidents that made them unsuitable for further use. These are exceptional cases which cannot be compared with normal decommissioning activities. They are, nevertheless, akin to decommissioning and hence are worthy of note.

The Three Mile Island (TMI) Unit 2 reactor in Pennsylvania, USA, is a 900-MWe pressurized water reactor which first came on line in December 1978. About three months later a severe accident occurred at the facility while the reactor was operating at 97% of its rated power. The accident resulted in massive degradation of the core and reactor internal structures. As a result of the accident the reactor has had to be partly decommissioned, first through decontamination of the auxiliary building, the containment building and equipment peripheral to the main reactor located inside the containment building, followed by lengthy and tedious removal of the highly radioactive core debris and internals from the pressure vessel. These materials have been packaged and shipped to the Hanford Reservation in the State of Washington, USA, for examination and subsequent burial.

The cost of the cleanup is extremely high (about $973 million) owing to the difficulties of removing the disintegrated core and structural materials inside the pressure vessel, and the need to use specially designed remote handling equipment for the protection of the plant personnel from the very high radiation fields present inside the reactor vessel. The cost has been paid through insurance and special grants from the US government. The high cost should not be considered indicative of that expected in normal decommissioning because of the totally unique problems which will not be encountered when an undamaged reactor is decommissioned.

The accident to the No. 4 reactor at Chernobyl, USSR, in April 1986, was many orders of magnitude more severe than the TMI accident in terms of the radioactivity released to the atmosphere and the damage done to the reactor and associated buildings. The Chernobyl reactor, a graphite-water pressure tube reactor, is radically different from the light water reactors currently in use elsewhere in the world. Following operator experiments (which violated operational procedures) to explore the allowed safety limits, a sudden uncontrolled power surge developed in the reactor which resulted in massive destruction of the plant and an uncontrolled fire to the graphite and fuel, leading to large releases of radioactivity that reached most European countries. The accident at Chernobyl is the most severe accident in a nuclear facility to date and has had profound worldwide repercussions on public attitudes towards nuclear power.

Since the remains of the No. 4 reactor at Chernobyl were so heavily contaminated and were causing continuous release of radioactivity, the Soviet Government decided that the only sensible course of action was to completely seal off the facility through entombment in a concrete structure called a "Sarcophagus".
The experience gained in this operation is of limited applicability to the carefully planned entombment that would occur at the end of the useful life of an undamaged plant and following complete fuel removal, if a decision were taken to entomb it. Nevertheless, some useful lessons have been learned, such as burrowing beneath the reactor to place an impervious concrete mat under it, which may be applied if the entombment option were ever exercised.
4.0 REGULATORY ASPECTS

Three principal aspects of decommissioning have been identified for which regulatory authorities in various countries have determined a need for regulation:

- standards for decommissioning, i.e., criteria for maximum levels of radioactivity which may be present before a license may be terminated and the facility and site released for unrestricted use;
- accepted methods of plant decommissioning; and
- requirements for financial assurance by plant owners that there will be sufficient funds available to decommission a plant.

These three areas of regulation are examined in greater detail in the following paras. of this Section.

4.1 DECOMMISSIONING STANDARDS

Safety and environmental standards that govern the normal operation of nuclear facilities, such as radiation protection and effluent standards, apply also during decommissioning in order to limit radiation exposure of personnel working at the reactor during decommissioning activities.

Specific standards for decommissioning are necessary in order to determine the radioactivity level at which the materials and equipment removed from a plant and the site itself, may be released for unrestricted use. Up to now, standards have been developed and applied on a case-by-case basis in the decommissioning projects that have been carried out. In the future, when a number of facilities become ready for decommissioning, regulators in individual countries are likely to develop uniform sets of requirements which will apply to all nuclear facilities in that country. Such regulations will likely be based on guidance provided by the International Atomic Energy Agency. Such guidance will certainly simplify the process and reduce the cost of decommissioning planning. This is particularly important for the licensees who need to know in advance how much of the plant materials would be acceptable for disposal as regular solid waste and which materials and equipment would be acceptable for reuse.

Several countries, including the United States, the FRG, and France are or will soon be in the process of setting criteria identifying maximum radioactivity levels that

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may be present for a site to be released for unrestricted use. In the USA, the Nuclear Regulatory Commission (NRC) has already published a Regulatory Guide that establishes acceptable contamination levels for the release of areas for unrestricted use. Also a Federal interagency task force led by the Environmental Protection Agency (EPA) is now developing general principles for determining upper limits for residual radioactivity. EPA intends to propose such limits in 1990 and issue final regulations in 1993. The principles now under development are based on the magnitude of current and future risks to individuals; the cumulative effects on populations taking into account the half-life and environmental mobility of residual contamination; and the technical and economic practicality of cleanup.

EPA has requested public comments on the health and environmental benefits, costs, and technical feasibility of achieving various levels of cleanup; the conditions under which recycling of equipment and materials is acceptable from a public health standpoint; and whether there should be a time limit placed on the period for which institutional controls would be acceptable as an interim strategy until decontamination is completed.

Another approach, followed in the FRG and Sweden, is to require applicants for reactor operating licenses to submit, as part of the licensing documentation, a concept or plan for decommissioning the facility. In the FRG, the facility design must take into account ease of decommissioning in a way that will result in the lowest possible radiation doses to personnel. Experience, however, is very limited since few reactors have reached the decommissioning stage.

4.2 ACCEPTED DECOMMISSIONING METHODS

Regulatory authorities throughout the world have not expressed definitive positions on the decommissioning strategies they consider acceptable. It is expected that plant owners would submit decommissioning and license termination plans for each facility and the authorities would approve such plans on a case-by-case basis. For example, NRC's new rule on decommissioning requires that at the time of termination of operations, licensees must submit a proposed decommissioning plan to NRC which contains an indication of:

- the decommissioning alternative to be used (NRC states in its regulations that generally, for an electric utility licensee, an alternative is acceptable if it provides for completion of decommissioning within 60 years, and, for other licensees, if it provides for completion of decommissioning "without significant delay");
- a description of the activities involved;
- a description of the controls and limits on procedures and equipment to protect occupational and public health and safety for that alternative;
• a current cost estimate for the chosen alternative; and

• a description of technical specifications, quality assurance provisions and physical security plans.

If the plan demonstrates that the decommissioning will be in accordance with regulations, the Commission will approve and issue an order authorizing the decommissioning.

Although NRC's rule does not include discussion of acceptable decommissioning methods, supplementary information accompanying the rule states that either immediate decontamination and dismantling, or interim surveillance and maintenance followed by decontamination and dismantling, are "reasonable options for decommissioning light water power reactors". Furthermore, they believe that the entombment alternative should not be specifically precluded in the rule because there may be instances in which it would be an allowable alternative. These instances might include smaller reactor facilities, reactors that do not run to the end of their lifetimes, or other cases where long-lived isotopes do not build up to significant levels or where there are other site-specific factors.

4.3 FINANCIAL ASSURANCE REQUIREMENTS

Regulations requiring plant owners to ensure availability of sufficient funds for safe plant decommissioning have been or will be promulgated in several countries. Two examples of such regulations in the US and Sweden are given in this Section.

NRC's new rules on decommissioning, issued in June 1988, require future applicants for reactor operating licenses to submit information indicating how reasonable assurance will be provided that funds will be available to decommission the facility. Also, by July 1990, all current license holders must submit this information. The rule states that this report must certify that financial assurance will be provided in an amount at least as large as indicated in Table 4.1.
Table 4.1
Financial Requirements for Nuclear Plant Decommissioning

Minimum Funds Required

<table>
<thead>
<tr>
<th>For a Pressurized Water Reactor (PWR):</th>
<th>US$-Millions a/</th>
</tr>
</thead>
<tbody>
<tr>
<td>greater than or equal to 3400 MWt</td>
<td>105</td>
</tr>
<tr>
<td>between 1200 MWt and 3400 MWt</td>
<td>(75 + 0.0088P) b/</td>
</tr>
<tr>
<td>(for a PWR of less than 1200 MWt, use P=1200)</td>
<td></td>
</tr>
</tbody>
</table>

For a Boiling Water Reactor (BWR):

<table>
<thead>
<tr>
<th>greater than or equal to 3400 MWt</th>
<th>135</th>
</tr>
</thead>
<tbody>
<tr>
<td>between 1200 MWt and 3400 MWt</td>
<td>(104 + 0.009P)</td>
</tr>
<tr>
<td>(for a BWR of less than 1200 MWt, use P=1200)</td>
<td></td>
</tr>
</tbody>
</table>

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a/ Amounts do not include the cost of removal and disposal of spent fuel or of non-radioactive structures and materials beyond that necessary to terminate the license. Figures are expressed in constant 1986 US$.

b/ P is the power in MWt (megawatts thermal), which is the thermal power released in the reactor; with a thermal efficiency of 0.33, about 3 MWt are required to produce 1 MWe (megawatt electric).

The NRC rule identifies the following four methods as acceptable ways of providing financial assurance for these funds:

a/ **Prepayment**: deposit prior to the start of operation into an account segregated from licensee assets and outside the licensee's administrative control of cash or liquid assets such that the amount of funds would be sufficient to pay decommissioning costs.

b/ **External sinking fund**: a fund established and maintained by setting funds aside periodically in an account segregated from licensee assets and outside the licensee's administrative control in which the total amount of funds would be sufficient to pay decommissioning costs at the time termination of operation is expected.
c) **Surety method, insurance, or other guarantee method:** these methods guarantee that decommissioning costs will be paid should the licensee default. A surety method may be in the form of a surety bond, letter of credit, or line of credit.

d) **Federal, State, or local government licensees:** such licensees may provide a statement of intent containing a cost estimate for decommissioning and indicating that funds for decommissioning will be obtained when necessary.

In Sweden, the Act on Financing of Future Expenses for Spent Nuclear Fuel, enacted in 1984, requires reactor licensees to defray the costs for decommissioning as well as for spent fuel and radioactive waste handling and disposal. The reactor owners annually submit cost estimates for these activities to the National Board for Spent Nuclear Fuel, which calculates a fee per kWh and collects this fee from each owner over the life of the plant. The resulting fund is used at the time of decommissioning to reimburse costs incurred by the owners in carrying out their waste management and decommissioning activities.
5.0 COST AND FINANCING CONSIDERATIONS

5.1 COST ESTIMATES

Experience to-date in decommissioning small nuclear facilities provides a limited basis for estimating the costs of decommissioning larger nuclear power plants, but many uncertainties still exist in the factors influencing these costs. Some of these are site-specific while others are country-specific. This latter point is illustrated in Table 5.1, based on information in a 1988 Report of the Joint Working Group of the Nuclear Energy Agency and International Energy Agency (NEA/IEA) from Member States showing the anticipated decommissioning costs for certain countries with substantial nuclear programs. A breakdown of decommissioning costs is given in Annex III.

Table 5.1
Estimated Decommissioning Costs

<table>
<thead>
<tr>
<th>Country</th>
<th>Undiscounted Capital Investment Cost (1987, 5% d.r.)</th>
<th>Discounted US$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>159 US$/kW 10% of Total</td>
<td>29 US$/kW</td>
</tr>
<tr>
<td>UK</td>
<td>254 US$/kW 12% of Total</td>
<td>25 US$/kW</td>
</tr>
<tr>
<td>Japan</td>
<td>170 US$/kW 8% of Total</td>
<td>38 US$/kW</td>
</tr>
<tr>
<td>Germany</td>
<td>221 US$/kW 10% of Total</td>
<td>36 US$/kW</td>
</tr>
<tr>
<td>USA</td>
<td>114 US$/kW 6% of Total</td>
<td>34 US$/kW</td>
</tr>
</tbody>
</table>

These decommissioning cost estimates can be compared with the average capital cost of $4000/kW for new plants in the US in 1987 as assessed by the Utility Data Institute.

Since not enough commercial nuclear power plants have been decommissioned as yet, and as a result, little actual cost data exist, the figures supplied are uncertain. In 1988, the United States General Accounting Office (GAO) was requested by a Congressional subcommittee to examine the cost estimates used by the NRC in drawing up the regulations referred to in Section 4.3. In carrying out this investigation, the GAO consulted a number of expert sources and reported that the estimates from the groups consulted ranged over a wide spectrum. For example, a consumer group estimated the cost of decommissioning the three units of the Palo Verde power station in Arizona at about $792-million and about $628-million for decommissioning the two units of the Diablo Canyon, California station. On the other hand the former Director of the Shippingport Project told the GAO that decommissioning costs for most 1000-MW plants would range from $100 million to $200 million. Most of those consulted thought that the NRC's estimates were too low, although one group thought they were too high.

Several factors contribute to the spread in estimated decommissioning cost. Many cost items are calculated on the basis of a unit cost estimate and number of units. Overstated unit cost factors can significantly inflate the cost estimates because large quantities of work units will be performed. For example, the productivity rate used by many utilities for the removal of small-bore pipe (less than 8 inches in diameters) is one foot per worker-hour. At Shippingport, the productivity rate was 6 ft. per worker-hour. When applied to a total inventory of 60,000 ft. of contaminated pipe, the low productivity rate used by many utilities, leads to an over-estimate of about 50,000 worker-hours in removal time. At US$20 per worker-hour, and including a 25% contingency, this over-estimate amounts to US$1.25 million. Similarly, estimates of productivity losses in all types of work, caused by the radioactive environment vary widely. DOE's estimates for the Shippingport decommissioning used a productivity loss of two out of eight hours, whereas the Atomic Industrial Forum/National Environmental Studies Project guidelines produced a range of approximately 2.5 to 4.5 hours of productivity lost per eight-hour day. In recent litigation at the U.S. Federal Energy Regulatory Commission (FERC), a utility claimed the upper limit of 4.5 hours. DOE's decommissioning Handbook recommends a productivity loss of two hours out of an eight-hour day. Another impact to the estimate is decommissioning project duration. NRC's analysis (performed by Pacific Northwest Laboratories) produced an estimate of six years for a 1100-MW unit, including two years of preparatory work before final shutdown. In contrast, many utility studies adopt a generic eight-year project duration, including preparatory work beginning

\[\] This cost does not reflect average worldwide experience. A range of US$1,700-3,000 would be more representative of cost experience outside the US.
two years before final shut-down. Other factors of uncertainty are the extent of planning and engineering work, and the tasks to be performed by an outside contractor.

The choice of a decommissioning alternative also influences the cost of a decommissioning project as does the timing of decommissioning, e.g., whether immediate decontamination and dismantling are performed, or whether the plant is first placed under surveillance and maintenance for an interim period. Specific factors which may influence decommissioning costs, depending on the alternative chosen, include: labor costs; waste shipment and burial costs; plant size and site structures (such as cooling towers); and extent of secondary system contamination (such as turbines, condensers, etc.). In the US and elsewhere, cost increases for many of these items over the last few years, particularly higher fees for waste packaging, transportation and disposal, have caused sharp increases in the estimated costs of decommissioning large power reactors. To account for the potential for such increases, an expert group of the OECD Nuclear Energy Agency has suggested applying a contingency factor of 25% to ensure conservatism in cost estimates.1

Comparison of the costs of the immediate and the deferred decommissioning options depends heavily on the discount rates used in calculations. Furthermore, the actual level of decommissioning effort required for the various timing options will vary, since radioactive decay would occur during an interim storage period, thus lowering the extent of contamination. Postponing decommissioning and opting for interim surveillance and maintenance of a plant would reduce the total requirement for decontamination, remote operations, and worker protection, since the plant's total radioactivity would have decayed to a lower level, leading to cost savings. On the other hand, there would be annual costs for maintaining the plant during this interim period, including monitoring, security, insurance, licensing fees, etc. Thus, the optimum decommissioning strategy needs to be identified on a case-by-case basis, focusing on site specific factors such as the types and quantities of radioactive contamination present and the resulting requirements in terms of labor, shielding, remote operations and waste management.

5.2 DECOMMISSIONING COST IN DEVELOPING COUNTRIES

Estimates for nuclear power plant decommissioning in developing countries are not available. However, there seems to be no strong reason for these costs to be substantially different than those in industrial countries.

Since decommissioning is a labor intensive activity and since labor costs are generally lower in developing countries, this component would tend to drive downward the cost of decommissioning in developing countries. On the other hand, expatriate

1/ One state in the USA has allowed a 50% contingency and other states have disallowed any contingency.
consultants may be required to assist in the decommissioning task and a larger portion of tools, equipment, and materials may have to be imported than in developed countries; also the process may be slower and less efficient, which would tend to drive the cost upward. Overall it is reasonable to assume that, under normal circumstances, the range of cost figures quoted in Table 5.1 would cover the cost range of decommissioning in developing countries and that the relative cost would be a few percent, perhaps as high as 10%, of the total cost of electricity generation.

5.3 SUMMARY OF COST ESTIMATES

The estimates for large nuclear plant decommissioning cost, reported by various countries cover a rather wide range of cost, differing by more than a factor of two. Decommissioning costs should be based on site-specific cost studies. The site-specific study should be based on "hard data" rather than on engineering judgement, whenever possible. At present the experience at Shippingport is the best basis for estimating many decommissioning costs. The information base will gradually grow as more plants are decommissioned (about 15 plants are scheduled for retirement in the US by the year 2000).

In any case, regardless of the decommissioning method, and taking into account the substantial uncertainties in estimating decommissioning cost this cost will have a relatively small effect, perhaps up to 10 percent, on the cost of electricity generation by nuclear power. OECD's Nuclear Energy Agency has estimated the impact of decommissioning on power generation costs to be from 0.1 to 0.4 mills per kilowatt-hour. For reference, the average annual operating cost of a nuclear power plant in the US is roughly 4 to 5 cents per kWh, according to the USDOE Energy Information Administration. Similarly, the Long-Run Marginal Cost (LRMC) of electricity generation in most countries is calculated in the range of 4 to 5 US cents per kWh (in constant 1988 units). NEA has also found that delayed decommissioning strategies generally have lower cost estimates than immediate decommissioning strategies.

5.4 FINANCING ARRANGEMENTS

Methods of ensuring that funds will be available to cover future decommissioning costs will vary from country to country. In cases where a utility is owned by the national government or where there is otherwise sufficient confidence that it will remain financially solvent for a long period of time, it may be acceptable for the utility to pay decommissioning costs at the time such costs are incurred.

On the other hand, for privately-owned and other utilities, regulatory authorities are keen on obtaining assurance that funds will be available to pay for decommissioning and have established strategies to raise such funds during the operating life of licensed plants, as discussed in Section 4. In the US, the NRC has published a schedule of amounts that must be guaranteed for a given type and size of nuclear power plant (see Section 4.3), and has identified prepayment, external sinking funds, and surety methods
or insurance as acceptable methods of providing such financial assurance. Swedish law requires reactor licensees to pay an annual fee into a fund administered by a Federal agency from which these licensees would be reimbursed to cover actual costs incurred in future decommissioning activities.

The Canadian approach is that when the costs of removal of fixed assets can be reasonably estimated, the amounts are treated as an operating expense over the remaining life of the plant. Finnish utilities are obliged to set aside funds for decommissioning. In the FRG, funds are also collected during the operations phase; the specific financial assurance methods are decided for each plant individually.

For developing countries, similar financial arrangements for covering the costs of decommissioning would be possible. However, since most nuclear power plants in developing countries are likely to be state-owned, imposing a surcharge on electricity rates during the working life of a plant so as to cover expected decommissioning costs may be strongly resisted by local authorities, given the public pressures in this regard. If a recovery scheme were not in place to allow accumulation of the needed funds for decommissioning, the utility (or the Government/owner) would be faced with a heavy financial burden at the end of plant life.

The provision of adequate financing for decommissioning is a question to be considered by the institutions financing the plant. Prepayment for decommissioning may be included in the loan at the outset, but as it may be some 40 to 50 years before that money is being used, specific assurances should be provided by the borrower and provisions made for the required funds to be available at the appropriate time. Other financing schemes may also be possible. In any case, for sound financial management a scheme should be instituted and implemented to allow for the recovery of the cost of decommissioning at the end of the plant’s useful life in a manner consistent with the country’s regulatory requirements for public health and environmental protection. This would likely be reflected in the utility’s tariff levels or would be covered through special fees, Government contributions, or other means of recovery.

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These pressures, present also in developed countries, are stronger in developing ones since the ratio of electricity bills to income levels is higher.
6.0 SELECTED BIBLIOGRAPHY


SELECTED EXPERIENCE FROM DECOMMISSIONING RESEARCH AND POWER DEMONSTRATION REACTORS AND FUEL CYCLE FACILITIES

(References 9 through 14)

### Reactors

<table>
<thead>
<tr>
<th>Facility name and location</th>
<th>Reactor type</th>
<th>Power rating</th>
<th>Decommissioning stage</th>
<th>Date</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carolina/Virginia Tube Reactor (CVTR) Parr, South Carolina</td>
<td>HWR</td>
<td>65 MW(th)</td>
<td>Stage 1</td>
<td>1968</td>
<td>Basic Stage 1 applicable to industrial scale reactor; procedures developed for periodic surveillance.</td>
</tr>
<tr>
<td>Pathfinder, Sioux Falls, South Dakota</td>
<td>BWR nuclear superheat</td>
<td>190 MW(th)</td>
<td>Stage 1, conversion of facility to other use</td>
<td>1972</td>
<td>Isolation of steam plant and replacement of nuclear reactor with fossil fired boiler; continuous surveillance.</td>
</tr>
<tr>
<td>Saxton, Saxton, Pennsylvania</td>
<td>PWR</td>
<td>23.5 MW(th)</td>
<td>Stage 1</td>
<td>1973</td>
<td>Remote intrusion alarms for security to minimise work force.</td>
</tr>
<tr>
<td>Fermi I Monroe County, Michigan</td>
<td>Sodium cooled fast reactor</td>
<td>200 MW(th)</td>
<td>Stage 1</td>
<td>1975</td>
<td>Sodium handing experience for Stage I.</td>
</tr>
<tr>
<td>Peach Bottom I York County, Pennsylvania</td>
<td>HTGR</td>
<td>115 MW(th)</td>
<td>Stage 1</td>
<td>1978</td>
<td>Core graphite fuel handling and disposal for Stage I.</td>
</tr>
<tr>
<td>Hallam, Hallam, Nebraska</td>
<td>Graphite moderated, sodium cooled</td>
<td>256 MW(th)</td>
<td>Stage 2</td>
<td>1968</td>
<td>Basic Stage 2 procedures developed; no continuous surveillance.</td>
</tr>
<tr>
<td>Piqua Reactor, Piqua, Ohio</td>
<td>Organic cooled and moderated</td>
<td>45 MW(th)</td>
<td>Stage 2</td>
<td>1969</td>
<td>Entombment with conversion of reactor building to warehouse; reactor vessel entombed in sand; no continuous surveillance.</td>
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<tr>
<td>Boiling Nuclear Superheat Reactor (BONUS), Rincon, Puerto Rico</td>
<td>BWR with nuclear superheat</td>
<td>50 MW(th)</td>
<td>Stage 2</td>
<td>1970</td>
<td>Concrete entombment of vessel; decontamination of systems; release of site as exhibition center; no continuous surveillance.</td>
</tr>
<tr>
<td>Elk River Reactor (ERR) Elk River, Minnesota</td>
<td>BWR fossil-fuelled superheater</td>
<td>58 MW(th)</td>
<td>Stage 3</td>
<td>1974</td>
<td>Remote segmentation of vessel and internals; explosive demolition of concrete; survey and release of site for unrestricted use.</td>
</tr>
<tr>
<td>Sodium Reactor Experiment (SRE) Santa Susana, California</td>
<td>Graphite moderated, sodium cooled</td>
<td>30 MW(th)</td>
<td>Stage 3</td>
<td>1983</td>
<td>Remote segmentation of vessel and internals; explosive cutting of piping; release of site for unrestricted uses.</td>
</tr>
<tr>
<td>France</td>
<td></td>
<td></td>
<td></td>
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<td>Chinon A1 Reactor, Chinon</td>
<td>GCR</td>
<td>309 MW(th)</td>
<td>Stage 1</td>
<td>1980</td>
<td>Insulation of capacities from main piping to avoid moisture and radionuclide transfer.</td>
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<tr>
<td>EL 3 Saclay</td>
<td>HWR</td>
<td>20 MW(th)</td>
<td>Stage 2</td>
<td>1986</td>
<td>Development of tritiated waste embedment.</td>
</tr>
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<td>Pegase Reactor, Cadarache</td>
<td>LWR</td>
<td>35 MW(th)</td>
<td>Stage 3</td>
<td>1978</td>
<td>Decommissioned and transformed to a fuel storage facility.</td>
</tr>
<tr>
<td>Federal Republic of Germany</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forschungszentrum Neuenberg</td>
<td>HWR</td>
<td>1 MW(th)</td>
<td>Stage 2</td>
<td>1983</td>
<td>Safe and irreversible enclosure of irradiated reactor components.</td>
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Source: Decommissioning of Nuclear Facilities: Feasibility, Needs and Costs
OECD/Nuclear Energy Agency, Paris 1986
REACTORS (cont’d)

<table>
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<tr>
<th>Facility name and location</th>
<th>Reactor type</th>
<th>Power rating</th>
<th>Decommissioning stage</th>
<th>Date</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heissadampreaktor Grossweilheim</td>
<td>BWR</td>
<td>100 MW(th)</td>
<td>Stage 1</td>
<td></td>
<td>Stage 1 decommissioning, remove segmentation of pressure-vessel internals, conversion of a reactor to a test facility.</td>
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<tr>
<td>NS Otto Hahn</td>
<td>PWR</td>
<td>38 MW(th)</td>
<td>Stage 3</td>
<td>1981</td>
<td>Stage 3 decommissioning of the NSSS of a ship, one-piece reactor vessel removal.</td>
</tr>
<tr>
<td>Niederschlesisches Nuclear Power Station</td>
<td>GCHWR</td>
<td>100 MW(e)</td>
<td>Stage 2</td>
<td>1981</td>
<td>Stage 2 decommissioning and licensing.</td>
</tr>
<tr>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agesta</td>
<td>PHWR</td>
<td>80 MW(e)</td>
<td>Stage 1</td>
<td>1975</td>
<td>Procedure for Stage I decommissioning with limited surveillance.</td>
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<tr>
<td>United Kingdom</td>
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</tr>
<tr>
<td>BEPO Graphite-Moderated Reactor, AERE Harwell</td>
<td>GCR</td>
<td>6.5 MW(th)</td>
<td>Stage 2</td>
<td></td>
<td>With emphasis on release of scrap metal for recovery.</td>
</tr>
</tbody>
</table>

a) See Glossary for explanation of abbreviations.

FUEL CYCLE FACILITIES

<table>
<thead>
<tr>
<th>Facility Name and Location</th>
<th>Facility type</th>
<th>Capacity</th>
<th>Decommissioning stage</th>
<th>Date</th>
<th>Experience</th>
</tr>
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<tr>
<td>United States</td>
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<tr>
<td>Belgium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eurochemic</td>
<td>Reprocessing facility</td>
<td></td>
<td>Stage 2 and re-use</td>
<td></td>
<td>Decontamination of process cells and equipment; decontamination, sectioning and removal of experimental glove boxes and equipment.</td>
</tr>
<tr>
<td>Federal Republic of Germany</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkem</td>
<td>Pu-U fuel fabrication</td>
<td>Pilot-Size</td>
<td>Stage 3</td>
<td>1972</td>
<td>Decontamination, sectioning and removal of glove boxes and equipment.</td>
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</table>
### CURRENT AND PLANNED DECOMMISSIONING PROJECTS
(Refs 10 and 16)

<table>
<thead>
<tr>
<th>Facility Name and Location</th>
<th>Reactor Type</th>
<th>Power Rating</th>
<th>Decommissioning Stage</th>
<th>Project Period</th>
<th>Expected Experience</th>
</tr>
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<tbody>
<tr>
<td><strong>United States</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shippingport Atomic Power Station, Shippingport, Pennsylvania</td>
<td>PWR</td>
<td>72 MW(e)</td>
<td>Stage 3</td>
<td>1985-1990</td>
<td>Dismantling of reactor systems including one-piece reactor vessel removal.</td>
</tr>
<tr>
<td>Humboldt Bay Reactor, Humboldt Bay, California</td>
<td>BWR</td>
<td>63 MW(e)</td>
<td>Stage 1</td>
<td>1983-1985</td>
<td>Stage I for several decades.</td>
</tr>
<tr>
<td>Dresden I Reactor, Morris, Illinois</td>
<td>BWR</td>
<td>207 MW(e)</td>
<td>Stage 1</td>
<td></td>
<td>Primary loop decontamination for larger BWR.</td>
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<tr>
<td><strong>France</strong></td>
<td></td>
<td></td>
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<tr>
<td>Chinon A2, Chinon</td>
<td>GCR</td>
<td>230 MW(e)</td>
<td></td>
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<tr>
<td>EL4 Reactor, Brennilis</td>
<td>HWR</td>
<td>70 MW(e)</td>
<td></td>
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<td></td>
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<tr>
<td>Rapsodie Reactor, Cadarache</td>
<td>LMFBR</td>
<td>40 MW(th)</td>
<td>Stage 2</td>
<td>1985</td>
<td>Dismantling an LMFBR.</td>
</tr>
<tr>
<td>G1 Reactor, Marcoule</td>
<td>GCR</td>
<td>46 MW(th)</td>
<td>Stage 2</td>
<td>1989</td>
<td>Decontamination to unrestricted release.</td>
</tr>
<tr>
<td>G2 Reactor, Marcoule</td>
<td>GCR</td>
<td>40 MW(e)</td>
<td>Stage 2</td>
<td>1990</td>
<td>Currently in Stage 2, will be proceeding to Stage 3 with removal and disposal of graphite internals.</td>
</tr>
<tr>
<td>G3 Reactor, Marcoule</td>
<td>GCR</td>
<td>40 MW(e)</td>
<td>Stage 2</td>
<td>1994</td>
<td>Currently in Stage 2, will be proceeding to Stage 3 with removal and disposal of graphite internals.</td>
</tr>
<tr>
<td><strong>Federal Republic of Germany</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niederaichbach Nuclear Power Station, Landshut, Bavaria</td>
<td>GCHWR</td>
<td>100 MW(e)</td>
<td>Stage 3</td>
<td>1984-1990</td>
<td>Stage 3 dismantlement of a reactor including cutting up of a reactor and structures.</td>
</tr>
<tr>
<td>Lingen Nuclear Power Station, Lingen</td>
<td>BWR</td>
<td>240 MW(e)</td>
<td>Stage 1</td>
<td>1979</td>
<td>Stage 1 decommissioning with surveillance and maintenance for about 30 years.</td>
</tr>
<tr>
<td>Gundremmingen Nuclear Power Station</td>
<td>BWR</td>
<td>237 MW(e)</td>
<td>Stage 1</td>
<td>1983-1987</td>
<td>Development of electrolytic decontamination with 90% recovery of contaminated wastes, decontamination of most parts of the steam loop.</td>
</tr>
<tr>
<td>Mehrzweckforschungs-reaktor, Karlsruhe</td>
<td>PHWR</td>
<td>50 MW(e)</td>
<td>Stage 1</td>
<td>1984-1987</td>
<td>Decommissioning of a heavy water cooled reactor.</td>
</tr>
<tr>
<td>FR2, Karlsruhe</td>
<td>HWR</td>
<td>44 MW(th)</td>
<td>Stage 2</td>
<td>1982-1988</td>
<td>Decommissioning of a heavy water cooled reactor, converting the reactor building into test laboratory.</td>
</tr>
<tr>
<td><strong>Italy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garigliano Reactor</td>
<td>BWR</td>
<td>160 MW(e)</td>
<td>Stage 1</td>
<td></td>
<td>Stage 1 for 30 years.</td>
</tr>
<tr>
<td><strong>Japan</strong></td>
<td></td>
<td></td>
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Source: Decommissioning of Nuclear Facilities: Feasibility, Needs and Costs
OECD/Nuclear Energy Agency, Paris 1986
**ANNEX II**  
Page 2 of 2

### REACTORS (cont'd)

<table>
<thead>
<tr>
<th>Facility Name and Location</th>
<th>Reactor Type</th>
<th>Power Rating</th>
<th>Decommissioning Stage</th>
<th>Project Period</th>
<th>Expected Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gentilly-1</td>
<td>PHWR</td>
<td>250 MW(e)</td>
<td>Static State (between Stage 1 and Stage 2)</td>
<td>1984-1986</td>
<td>Decontamination using hydrolaser, dismantling of systems and components for building isolation, removal of asbestos, dry storage of spent fuel.</td>
</tr>
<tr>
<td><strong>United Kingdom</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windscale Reactor</td>
<td>AGR</td>
<td>33 MW(e)</td>
<td>Stage 3</td>
<td>1981-1995</td>
<td>Developing methods of thermal cutting (oxypropane plasma arc cuttings).</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mound Lab, ANSPD Area, Ohio</td>
<td>Pu-238 Fabrication</td>
<td>Stage 3 for re-use</td>
<td>1978-1988</td>
<td>Clean up and restoration of highly contaminated plutonium facility.</td>
<td></td>
</tr>
<tr>
<td><strong>France</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT1, La Hague</td>
<td>Reprocessing pilot plant for fast breeder fuel elements</td>
<td>1 Kg/day</td>
<td>Stage 3</td>
<td>1982-1990</td>
<td>Dismantling of highly contaminated plutonium glove boxes and hot cells, Waste handling procedures.</td>
</tr>
<tr>
<td><strong>United Kingdom</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windscale</td>
<td>Mixed Pu-U oxide production plant</td>
<td>50 kg/day</td>
<td>Stage 2</td>
<td>1985-1989</td>
<td>Decontamination and dismantling of highly contaminated plutonium equipment and glove boxes.</td>
</tr>
</tbody>
</table>

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*See Glossary for explanation of abbreviations.*
### Annex III

#### Nuclear Plant Decommissioning Cost Breakdown

<table>
<thead>
<tr>
<th></th>
<th>PWR</th>
<th>BWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Removal</td>
<td>31%</td>
<td>35%</td>
</tr>
<tr>
<td>Shipping</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Burial</td>
<td>13%</td>
<td>17%</td>
</tr>
<tr>
<td>Packaging</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Management</td>
<td>21%</td>
<td>14%</td>
</tr>
<tr>
<td>Decontamination</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Contingency</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Other 2/</td>
<td>11%</td>
<td>6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

---


2/ "Other" includes engineering, energy, insurance and staff relocation expenses.
GLOSSARY

ABSORPTION, NEUTRON - Any reaction in which a free neutron is absorbed by a nucleus, including capture and fission.

ACTINIDES - A chemical group of heavy elements, including actinium, thorium, protactinium, uranium, neptunium, americium, and curium.

CAPTURE, NEUTRON - A reaction in which a nucleus absorbs a neutron (and may emit a gamma ray, but does not fission).

CHAIN REACTION, NUCLEAR - The sequence of reactions in which neutrons, the products of fission reactions, induce subsequent fission reactions.

CLADDING - The material that surrounds the nuclear fuel material; in many reactors, the cladding is a metal can.

CONTAINMENT - A structure designed to contain the products (primarily radioactive) of any incident or accident.

CORE - The region of a reactor containing the nuclear fuel. It is in this region that the nuclear reactions occur.

DECAY, RADIOACTIVE - The process by which a nucleus of one type transforms into another, accompanied by emission of radiation.

FISSION - The splitting of a heavy nucleus to form two lighter "fission fragments," as well as less massive particles, such as neutrons.

FISSION PRODUCTS (FRAGMENTS) - The medium-weight nuclear products (ordinarily two per fission) resulting from the splitting of a heavy nucleus.

FUEL - Basic chain-reacting material, including both fissile and fertile materials. In most light water reactors the fuel consists of slightly enriched (2-3%) uranium.

ISOTOPE - A particular species of a given element; the element is specified by the proton number, and the isotope by mass (proton plus neutron) number.

NEUTRON - An uncharged nuclear particle, one of the two principal components of nuclei, with mass similar to that of a proton.

RADIOACTIVE - Having the ability to decay spontaneously, thereby changing to another nuclide.

RADIONUCLIDE - A radioactive nuclide.

REACTION, NUCLEAR - An interaction between two (or more) nuclei, nuclear particles, or radiation, possibly causing transformation of nuclear type; includes, for example, fission, capture, elastic scattering.

REACTOR - The core, its support, control rods and other components contained in the reactor pressure vessel.
REACTOR VESSEL - The container of the nuclear core or critical assembly; may be a steel pressure vessel, a prestressed concrete reactor vessel (PCRV), a low-pressure vessel (such as a calandria or sodium pot), etc.

STEAM GENERATOR (BOILER) - A heat exchanger in which steam is produced by heat that is transferred from the primary coolant or even from a secondary fluid.

WASTE DISPOSAL - The disposition of nuclear wastes, including fission products or actinides, at a site for long-term or permanent storage or burial.
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<th>No.</th>
<th>Title</th>
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<td>February 1989</td>
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<tr>
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<td>Emerging Patterns of International Competition in Selected Industrial Product Groups</td>
<td>February 1989</td>
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<tr>
<td>3</td>
<td>Changing Firm Boundaries: Analysis of Technology-Sharing Alliances</td>
<td>February 1989</td>
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<td>4</td>
<td>Technological Advance and Organizational Innovation in the Engineering Industry</td>
<td>March 1989</td>
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<td>5</td>
<td>Export Catalyst in Low-Income Countries</td>
<td>November 1989</td>
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<td>6</td>
<td>Overview of Japanese Industrial Technology Development</td>
<td>March 1989</td>
</tr>
<tr>
<td>7</td>
<td>Reform of Ownership and Control Mechanisms in Hungary and China</td>
<td>April 1989</td>
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<tr>
<td>8</td>
<td>The Computer Industry in Industrialized Economies: Lessons for the Newly Industrializing</td>
<td>February 1989</td>
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<td>9</td>
<td>Institutions and Dynamic Comparative Advantage Electronics Industry in South Korea and Taiwan</td>
<td>June 1989</td>
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<tr>
<td>10</td>
<td>New Environment for Intellectual Property</td>
<td>June 1989</td>
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<tr>
<td>11</td>
<td>Managing Entry Into International Markets: Lessons From the East Asian Experience</td>
<td>June 1989</td>
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<td>12</td>
<td>Impact of Technological Change on Industrial Prospects for the LDCs</td>
<td>June 1989</td>
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<td>13</td>
<td>The Protection of Intellectual Property Rights and Industrial Technology Development in Brazil</td>
<td>September 1989</td>
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<td>Regional Integration and Economic Development</td>
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<td>15</td>
<td>Specialization, Technical Change and Competitiveness in the Brazilian Electronics Industry</td>
<td>November 1989</td>
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