Option Approach to Investment in Modular Nuclear Electricity-Generating Capacity

by

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Submitted to the Department of Civil and Environmental Engineering in partial
fulfillment of requirement for the Degree of

Master of Science in
Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2002

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Intensive research efforts are currently taking place in the United States and abroad to shape the next generation of nuclear power systems offering enhanced reliability and safety along with better economics. Two design philosophies, with different technological and market perspectives, are considered. One is to develop large systems relying on evolutionary versions of the current dominant design, and the other is to go with small and modular reactor technology such as the Modular Pebble Bed Reactor (MPBR).

This thesis examines the modular technology and its flexibility to add incremental capacity to timely respond to market demand. The decision to invest in a ten-module 1,100MWe MPBR plant is analyzed as a *sequence of compound options*, where the construction of each single module provides the decision maker with the option to build the next module. The proposed valuation model uses an original binomial approach. We demonstrate that, at any point in time, the value of a modular nuclear power plant has two components: the value of the installed capacity and the value of the firm's option to add capacity incrementally in the future. The modular technology provides additional economic value due to its flexibility that the traditional Busbar cost analysis fails to capture.

We analyze different scenarios that highlight the fact that the value of the expansion option is particularly sensitive to the cost of the first module as compared with the following ones. In addition we show that the expansion option value grows when the cost is equalized among the modules to be built. This result leads to recommendations as to the design of the peripheral support facilities and to a larger extent to the overall plant layout.

This thesis ends by exposing policy recommendations as to the use of the real options valuation methods in the regulatory framework that governs technology selection and energy capacity expansion decisions.

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Acknowledgments

I would like to express my sincere gratitude to my Supervisors, Professor Fred Moavenzadeh and Professor Gordon Kaufman, whose invaluable guidance, critics and patience were instrumental to the completion of this work. Their profound theoretic knowledge and their rigor were inspiring. To Professor Gordon Kaufman, I am thankful for his kind encouragements and his availability when I needed it most.

I wish to address special thanks to Professor Andrew Kadak, who provided me with great insights in the MPBR technology and gave me access to the data I needed to complete this study. His advice and the time he spend reviewing my work are greatly appreciated.

I also wish to thank Professor Marc Badoux, Professor Ian Smith, Professor Mike Kreger, and Gérard Chessex who supported me in my ambition to study at MIT.

I am thankful to all the people and friends I met at MIT who, in different ways, contributed to make the past two years unforgettable: Bérangère, Laurianne, Aurelie, Tracy, Andres, Ced, Tilou, Patrick, Ben... and everyone, students and staff, from the Construction and Management program. Special thanks to Carlos for sharing with me his knowledge of the nuclear power industry.

Finally, my deepest gratitude goes to my parents and my brother David, whose consistent and unfailing support, encouragements, love and dedication kept me going. How could I ever thank them enough?

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Chapter 1 Introduction

1.1 Background

Currently, numerous research activities to develop the next generation of nuclear power energy systems are taking place in the United States and abroad. The goal of these research programs is to develop new nuclear technologies offering significant advances in the areas of safety, reliability and economics.

Two very different design philosophies are being investigated: on the one hand, large systems relying mainly on evolutionary versions of the current Light Water Reactor (LWR) dominant design and on the other hand small modular systems departing substantially from the dominant design. While LWRs are typically large and complex systems, modular reactors in contrast concentrate on simpler and more compact designs offering inherent passive safety. In particular, the Modular Pebble Bed Reactor (MPBR) is an 110MWe electric power reactor that relies on a self-controlling fission process eliminating the need for complex active safety systems. The envisaged MPBR system has the potential to drastically reduce operation and maintenance costs as well as construction costs through design standardization, modularization and prefabrication of major components.

The conceptual MPBR plant consists of ten (10) independent and identical 110MWe modules sharing a common control room and other peripheral support facilities. The small size of each reactor enables *incremental (or modular) capacity extension*: modules can be built sequentially, adding capacity as needed. Such modularity allows to generate early revenues, reduce financial charges, and minimize capital at risk. Moreover, modular capacity extension enables rapid sequential completion if market conditions are favorable or to delay capital expenditures if market expectations are low.

1.2 Objective and Scope

While the addition of nuclear power capacity depends mainly on governmental energy policy and national and regional demand for electricity, the recent electricity markets deregulation within the Organization for Economic Co-Operation and Development (OECD) countries has produced strong incentives for economic decision-making in the electric power industry. Hence, the competitiveness of new nuclear technologies as compared with alternative energy sources has become a prerequisite to their commercial deployment.

Traditionally, capital investments in the power industry are valued using a static discounted cash flow (DCF) analysis of the costs of producing electricity averaged over the life-cycle of the plant, namely the lifetime-levelized Busbar cost of electricity. However, DCF valuation techniques present inherent limitations resulting in the undervaluation of uncertain capital investments when significant managerial flexibility is present.

The objective of the present Thesis is to demonstrate that the flexible capacity expansion offered by modular nuclear technologies is a significant source of economic value, which is not captured by the traditional Busbar cost analysis. Hence, we propose a *real option approach* to value the opportunity to invest in a ten module 1,100MWe MPBR plant. We focus on the additional value that incremental capacity expansion can confer to the overall investment program. The proposed economic valuation is based on a binomial model. While we recognize that this model is a simplification of the realty, it makes intermediate values and decision points visible and therefore enables to build strong intuition about the sources of value embedded in the investment program.

The decision to invest in a ten-module 1,100MWe MPBR plant is viewed as a *sequence of compound options*, where the construction of each single module provides the decision maker with the option to build the next module. In fact, the decision of starting the construction of one 110MWe module is independent of the decision to build the next modules. At the start of the project and indeed at any time during the construction of the plant, the firm has the option to start or to delay the construction of the next module. Upon completion of one module, the firm receives the value of the completed asset and the option to invest in the next module.

The valuation of sequential compound options is a path-dependant problem difficult to handle with binomial models. We present in Chapter 4 what we believe to be an original algorithm that simplifies the analysis and yields a lower bound for the value of sequential compound options.

1.3 Outline

The present Thesis is organized in six (6) chapters.

Chapter 2 presents the role of nuclear power in electricity generation in the United States and other OECD countries. The current characteristics and performances of the U.S. nuclear power industry are presented in perspective with the economic challenges faced by the industry for the deployment of new capacity.

Chapter 3 concentrates on the commercial economics of nuclear power. We discuss the main cost drivers of producing electricity from a nuclear power source, introduce the traditional Busbar cost analysis and highlight how new design concepts can improve the economics of nuclear power. In doing so, we also show why the traditional approach to capital investment in the power sector is inadequate to properly value the next generation of nuclear power systems. Finally, we present an overview of the MPBR technology and its key innovative features along with the cost data necessary for the real option model in Chapter 4.

Chapter 4 proposes first a review of the real options theory in capital investments. Then, we explain why the decision to invest in a ten-module 1,100MWe MPBR plant should be analyzed and valued as a sequential compound options problem. We introduce in Section 4.3 what we believe to be a novel binomial algorithm for solving sequential compound options. We explain in details the recursive formulas and the logical tests incorporated in the algorithm. The proposed algorithm constitutes an approximation that greatly simplifies the analysis of sequential compound options and yields a lower bound for the value of the options (i.e. this is a conservative approach).

Chapter 5 presents and interprets the results of the numerical simulations done using the model in Chapter 4. We base our analysis on three scenarios, each defined by a different allocation of capital costs to each individual module. The results are subjected to sensitivity analysis for the main parameters of the model.

Finally, Chapter 6 concludes the present Thesis and proposes some guidelines for the development of a flexible construction schedule for the MPBR system. We extend our conclusions to include some notable policy implications regarding the nuclear regulatory framework.

Chapter 2 Prospects and Challenges for Nuclear Power in the United States

Recent electricity market deregulation within the Organization for Economic Co-Operation and Development (OECD) countries is producing strong incentives for cost reduction and economic decision-making in the operation of and capital investments in electricity-generating assets. The outlook for nuclear power, as for other power sources, will thus be based increasingly on economic criteria.

Existing nuclear plants have been constantly improving their operating performance and offer today operating costs competitive with fossil-fuelled plants. However, high capital costs and long lead-time constitute the main economic drawbacks for the construction of new nuclear power plants.

Currently, there is no clear advantage for any type of power plant and generating costs depend largely upon governmental and local regulations. Nevertheless several factors could favor the development of nuclear power such as increasing fossil fuel prices and price volatility, restrictive carbon dioxide emissions regulations, simpler nuclear regulatory frameworks, and positive results of ongoing research and development efforts in nuclear engineering.

Commercial efficiency is a key component for the promotion of nuclear power but it should be emphasized that wider energy, health, and environmental policy issues are critical to any assessment of nuclear power. This Chapter concentrates on the commercial economics[1] of nuclear power and is organized as follows. Sections 2.1 to 2.3 present an overview of the current role of nuclear power in the United States and offer some comparisons with other OECD countries. Section 2.2 offers a schematic view of the U.S. nuclear regulatory framework and Section 2.3 explains the evolution of the U.S. commercial nuclear power and the performance of the industry. The recent consolidation in the nuclear power industry is particularly emphasized in Section 2.4. Finally, Section 2.5 addresses the economic challenges that nuclear power faces for its expansion.

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[1] Commercial economics of nuclear power does not include the evaluation of externalities, such as energy security or pollution. "An externality exists when an economic transaction leads to uncompensated gain or loss of welfare to another." (OECD/IEA, 2001)

2.1 Current Role of Nuclear Power in Electricity Generation

Even though nuclear power plants account for only 15% of the installed electricity generating capacity in the countries of the OECD, they provide about one-quarter of the total electricity generation. Figure 2.1 compares the share of electricity generation for the different sources of fuel in the OECD, showing the respective share of nuclear. There are wide variations among countries of the OECD from less than 4% of the production in the Netherlands to more than three-quarter in France (OECD/IEA, 2001).

With 103 nuclear reactors in operation, the United States account for 30% of the OECD nuclear capacity. In the U.S., the share of nuclear in electricity generation is around 20% for only 12% of the total installed capacity. The reason for this discrepancy is that nuclear power plants, by nature, are used almost exclusively for continuous power production at their rated capacity, i.e. *baseload power production*. Due to low operating costs, nuclear power plants are generally used whenever they are available. This is reflected in the high utilization rate of nuclear power as shown in the electricity supply curve for the OECD (around 75% of the total annual productive hours, Figure 2.2). The exception to the strict baseload utilization of nuclear power is France, where nuclear provides such a high proportion of the power that load-following operations are typically used (OECD/IEA, 2001).

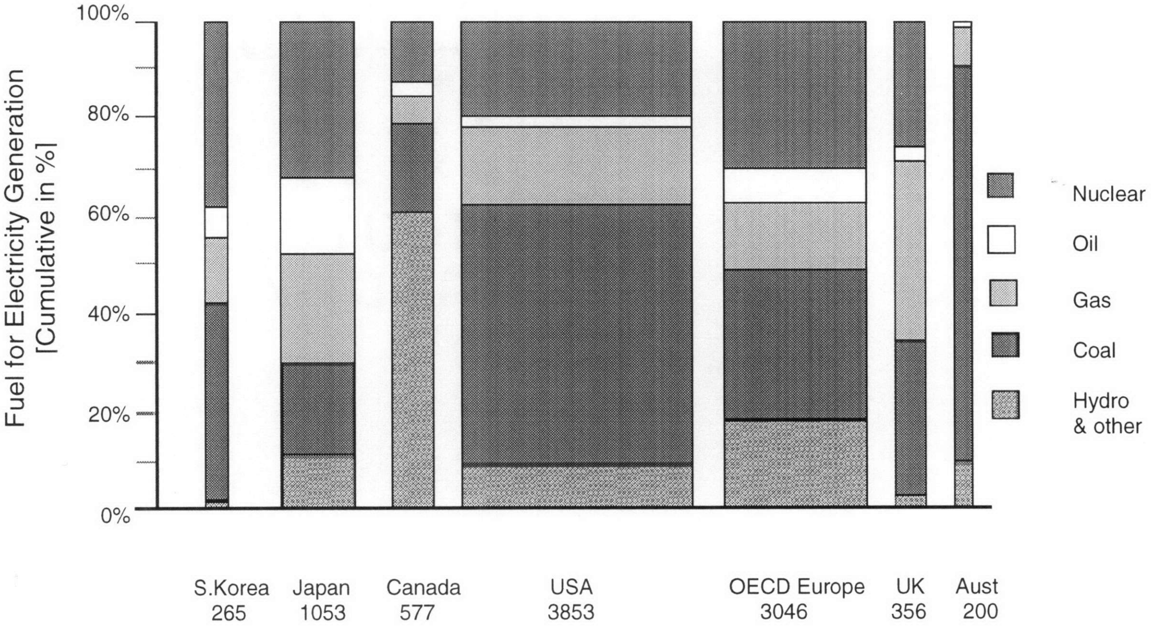

Figure 2.1: Electricity generation by fuel category, 2000.
Width of each bar indicative of the gross power generated (TWh).
Source: OECD/IEA 2000.

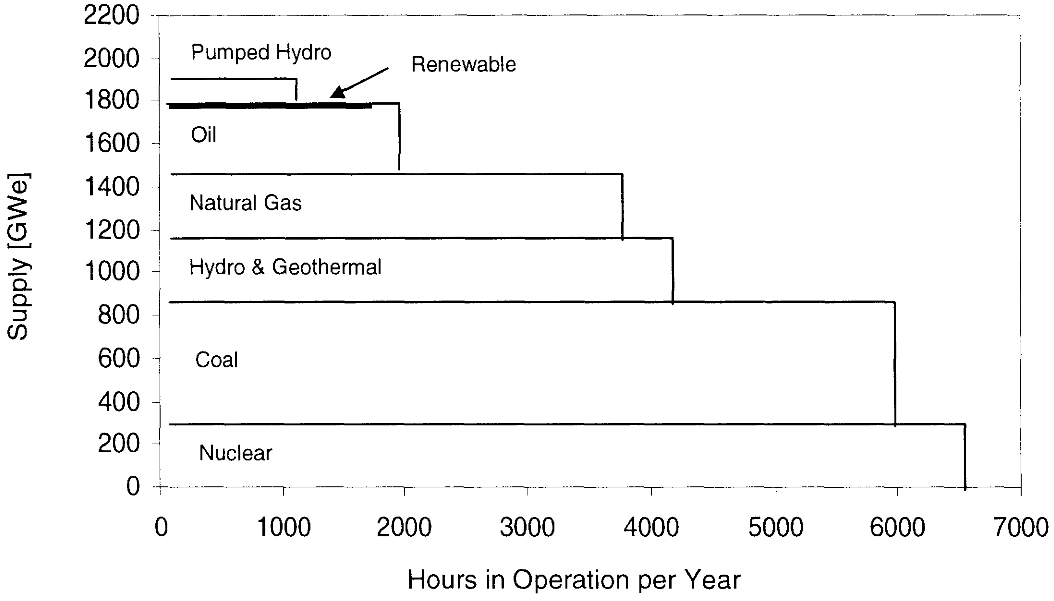

Figure 2.2: OECD electricity supply curve, 1998 (8,766 productive hours per year). Source: IEA Electricity Information (OECD/IEA, 2001).

2.2 U.S. Regulatory Framework

The nature of nuclear power entails a series of safety measures regulated by governmental agencies at the Federal and State levels. The ultimate goal of these regulations is to control commercial nuclear power activity and minimize the chances of public exposure to radioactivity as a result of inappropriate operations or accidents. The US regulatory framework is presented schematically in Figure 2.3. Two agencies play a major role in regulating and controlling commercial nuclear activities:

- The Nuclear Regulatory Commission (NRC), which grants licenses for new reactor design, plant construction and operations, and overviews license transfers in mergers and acquisitions;

- The Department of Energy (DOE), which principally overviews the fuel cycle and the management of radioactive wastes resulting from decommissioning.

Generally, once a plant design has been approved by the NRC and construction permit has been granted, a site-specific permit is required at the State level for construction of a new plant. Licensing strategies can become quite complex and the process is time-consuming.

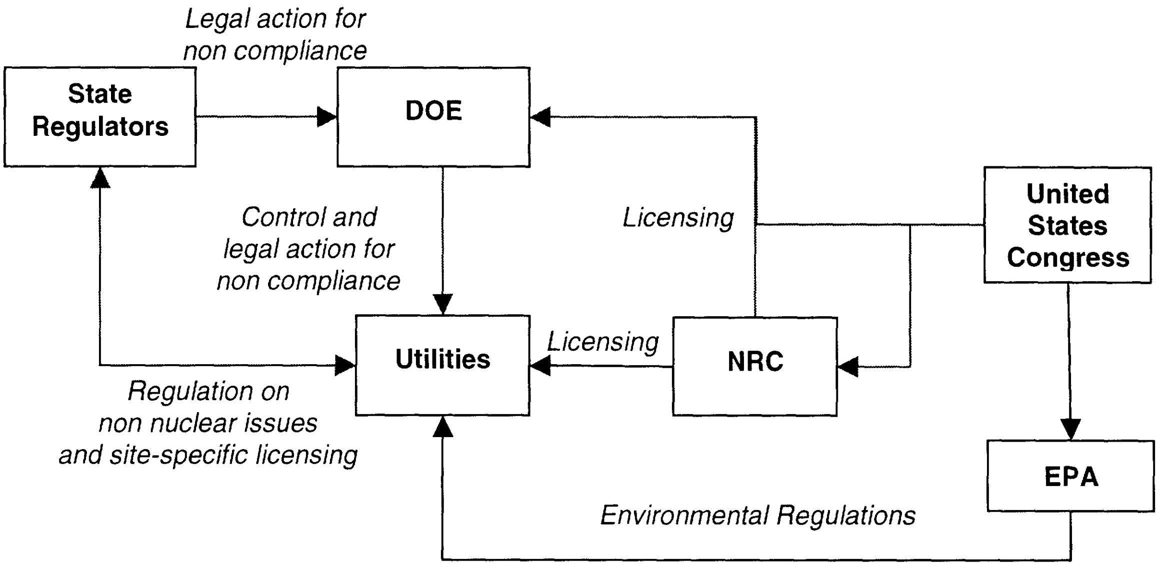

Figure 2.3: Schematic view of the U.S. nuclear regulatory framework. DOE: Department of Energy. NRC: Nuclear Regulatory Commission. EPA: Environmental Protection Agency

2.3 Development of Commercial Nuclear Power

The development of civilian nuclear technology originated in the early 1950s from nuclear weapon military programs carried out by the United States, the United Kingdom, and France. Nuclear power for civilian electricity generation started in the United Kingdom in 1956 with the 50MWe Unit 1 of Calder Hall Station.

The US Navy research for the development of nuclear submarines had the most profound impact on civilian nuclear technology and resulted in the current dominant design. The goal of the program was to develop small nuclear reactor allowing for extended autonomy for submarines and resulted in pressurized water reactors (PWR) and boiling water reactors (BWR). These two types of reactors, regrouped under the generic category of light water reactors, account today for 90% of the OECD nuclear capacity, and the quasi-totality of the United States capacity. Those reactors require enriched uranium, of which the United States had a ready supply from enrichment plants built for military applications.

The rapid extension of civilian nuclear capacity in the 1960s coincided with rapid economic growth and sharp increase in electricity demand. Early nuclear commercial applications and research programs were financially supported by national governments in the OECD resulting in a 40% growth of nuclear capacity in the 1960s.

Nuclear capacity continued to grow rapidly in the 1970s at an average rate of 27%, reaching 10% of the total OECD electric capacity at the end of the decade. The two oil chocks of 1973 and 1979/80 contributed to increasing the share of nuclear in total electricity generation, as many countries were forced to re-evaluate their energy security policy, despite reduced growth in total electricity demand (EIA, 2001). During the same period, the United States directed its energy policy towards more nuclear power. Between the two shocks, nuclear capacity in the United States was multiplied by 2.3 (Figure 2.4) while total energy demand grew only 21% (Figure 2.5). Nuclear share accounted for 12.5 % of the US electricity generation in 1979.

The growth of nuclear capacity drastically slowed down in the United States during the mid 1980s for two different reasons. First, the second oil shock decreased the overall growth in electricity demand (Figure 2.5), reducing the need for any addition of capacity. Second, the 1979 accident at the Three Mile Island nuclear power plant's unit 2 (TMI 2), the first serious accident with nuclear power, raised the question of nuclear safety and had long term effects on nuclear power plant development in the United States.

As a result of the TMI 2 accident, the Nuclear Regulatory Commission (NRC) established a moratorium on licensing: only plants ordered before 1979 were granted operating licenses (57 operating licenses have been granted since 1980). No new construction permits have been issued in the United States since 1978 resulting in a stagnation of the installed nuclear capacity since the beginning of the 1990s (Figure 2.4). This capacity is currently decreasing as more and more nuclear power plants are being decommissioned.

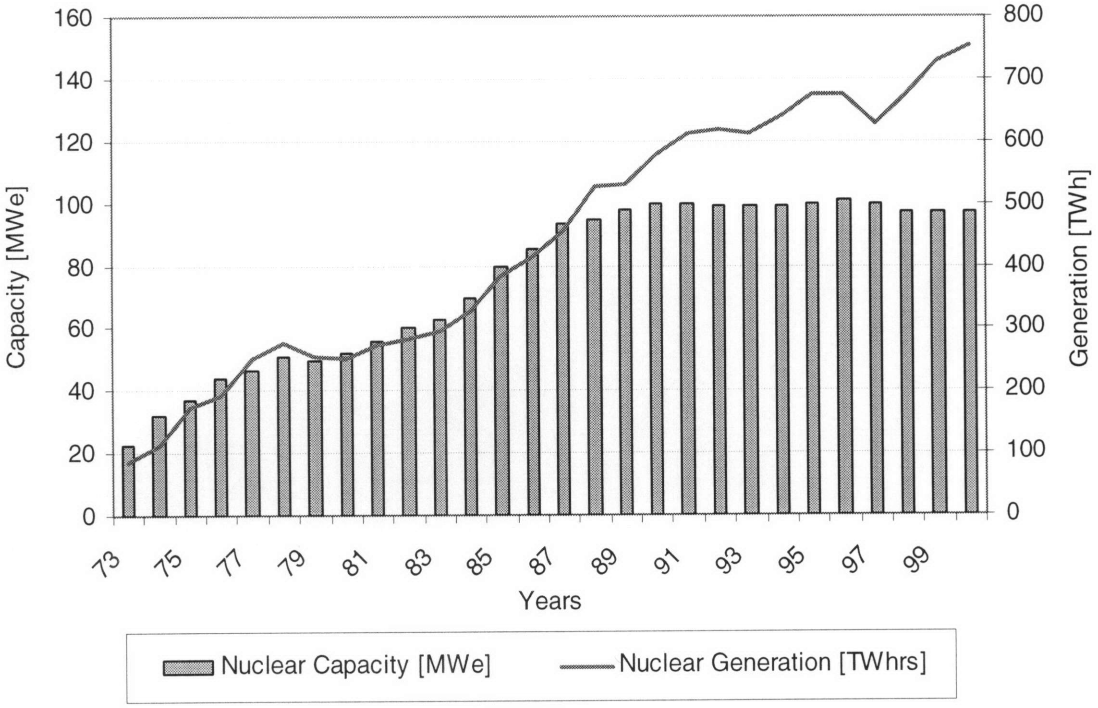

Figure 2.4: Total net summer capacity VS. net generation of nuclear electric power plants in the United States (1973-2000). Source: IEA.

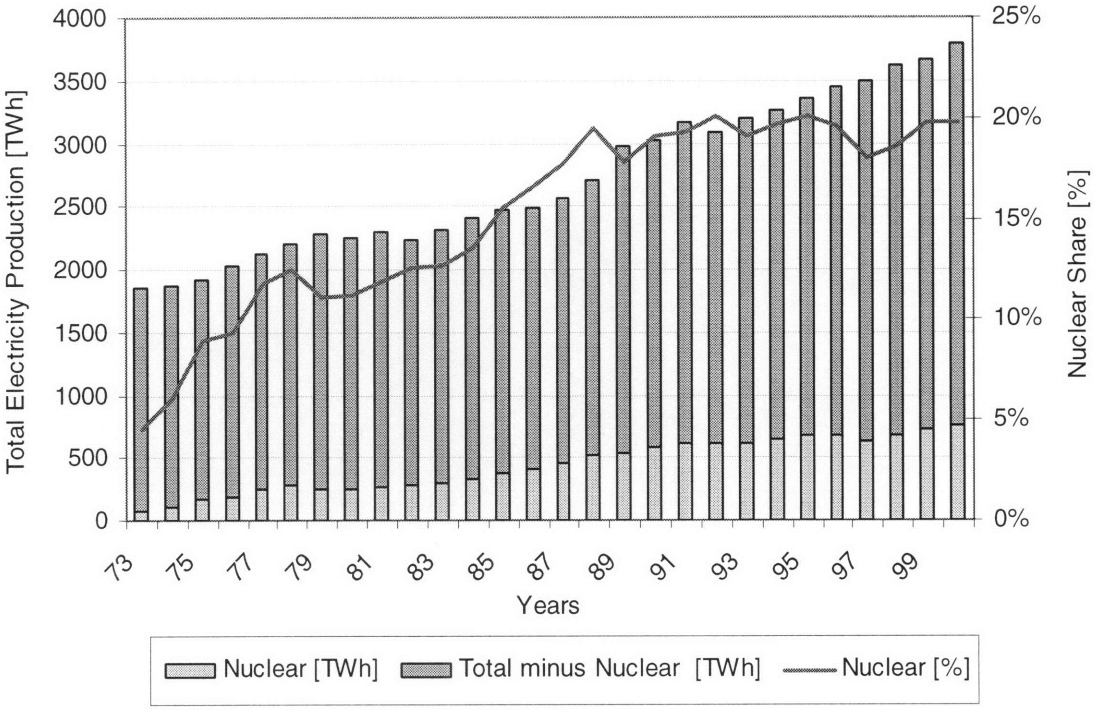

Figure 2.5: Share of nuclear in total electricity generation in the United States (1973-2000). Source: IEA.

However, during the past decade, net generation from nuclear power in the U.S. has increased by 42% while capacity slightly decreased, as highlighted in Figure 2.4. Similarly, since the beginning of the 1990s the share of nuclear in the total electricity generated in the United States has been maintained approximately constant (around 19-20%) while the total electricity production continued to grow up at an average rate of 21% over the decade (Figure 2.5).

This trend is explained by the steadily increasing utilization rate and improving performance of plants in operation over the past two decades reflected in higher capacity factors[2] (Figure 2.6) and shorter refueling outage[3] (Figure 2.7). Enhanced operational safety also contributed significantly to improving operations by decreasing the number and time of scheduled and unscheduled shutdowns. These indicators show that plants currently in operation are most probably approaching their maximum capacity factor, which is limited by the need for periodic refueling (every 12 to 18 months), maintenance and repair.

Recently, the U.S. nuclear power industry has witnessed an unprecedented merger and acquisition wave resulting in a much more concentrated industry. The motivation for consolidation is the belief on the part of many utilities that a company with several nuclear power plants can operate them more efficiently than a company operating only one or a few plants. The improved operating performance of nuclear power plants has been largely supported by the consolidation of ownership and operations in the industry.

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[2] Capacity factor *or* utilization rate: ratio of the annual energy output over the rated capacity (i.e. maximum electrical energy output).

[3] Refueling outage: time necessary to change the nuclear fuel during which the plant is shut down.

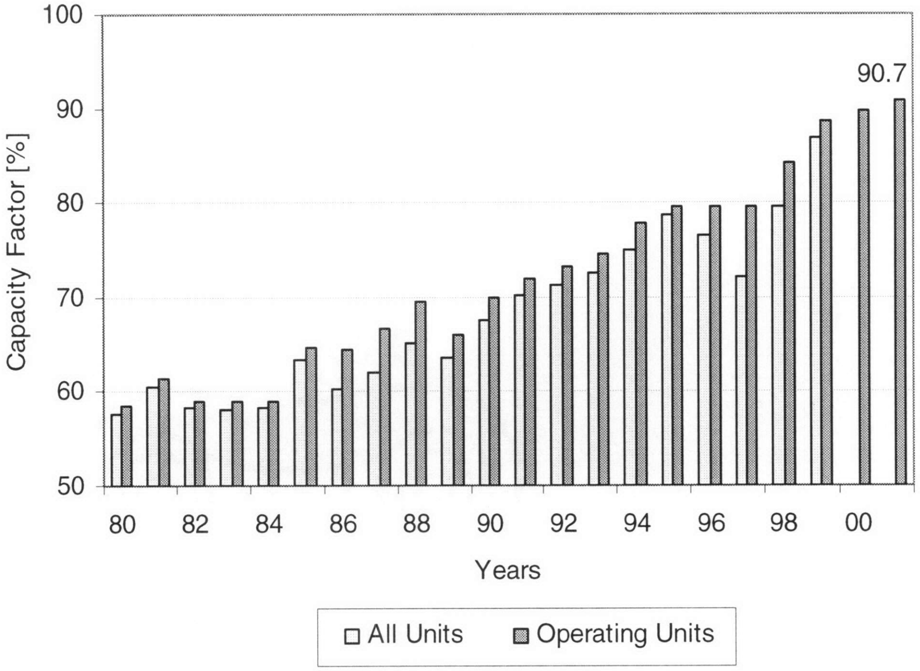

Figure 2.6: U.S. nuclear industry net capacity factor (1980-2001) Source: Nuclear Energy Institute.

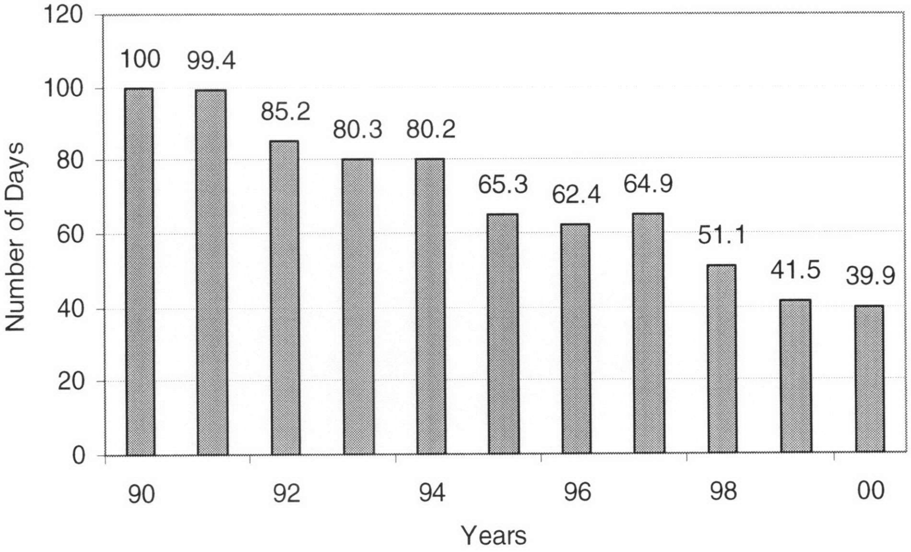

Figure 2.7 Average duration of nuclear refueling outage in the United States. Source: Nuclear Energy Institute.

2.4 Consolidation of the U.S. Nuclear Power Industry

Benefits of deregulated electricity markets are controversial among all, especially on the demand side of the market. On the supply side however, competition produces strong incentives to reduce capital and operating costs among utilities, suppliers of nuclear equipment, fuel and services. Since the Energy Policy Act in 1992, marking the beginning of electricity market deregulation in the U.S., generating companies have been seeking to improve commercial performance by pooling expertise and consolidating operations. Formally vertically-integrated, the industry is evolving towards segmentation in generation, transmission, and distribution.

In particular, utilities have been prompt in concentrating ownership of nuclear power plants in search of operating efficiency resulting from specialization and economies of scale in operations. The emerging companies concentrate their core business in operating nuclear plants (Table 2.1). They benefit from the centralization of competence necessary to manage nuclear activities and from resource sharing among a large collection of nuclear plants (Cave 2001, Rosenberg 2001). Figure 2.8 illustrates this mechanism.

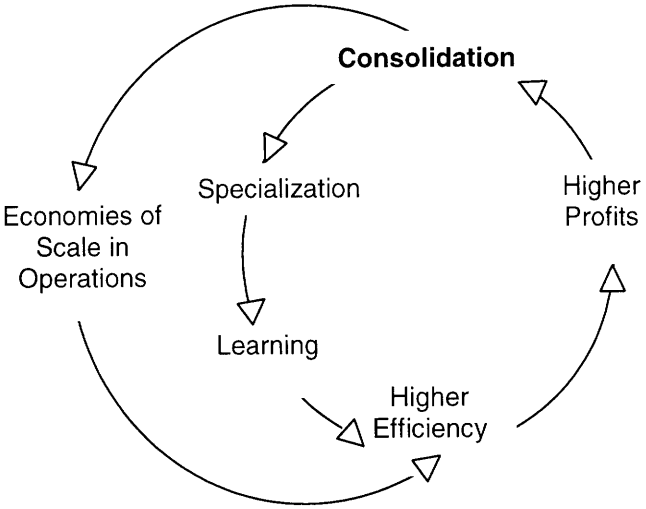

Figure 2.8: Effects of consolidation of ownership or operation in the nuclear industry: Specialization and economies of scale in operation.

Over the past decade, sales of nuclear units, mergers and acquisitions, and the creation of nuclear joint-operating companies have resulted in far fewer and more specialized companies. By early 2001, about 27 GWe of nuclear power, or over one-quarter of the U.S. capacity, had been affected by the consolidation of nuclear capacity (Table 2.2).

As of the end of 1989, a total of 54 individual utilities had ownership interests in one of the 112 operable nuclear plants. In 1995, 46 companies owned 108 plants, and only 24 companies owned 103 plants in 2001 (Cave, 2001). Figure 2.9 shows the recent evolution of the number of firms in the nuclear industry and their respective share of the U.S. capacity. Resulting firms have also increased their level of specialization in nuclear activities. Today, half of the U.S. nuclear capacity is concentrated in six major companies. Exelon, issued from the merger of PECO Energy and Unicom, holds alone around 18% of this capacity (Figure 2.9 and Table 2.1).

As a consequence, most existing nuclear power plants are today in a sound economic position and have operating costs[4] competitive with fossil-fueled plants. However, the U.S. fleet is aging and total capacity is decreasing. Prospects for existing and potential new plants are subject to a wide range of economic and policy uncertainties that will affect eventual addition of capacity.

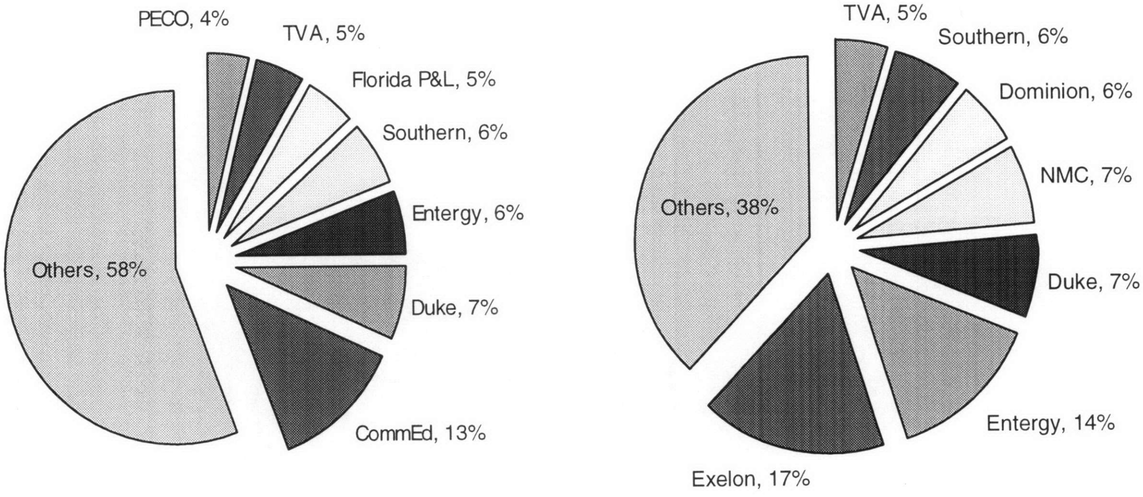

Figure 2.9: Major players in the U.S. nuclear power industry in 1998 (on the left) and in 2001 (on the right). Percentages indicative of the number of nuclear units held by the company. NMC: Nuclear Management Company, TVA: Tennessee Valley Authority. Source: Cave (2001) and companies web sites as of March 2002.

Table 2.1: Level of specialization in nuclear power of the main U.S. utilities and operators in 2002. Ranking by nuclear capacity level.

	Total Installed Capacity [MWe]	Nuclear Capacity [MWe]	Share of Nuclear Power [%]
Exelon	22,500	18,500	82%
Entergy	30,000	8,400	28%
Duke	19,300	7,000	36%
Dominion	21,000	5,300	25%
NMC*	4,500	4,500	100%
First Energy	13,000	3,800	29%

**NMC: Nuclear Management Company*
Source: Companies web site as of March 2002.

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[4] Operating costs do not include construction costs and associated financing costs. See Section 3.1.

Table 2.2: Consolidation of ownership or operation of US nuclear power plants as of January 2001.

Plant Name	Net Capacity [MWe]	New Owner or Operator	Type of consolidation
Beaver Valley 1&2	1,630	FirstEnergy	Asset exchange (498 MWe)
Clinton 1	930	AmerGen (now Exelon)	Sale / merger
Duane Arnold	520	Nuclear Management Co.	Inter-utility management Co.
Fitzpatrick	816	Entergy	Sale
Hope Creek	1,030	PSEG Power	Sale (52 MWe share)
Indian Point 2	994	undecided	Sale
Indian Point 3	965	Entergy	Sale
Kewaunee	511	Nuclear Management Co.	Inter-utility management Co.
Monticello	544	Nuclear Management Co.	Inter-utility management Co.
Milstone 2&3	2,024	Dominion Resources	Sale
Nine Mile Point 1&2	1670	Constellation Energy	Sale
Oyster Ceek	650	AmerGen (now Exelon)	Sale / merger
Palo Verde	3,810	Pinnacle West (APS)	Sale (610 MWe share)
Peach Bottom 2&3	2,200	PSEG Power, PECO	Sale (328 MWe share)
Perry 1	1,160	First Energy	Asset exchange (164 MWe)
Pilgrim 1	670	Entergy	Sale
Point Beach 1&2	970	Nuclear Management Co.	Inter-utility management Co.
Prairie Island 1&2	1,025	Nuclear Management Co.	Inter-utility management Co.
Salem 1&2	2,230	PSEG Power	Sale (328 MWe share)
Seabrook	1150	Great Bay Power	Sale (35 MWe share)
Three Mile Island 1	786	AmerGen (now Exelon)	Sale / merger
Vermont Yankee	510	undecided	Sale
Total Affected Capacity	**26,796**		

Source: OECD/IEA, 2001.

2.5 Prospects for Existing Plants

Recently, many nuclear power plants reaching the end of their original 40 year expected service life have been granted extension or renewal of their operating license by the Nuclear Regulatory Commission. Current expected operating life after license renewal reaches up to 60 years.

There are strong economic incentives to extending the lifetime of nuclear plants in a competitive electricity marketplace. Comparing both capital costs and total generating costs of alternatives, it is often more attractive to keep operating nuclear plants running than to build any other type of plant. Indeed, by keeping the plant in operation, the owner delays substantial decommissioning costs, which typically range from $300 to $500 million per unit ($400k/MWe to $2,250k/MWe depending on the size of the plant) and postpone capital costs associated with the construction of a new plant. On the other hand, the license renewal process requires a formal review of the plant by the NRC for a cost ranging from $10 to $50/kWe. Major capital refurbishments necessary for continuing operation typically range from $100 to $300/kWe. Extending the operating life of nuclear power plants is today competitive with investing in a new fossil-fueled plant or refurbishing a coal plant (OECD/IEA, 2001).

However, as nuclear plants age, capital expenditures for maintenance and repair are likely to increase substantially and place a high burden on generating costs. Eventually, owners will face the need to compare closely the economics of continuing operations with investing in new capacity. At that time, the alternative of refurbishing the plant and extending the operating life further would not be an option anymore. Hence, owners will have to consider building new capacity and will have to choose between evolutionary versions of the current dominant design or disruptive technologies. New nuclear power technologies, such as the new modular reactors currently under development (see Chapter 3) would most probably be available at that time. Therefore, such technologies should be carefully evaluated using appropriate valuation techniques.

Chapter 3 Toward Modular Nuclear Technology

Current research efforts in nuclear engineering are focusing on the development of the next generation of nuclear power systems. As exposed in Chapter 2, competitiveness is a pre-requisite to capital investment in the power industry and notably in nuclear power. Therefore, careful valuation of existing and forthcoming technological alternatives is a cornerstone to the deployment of new nuclear capacity.

This is not the purpose of the present Chapter to determine whether or not modular nuclear technologies are competitive with existing technologies or alternative energy sources. Rather, our goals are to (1) understand the main cost drivers of electricity generation form nuclear power, (2) provide a benchmark for the costs of conventional nuclear technologies and (3) point out how new design philosophy can improve the economics of nuclear power. In doing so, we highlight why the traditional approach to capital investment in the nuclear power sector is inadequate to value the next generation of nuclear power systems.

Hence, Section 3.1 introduces the traditional approach to economic valuation in the nuclear power industry and provides cost benchmarks for the current dominant design. Section 3.2 discusses the economic issues that new nuclear systems shall address for deployment and shows how current research paths may bring answers to these concerns. Section 3.3 presents the design concepts and the current cost estimates for the Modular Pebble Bed Reactor (MPBR) system. Emphasis is put on the modularity of the technology and the construction sequence. We define in this last Section the necessary cost data for the real option valuation of the MPBR system developed in Chapter 4 and Chapter 5.

3.1 Introduction to Nuclear Engineering Economics

This Section introduces the basics of commercial nuclear power economics necessary to characterize the main cost drivers of electricity generation from a nuclear power plant. Cost data presented in this Section reflect the actual costs of existing LWRs and are intended to provide the reader with a benchmark for the evaluation of new modular nuclear systems (Section 3.3). The total *generating cost* (or *Busbar cost*) is defined as the lifetime levelized cost of producing electrical energy, including capital and financing costs, operation and maintenance costs (including debt service), and fuel costs.

3.1.1 Capital Costs

The major component of generating cost from nuclear plants currently in operation is the capital cost, which typically accounts for 60 to 75% of the total generation cost, while reaching about 50% in coal-fired plants and only 25% in gas-fired plants.

Capital cost encompasses hard costs (or direct costs) and soft costs (or indirect costs). Included in hard costs are land acquisition cost, direct construction cost including materials, equipment and labor, and Mechanical, Electrical and Plumbing (MEP) cost and all other costs related to the procurement of the plant. Included in soft costs are permit, licensing and regulatory fees, architectural and engineering fees, and project management oversight and consultant services. Table 3.3 lists direct and indirect costs for a typical ten module 1,100 MWe MBPR plant.

Capital Cost = Hard (Direct) Cost + Soft (Indirect) Cost

The *overnight specific capital cost* [M$] is defined as the cost of the plant as if it could be constructed instantaneously, excluding of any financing costs associated with the construction. The *overnight unit capital cost* [$/kWe of installed capacity] is defined as the overnight specific capital cost divided by the plant capacity. Existing operating LWR plants have a overnight unit capital cost ranging from $1,400/KWe to $2,200/KWe as compared to $1,200/KWe for coal-fired plants and $500/KWe for combined-cycle gas-fired plants.

In a traditional nuclear engineering economic analysis (Section 3.1.3) the *total capital cost* [M$] includes the financing charges accrued during the construction phase, while the plant is not yet productive. These charges are accounted for in the Allowance for Funds Used During Construction (AFUDC) fund. It should be noted that other financing costs that are paid for during the operating phase are including in the operating costs.

Total Capital Cost = Overnight Specific Capital Cost
+ Allowance for Funds Used During Construction (AFUDC)

The two main cost drivers of the capital cost are (1) the financing costs accrued during construction and (2) the labor costs associated with the highly skilled labor force necessary for the construction of a nuclear power plant. The longer the construction time until start of operation, the larger the financial charges accrued during construction. In addition a longer construction period delays the generation and collection of revenue. Therefore, the economic value of a nuclear power plant is highly dependent on construction time[1] and the efficiencies resulting from economies of scale and/or standardization.

In the past, the average construction time of nuclear power plants in the U.S. has increased dramatically (Figure 3.1). In the 1960s it took five years on average to build a plant. From 1984 onward it took on average of over 12 years to complete a nuclear plant. In 1996 Watts Bar Unit 1, the last nuclear plant still under construction in the United States, finally entered in operation, 23 years after its construction permit was granted. All the plants in construction after the Three Mile Island (TMI) accident experienced extended delays, and numerous projects were suspended or even stopped during construction.

This past trend in the U.S. can be explained by a series of concomitant factors: the (sometime overstated) public opposition to nuclear power, the regulatory scrutiny resulting from the TMI accident, escalating costs, rapid expansion in size of units before all difficulties were understood, and the lack of standardization of the overall industry – utilities and manufacturers.

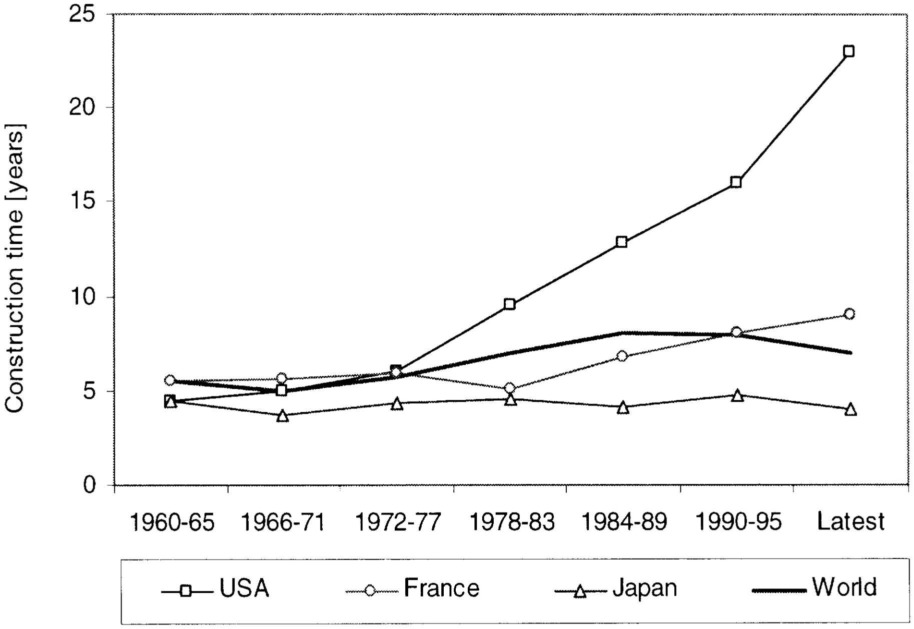

Figure 3.1: Average construction time for nuclear power plants.

Latest data are: USA 1996 (Watts Bar 1), France 2000 (Civaux 2), Japan 1996, World 1998.
Note: Average construction time is for plants connected
to the electrical network in the time interval indicated.
Source: IAEA, Reference Data Series No.1, 1999, Table 14 (in OECD/IEA 2001).

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[1] Construction time is the time period between start of pre-construction activities and connection to the electric network.

In the past, the lack of standardization on the part of some utilities (many plants were custom built to the utilities' specifications) and manufacturers in the United States and the introduction of new regulations resulted in extended construction periods and high capital costs. Countries such as France, Japan and Korea on the other hand have had a more centralized industry typically controlled by and supported by the governments and have enjoyed better cost control and faster construction time (Figure 3.1). The recent consolidation of the American nuclear power sector and the evolution of the regulatory framework should provide a better ground for improved construction time and construction management of new nuclear capacity.

3.1.2 Operating Costs

The main *operating costs* of a nuclear power plant are operation and maintenance (O&M), nuclear fuel, provisions for spent fuel management and disposal (or reprocessing), and provisions for final closure of the plant (*decommissioning*). Maintenance doe not include expenses for major refurbishments. The main driver of operating cost is O&M, which typically accounts for 50 to 75% of operating costs for LWRs, of which personnel is the single most important component: a medium size LWR plant typically requires about 600 personnel for operations. Nuclear fuel accounts for 20 to 30% of operating costs, most of which is for fuel preparation.

Regulations typically require utilities to make regular payments in a sinking fund to build up provisions for future liabilities, namely spent fuel management or disposal and decommissioning. Provisions for spent fuel account for roughly 10% of operating costs, and provisions for decommissioning account for less than 1%, on a levelized basis (IEA/OECD, 2001).

The price of nuclear fuel is mostly dependant on the cost of conversion, enrichment, fuel fabrication and final processing; uranium accounting only for 20 to 30% for LWRs' fuel cost. In the past, prices of nuclear fuel to utilities have not been subjected to volatile variations as other fossil fuels. The price trend has been declining since the mid-1980s and is forecasted to be approximately flat over the next 20 years (Figure 3.2).

Nuclear power plants are mainly used for baseload power generation and operate at full capacity whenever they operate. Hence operating costs are mostly constant. Coupled with relatively flat fuel prices, the cost of fuel, including spent fuel disposal, represents an approximately constant share of nuclear electricity generation (around 20%).

As discussed in Section 2.2, commercial nuclear activity is subjected to strict regulations and controls designed to ensure safe operations. Safety regulations impact all categories of costs, capital, O&M, and fuel costs, through licensing, controls and provisions.

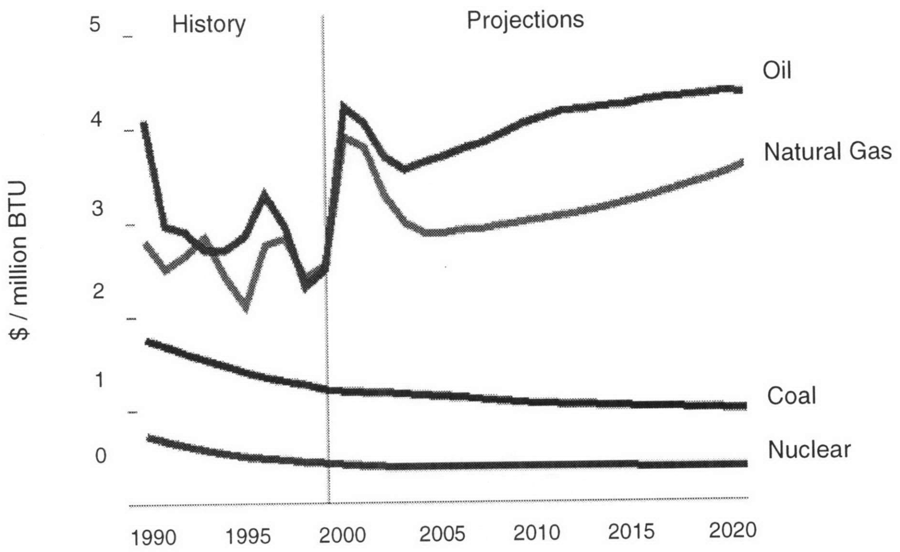

Figure 3.2: Historical and forecasted fuel prices as of 1999, 1990-2020. 1999 dollars per million BTU. Source: DOE/EIA, 1999.

3.1.3 Traditional Economic Analysis: Busbar Cost of Electrical Energy

The traditional approach to valuing electricity generating capacity relies on a static discounted cash flow (DCF) analysis of the costs of producing electricity averaged over the life-cycle of the plant (Driscoll, 2002). First, capital-related costs and operating costs are annualized (or *levelized*) by finding an uniform annual rate of expenditure (*levelized cost*) that makes the present value of all the capital and operating costs equal to the present value of the levelized cost. Formally, the equivalent uniform annual rate of expenditure, A_L, is found by solving the following equation:

$$\int_0^T A_L e^{-rt} dt = \int_0^T C(t) e^{-rt} dt$$

where C(t) represent the capital and operating costs as a function of time, and r is the firm's cost of capital.

The resulting levelized cost is then reduced to a unit generating cost by dividing it by the plant rated capacity times the average capacity factor. This formulation of the unit generating costs is called the *lifetime-levelized busbar[2] cost of electrical energy, e_b,* is expressed in cents per kilowatt-hour (¢/kWh) and is the sum of three terms: capital related costs, operating and maintenance costs and fuel related costs (Table 3.1).

---

[2] The busbar cost defines the generating cost at the exit of the plant, excluding transmission and distribution.

Table 3.1: Busbar cost of electrical energy [cents/kWh].

Capital-related costs[3]:

$$\frac{100\phi}{8766.L}(K)_{-C}\left[1+\frac{r}{2}\right]^{C}$$

+ Operating and Maintenance costs:

$$\frac{100}{8766.L}(K_{O\&M})_0\left[1+\frac{yT}{2}\right]$$

+ Fuel costs:

$$\frac{100}{24}\frac{F_0}{\eta B}\left[1+\frac{yT}{2}\right]$$

where:		Typical LWR value[4]
L	Capacity factor	0.85 -
ϕ	Annual rate of financial charges	0.15 / yr
r	Discount rate, or cost of capital, including inflation rate	0.12 / yr
$(K)_{-C}$	Overnight unit capital cost	$ 1,500/kWe
Y	Escalation rate of O&M and fuel cost, including inflation rate	0.04 / yr
C	Time required to construct the plant	5 yrs
T	Prescribed useful life of the plant	40 yrs
$(K_{O\&M})_0$	Specific O&M costs as of the start of operations	$95/kWe-yr
η	Plant thermodynamic efficiency, net kW electricity produced per kW of thermal energy consumed	0.33 -
F_0	Net unit cost of nuclear fuel, first steady-state reload batch, including financing and waste disposal, as of start of operations	$2,000/kg of uranium
B	Burnup of discharged nuclear fuel (or fuel energy utilization)	45,000 MW-days/metric ton

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[3] The term $[1+r/2]^C$ results from the Taylor series expansion of the exponential term in the levelized cost. The same remark holds for the O&M and fuel costs.

[4] Driscoll, 2002.

Using the representative values in Table 3.1, the generating cost for an existing LWR is estimated as follows[5]:

$$e_b = \overset{\text{Capital cost}}{4.1} + \overset{\text{O\&M Cost}}{2.2} + \overset{\text{Fuel Cost}}{0.9} = 7.2 \text{ cents/kWh}$$

The Busbar cost analysis is somewhat a controversial measure of economic performance as it accounts only for *costs* and is particularly sensitive to the discount rate, the rate of financial charges. For instance, using an annual rate of financial charges of 13% and a discount rate of 10% reduces the capital cost to 3.3 cents/kWh and the Busbar cost to 6.4 cents/kWh. However, this analysis is relevant for the evaluation of installed capacity given that all capital cost parameters are known with certainty after construction and given the small variability of operating costs.

3.2 Perspective for New Nuclear Capacity

Over the past decade, fossil-fueled plants have been favored by the industry despite more stringent emissions regulations, mostly for the low initial capital investment required. In particular, combined cycle gas-fired plants have shown the strongest growth thanks to less expensive generation equipments, failing gas prices and flexible operation. On the other hand, fossil-fueled plants are more sensitive to fuel price volatility than nuclear power plants and expected higher oil and gas prices (Figure 3.2) could have a major influence on the relative cost of new nuclear plants.

There is a lively debate as to whether new nuclear power plants shall be build or not, but in any case, numerous research activities to develop new nuclear energy systems are taking place in OECD countries, and particularly in the United States. While the future of nuclear power depends mainly on governmental energy policy and the national and regional demand for electricity, *competitiveness* as compared to fossil-fuelled power plants is a prerequisite to any deployment of new nuclear capacity. This Section discusses the economic issues that new nuclear systems shall address for deployment and shows how current research paths may bring answers to the economic concerns. It is not the purpose of this Section to demonstrate whether or not new generation of nuclear reactors can be competitive. Rather, the objective is to point out how new design philosophy can improve the economics of nuclear power.

As discussed in Sections 3.1.1 and 3.1.3, the capital cost is the major component of nuclear power's total generating cost. Hence, the construction of any new nuclear plant in the United States relies heavily on the ability to reduce construction costs through a combination of economies of scale, series construction, design standardization, and shorter construction time.

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[5] As noted in Section 2.4 the operating cot (i.e. O&M and fuel costs) is around 3.2 cents/kWh, which is competitive with the cost of producing electricity from alternative energy sources.

3.2.1 Advanced Conventional Reactors

Most improvements in conventional reactors designs have been introduced in an evolutionary fashion through small steps taking advantage of nuclear and non-nuclear technology developments, such as turbines, control and instrumentation (IAEA 1997 *in* OECD/IEA 2001). In the past, programs to develop advanced conventional reactors have concentrated on large size units (1,000 to 1,500 MWe) and mid-size units (around 600 MWe), (Table 3.2).

Efforts have been focused in reducing capital costs (NEA, 2000) and resulted in shorter construction time for the most recent units build in Korea and Japan (4 to 5 years, Figure 3.1). New plants also benefit from longer operating life up to 50 to 60 years, reducing the lifetime levelized generating cost. New designs aim at more compact and simpler configuration with fewer safety-related components and rely mostly on simpler designs and *economies of scale*.

According to the OECD's nuclear power survey actual plant construction has not always realized the expectation that net economies of scale can be achieved when total investment costs are considered because of greater system complexity (OECD/IEA, 2001). *Reducing complexity* of the system is a key to in improving commercial performance by reducing capital costs, construction time, as well as improving operating performance.

3.2.2 New Modular Reactors: Generation IV Initiative

It is argued that improving conventional reactors will not be sufficient to produce a clear competitive advantage and does not fully address increasing safety and sustainability concerns. As a result, new reactors departing substantially from the dominant design are currently being investigated. The emphasis is on simpler more compact designs offering inherent passive safety[6] with the potential to drastically reduce operating costs as well as construction cost through standardization.

In June 1999, the United States Department of Energy (DOE) launched the *Generation IV Nuclear Energy Systems* initiative in response to the need for development of advanced nuclear systems in the United States. The goal of the Generation IV initiative is to identify one or more next-generation nuclear energy systems and focus subsequent research activities. In January 2000 a group of countries (including Canada, France, Japan, Korea, the United Kingdom, and the United States among others) began discussing a multi-lateral effort to develop Generation IV reactors.

Selected systems should be commercially deployed before 2030 and offer significant advances in the areas of sustainability, safety and reliability, and economics. Sustainability goals focus on fuel utilization, waste management, and nuclear weapons

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[6] Cooling of the core in nuclear systems with passive safety is achieved via natural heat exchange from the core to the surroundings. No intervention is necessary. In the worse case scenario of complete loss of coolant, the core temperature stays below a certain threshold and no core meltdown can occur.

proliferation resistance. Safety and reliability goals focus on passive safety (eliminating the need for emergency response), reliable operation, and investment protection. Economics goals focus on competitive life-cycle generation costs and financial risk (NERAC 2001, Todreas 2001).

From the commercial perspective, future technologies should in particular anticipate the increased use of distributed power, which requires building smaller units. The concept of small reactors is appealing to developing nations seeking to build their electric grids and developed nations who want to add incremental capacity based on market demand. It is anticipated that while Generation IV nuclear energy systems will primarily produce electricity, they may also find it profitable to produce a broader range of energy products beyond electricity such as process heat for hydrogen or potable water production (Todreas 2001).

Many research efforts are currently focused on modular high-temperature gas-cooled reactors (HTGR). In these reactors, an inert gas such as helium is used to cool the reactor core (instead of water in LWR design). The gas is also used to transport the thermal energy and drive a gas turbine to produce electricity. Proponents of the technology cite the following advantages among others:

- Passive safety;
- Higher efficiency provided by gas turbines;
- Economic advantages at small size provided by design standardization, modular construction and series construction (Section 3.3.3).

The concept of HTGR is not completely new and early research work was done in the United States as early as the 1940s. The first prototypes were build simultaneously in 1959 in the United Kingdom (the Dragon reactor, 20MWe), in Germany (the AVR, 15 MWe) and in the United States (Peach Bottom 1, 40MWe). The German design consisted in a steel containment vessel and used spherical fuel elements, or *pebble bed*, that travel downward through the core. Commercial applications followed in the 1960s-1980s, but research programs were stopped after the Chernobyl accident. A detailed analysis of the evolution of the HTGR technology can be found in Brey, 2001.

Currently, renewed efforts (China, South Africa, and the United States) concentrate on the development of Modular High Temperature Gas Cooled Reactor (MHTGR) as a sustainable option for electricity generation. In particular, the Modular Pebble Bed Reactor (MPBR) is about one tenth the size of today's large nuclear reactor (110 MWe) and is the smallest commercial reactor currently under development (Table 3.2). The South African utility Eskom is leading a joint venture that has been developing a prototype reactor (called PBMR) since 1993 and plan to enter commercial operations by 2006. Their reactor follows the design licensed for operations in Germany in the 1980s.

Simultaneously, the Massachusetts Institute of Technology (MIT) and the Idaho National Engineering and Environmental Laboratory (INEEL) are developing an alternative design for the MPBR. The MIT-INEEL MPBR design benefits from economics advantages resulting from standardization, modularity, and series construction (Section 3.3). Moreover, its small unit size allows for incremental addition of capacity as modules are build in sequence resulting in early revenue generation, minimized capital at risk, and reduced financial charges.

Table 3.2: Main reactors currently under development.

Design	Type	Net Capacity [MWe]	Submitting Organization
European Pressurized Water Reactor (EPR)	ACR	1,500	Siemens & Framatome ANP
Advanced Boiling Water Reactor (ABWR)	ACR	1,350	General Electric Nuclear Energy
SWR 1000	ACR	1,000	Framatome ANP
AP1000	ACR	1,000	Westinghouse Electric Company
AP600	ACR	600	Westinghouse Electric Company
International Reactor Innovative and Secure (IRIS)	NR	350	Westinghouse Electric Company
Gas Turbine Modular Helium Reactor (GT-MHR)	NR	285	General Atomics
Pebble Bed Modular Reactor (PBMR)	NR	110	Eskom
Modular Pebble Bed Reactor (MPBR)	NR	110	MIT-INEEL

ACR: Advanced Conventional Reactor
NR: New Reactor
Source: Todreas, 2001.

3.3 Overview of the Modular Pebble Bed Reactor System

The specific design concept that will be presented and evaluated through rest of this study is the MIT-INEEL design currently under development. The analysis does not enter in the details of the nuclear engineering[7] as our focus is on the construction sequence and the cost estimates. Engineering and cost data provided in this Section reflect the current level of the research and development process of the MPBR technology. At this point in time, no demonstration reactor for the MIT-INEEL MPBR design has been built yet.

3.3.1 Description of the MPBR Technology

The major design feature of the MPBR is the inherent passive safety provided by the pebble bed fuel elements itself. In the pebble bed fuel design, the nuclear fuel is embedded in a protective coating (see Appendix) that constitutes the primary barrier to fission product release. However, this coating (silicon carbide layer) starts to breakdown after being continuously exposed to temperatures in excess of 1,600°C for more than 200 hours. Thus the reactor is designed so the operating temperature of the core never exceeds 1,600°C, even in the worse case scenario of complete loss of coolant and without any intervention. The solution to this problem is found in the natural laws of heat conduction, heat convection and radiation combined with a small reactor size. By limiting the power density of the reactor (to 3.54 MW/m^3) and allowing for natural cooling, the operating temperature of the core is kept below 1,600°C. This temperature is almost 1,500°C below the melting point of the uranium fuel which supports the design objective of a meltdown free design. The low power density condition limits the thermal power of the reactor to 250MWt. Moreover, neutronic considerations lead to a maximum core diameter of 3.5 meters. A schematic view of the reactor is presented in Appendix.

Helium is used to cool the reactor core and transport the thermal energy to an intermediate heat exchanger (IHX) that serves to separate the primary and the secondary systems. The secondary system drives a gas turbine to produce electricity. The high efficiency of gas turbines (45%) enables higher operating performance. The resulting reactor core is a relatively small unit of 8 to 10 meters high, 3 meters in diameter, 250MWt thermal power, 110MWe electric power (see Appendix). The 110MWe MPBR module regroup the reactor module, the IHX module, the turbomachinery module (including the gas turbines and support equipment such as recuperator, precoolers and compressors) and a forced-draft cooling system for heat rejection (Figure 3.3). This design does not require costly containment for nuclear safety purpose. However a concrete shield might be required to protect the reactor against external threats such as plane crash or terrorist attack.

Moreover, the pebble bed fuel enables on-line refueling thus eliminating refueling outage. This results in a higher capacity factor for a single 110MWe unit.

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[7] For complete description of the nuclear system and reactor and fuel physics, refer to INEEL-MIT (2000) and Kadak (2001c).

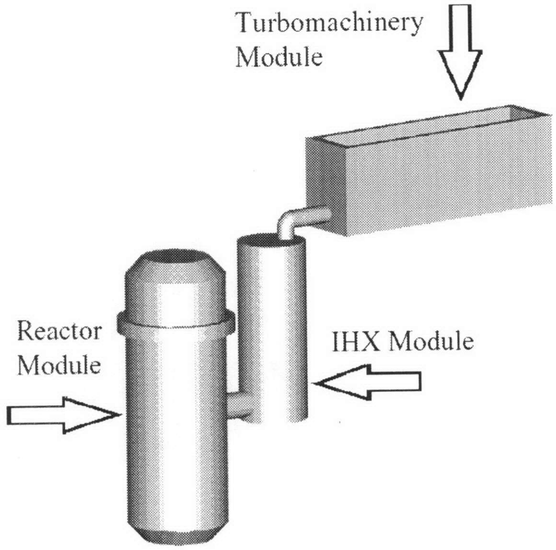

Figure 3.3: 3-D schematic view of the 110MWe MPBR module, MIT-INEEL design. Source: Kadak, 2001a.

3.3.2 Physical Plant Layout

A typical layout of the plant consists of ten identical modules built sequentially, sharing common control room, administration, and training and maintenance buildings (Figure 3.4). Ensuring equipment accessibility for maintenance and operations was a primary concern in the design of the plant layout.

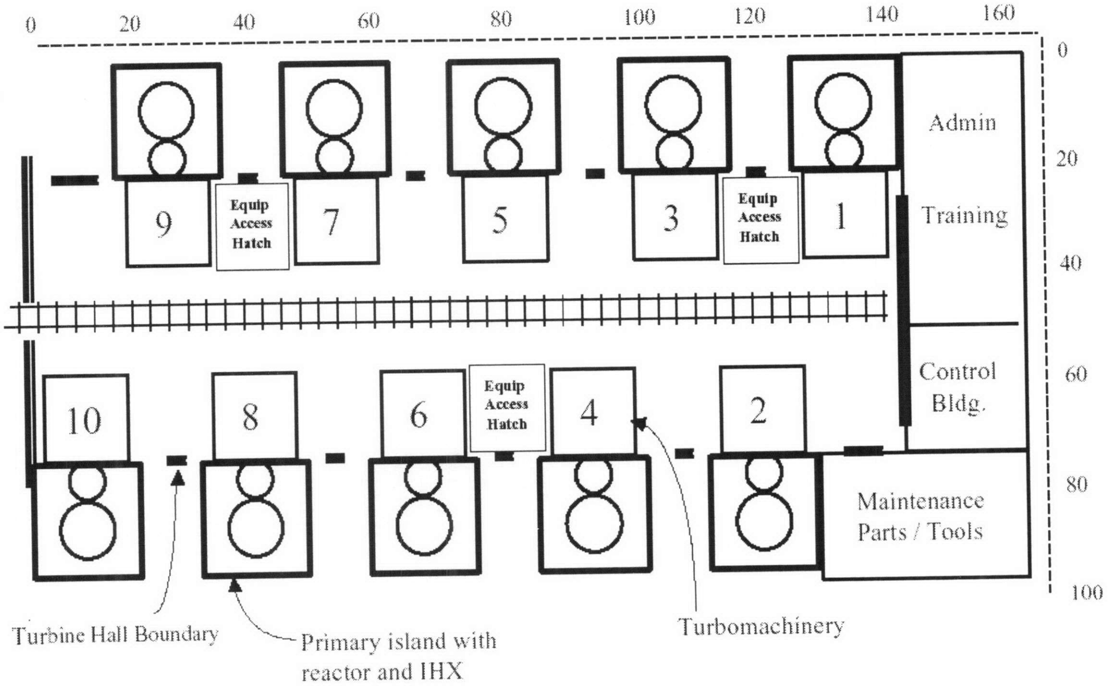

Figure 3.4: Ten-unit 1,100MWe MPBR plant layout (top view, distance in meters). Source: Kadak, 2001a.

3.3.3 Modularity

An alternative to economies of scale to reduce capital cost is to combine *design standardization, modular construction and series construction* on which the MPBR design is based. Lapp (1989) proposed a complete methodology for modular nuclear power plant design and construction. The benefits of this approach cannot yet be precisely estimated as reactor design is still on paper. However, initial research results on the MPBR are encouraging (Kadak *et al.*, 1998b, and Kadak, 2001a, b and c).

Design standardization resulting in a standard system design has the potential to generate economies in engineering, licensing, procurement, and administration. The Nuclear Regulatory Commission (NRC) has recently established a design certification process that allows designers to pre-certify their designs for construction. Several certifications have been issued by the NRC but due to the high capital costs of these plants, none have been built in the US to date. This approach should reduce the administrative burden and its associated costs and increase the predictability of the licensing process.

Given the small size of the system's components, a standard design enables series production in the controlled environment of a factory, which is expected to generate *economies in production due to learning effects*. Although there has been only limited experience with serial production of nuclear components, proponents of modular technologies argue that a parallel can be drawn with success in other industries such as jet engines and naval ship building.

Because the system's components were designed to fit on a flatbed truck, pre-assembled elements can then be shipped and assembled on site. Moreover, elements can be assembled into modules and tested while site preparation work is still in progress. When the site is ready, modules are simply moved into position and connected to the system. This *modular construction technique* reduces considerably the on-site labor required, the complexity of the on-site construction operations and the construction time.

Economies of scale for each individual reactor are limited; however series production of small units and modular construction techniques could provide a balance between design and manufacturing costs, and economies of scale (Kadak, 2001b and Kadak *et al.*, 1998b). The economic analysis for an n^{th}-of-a-kind (NOAK) module presented in Table 3.3 incorporates anticipated learning effects to account for the benefits of factory series construction and repetitive construction scheme.

A direct consequence of small generating capacity and modularity in construction is *modularity in capacity expansion*. Small modules can be built sequentially, adding capacity as needed and generating early revenue, reducing financial charges and minimizing capital at risk. Modularity in capacity extension enables rapid sequential completion if the market conditions are favorable or, to the contrary, to delay capital expenditures if market expectations are low. This modularity provides the MPBR technology with an additional source of value assessed captured by the real options analysis in Chapter 4.

The concept of modularity in construction extends to the maintenance and operation of the plant. Once a module is in operation, every component in the layout (Figure 3.4) is accessible for maintenance or replacement. Should a component breakdown, the corresponding unit would be shut down, the component removed and replaced by a similar standard component fresh from the factory. This operating strategy limits the down time necessary for repair. Moreover, only one unit out of the ten needs to be shut down in the event of breakdown, resulting in a much higher overall capacity factor.

3.3.4 Fabrication and Construction Schedule

The concept of consortium ownership plays a central role in the manufacturing of modular plant equipments. Usually, infrastructures (including nuclear plants) are procured through a bidding process in which potential architects and engineers, component manufacturers and building contractors participate. The MPBR design however requires equity partners in manufacturing the nuclear reactor, the turbines and compressor to fully benefit of serial fabrication, limit the time necessary for delivery and avoid compatibility issues. It is anticipated that a single major vendor (such as General Electric, Mitsubishi, or alike) would be contracted for those elements. Other components such as the heat exchanger are standard in the industry and do not require such partnership.

Estimated time from initial interest manifested by potential buyers until operation of the first unit is 166 weeks. Actual construction time, i.e. the time from issuing equipment purchase order and beginning site preparation until operation, is estimated to 123 weeks. A system dynamic model was build by Kadak *et al.* (1998b) to simulate the effect of delays in construction on early revenue generation and total capital costs. A complete fabrication and construction sequence is presented in Appendix.

3.3.5 MPBR Cost Estimate

The following cost projections for an nth-of-a-kind (NOAK) MPBR power plant are based on the analysis performed by the pebble bed group at MIT (Kadak *et al.*, 1998b). The cost estimates are in accordance with the ground rules and recommendations established by the Oak Ridge National Laboratory (1993), the Gas Cooled Reactor Associates (1993) and the particular assumptions of the MIT pebble bed group. Estimates are in millions of January 1992 US dollars. The scope of this cost estimate includes all costs to design, build and operate a MPBR plant over a 30 year lifetime.

Our purpose is not to discuss the assumptions or the exactitude of those estimates. Rather, we intend to build on those results to show in Chapters 4 and 5 how a real option approach can help uncover additional sources of value not captured in the traditional Busbar cost of electricity.

- Capital cost

The major categories of capital cost are presented in Table 3.3 for a 1,100MWe ten module plant. Total overnight specific capital cost is estimated at $2,2047million, the unit capital cost is $1,860/kWe, and the total capital cost after AFUDC is $2,296million. The resulting busbar cost is 25.0mills/kWh[8] with a fixed charge rate of 9.47%.

- O&M Cost

The MPBR annual O&M costs were estimated based on its simpler system design, its passive safety, and its high capacity factor. The staff size is significantly lower than the average 975 personnel required to operate current conventional American nuclear power plants. On-site staff is expected to be 150 personnel. The MPBR plant O&M costs is estimated to be $31.5million per year, and the busbar cost was 3.6mills/kWh at 90% capacity factor (Table 3.4). We assume the same O&M cost for each individual module.

- Fuel Cycle Cost

The estimate of the fuel cost is based on the following: One pebble cost $20.0, one third of the fuel pebbles is replace annually (i.e. 120,000 pebbles), and a fee of 1.0 mill/kWh is charged to fuel cost for spent fuel management and disposal. Total fuel cost is estimated to be $32.7 per year and the busbar cost 3.8 mills/kWh (Table 3.4).

- Decommissioning Cost

Decommissioning costs were estimated to be $211million for the entire plant, which corresponds to 0.6mill/kWh (Table 3.4).

- Total Generation Cost

Total generation costs are summarized in Table 3.4. The above estimates yield a lifetime levelized busbar cost of electricity of 33.0mills/kWh or 3.3 cents/kWh.

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[8] 1 cent = 10 mills.

Table 3.3: MPBR ten-module 1,100MWe plant capital cost estimate. Millions of January 1992 US dollars.

Account No.	Description	Cost Estimate
20	Land & Land Rights	2.5
21	Structures & Improvements	192
22	Reactor Plant Equipment	628
23	Turbine Plant Equipment	316
24	Electric Plant Equipment	64
25	Miscellaneous Plant Equipment	48
26	Heat Reject System	25
	TOTAL DIRECT COSTS	1,276
91	Construction Service	111
92	Home Office Eng. & Service	63
93	Field Office Supv. & Service	54
94	Owner's Cost	147
	TOTAL INDIRECT COSTS	375
TOTAL BASE CONSTRUCTION COST		1,651
Contengency		396
TOTAL OVERNIGHT SPECIFIC COST		**2,047**
UNIT CAPITAL COST [$/kWe]		**1,860**
AFUDC		250
TOTAL CAPITAL COST		**2,296**

Source: Kadak et al. (1998b).

Table 3.4: MPBR ten-module 1,100MWe plant Busbar generation cost estimate. January 1992 US dollars.

Reactor Thermal Power [MWt]	10 x 250
Net efficiency [%]	45.3
Net Electrical Rating [Mwe]	10 x 110
Capacity Factor [%]	90
Total Overnight Cost [M$]	**2,046**
Unit Capital Cost [$/kWe]	**1,860**
Total Capital Cost [$M]	2,296
Fixed Charge Rate [%]	9.47
30 Year Levelized Costs [M$/yr]	
Levelized Capital Cost	217
Annual O&M Cost	31.5
Level Fuel Cycle Cost	32.7
Level Decom. Cost	5.4
Revenue Requirement	286.6
BUSBAR COST [mill/kWh]	
Capital	25.0
O&M	3.6
Fuel	3.8
Decom.	0.6
TOTAL	**33.0**

Source: Kadak et al. (1998b).

Chapter 4 Real Option Approach to Investment in Modular Nuclear Capacity

As illustrated in Chapter 3, the conventional Busbar cost analysis is based on deterministic and static estimates of capital outlays, construction sequence and lead-time etc... Such discounted cash flows techniques fall short of valuing the effect of the sequential interdependence among uncertain capital investments over time.

We propose in this Chapter an option approach that incorporates the value of flexibility in capacity expansion brought about by the modular production technology. We focus on the incremental value that such flexibility confers to the investment program. The valuation proposed is based on a discrete-time model, which makes intermediate values and decision points visible and enables to build strong intuition about the source of value embedded in the investment program.

Section 4.1 proposes a review of options theory and shows how it is applied in capital investments with features similar to the investment decision we face. The binomial valuation method is exposed in detail as it is used in Section 4.3 and Chapter 5 for the resolution of the investment problem. Section 4.2 defines the option nature of the investment problem. Finally, we introduced in Section 4.3 what we believe to be a novel binomial algorithm for solving sequential compound options. We explain in details the recursive formulas and the logical tests incorporated in the algorithm. The results of the model are analyzed in Chapter 5.

4.1 Real Option Approach to Capital Investment

4.1.1 Background

Discounted Cash Flow (DCF) valuation techniques have inherent limitations when it comes to valuing uncertain investment opportunities with significant flexibility and often result in an undervaluation of projects. The Net Present Value (NPV) rule was first derived to value fixed income securities and is based on two assumptions somewhat inappropriate to value uncertain capital investments with managerial flexibility. NPV assumes either (1) that investments are reversible (i.e. expenditures can be recovered should market conditions turn unfavorable) or (2) that investments are in fact irreversible but the investment program is static and that investment cannot be delayed (i.e. invest now or lose the investment opportunity), (Dixit and Pindyck, 1995).

However, most capital investments are *irreversible* and *can be delayed*. A growing body of literature, known as Real Options or Contingent-Claims Analysis, shows that the ability to wait for new information and delay irreversible capital outlays can profoundly affect the economic value of a project and change the investment decision (see Dixit and Pindyck 1994 and 1995, Trigeorgis 1996, Luehrman 1997 and 1998, Brealey and Myers 2000, and Copeland and Antikarov 2001 for examples, valuation techniques and further references).

The real options theory is based on an important analogy between financial options and a firm's opportunity to invest in real assets. An option is a right, with no obligation, to buy (*call option*) or sell (*put option*) an asset at a fixed predetermined price (*exercise or strike price*) at any time before a given date (*American option*) or on a given date (*European option*).

Similarly, a firm holding an opportunity to invest in a real asset is holding an option on that asset (i.e. a claim on the stream of profits generated by that asset), comparable to a financial call option. When the firm decides to invest, it exercises its option by making an irreversible capital investment (equivalent to the strike price of a financial option). Management's ability to wait for new information and adapt its investment program consequently creates an asymmetry in the probability distribution of the program's NPV that expands its true value by improving its upside potential and limiting the downside. In this respect, the firm investment strategy can be regarded as the sequence of optimal exercise of the set of real options it posses.

By deciding to go ahead with an irreversible capital expenditure, the firm "kills" the option by giving up the opportunity to wait for new information that might have affected the value of the option and the optimal exercise decision. The loss of the option at the time of the investment represents an *opportunity cost* that must be incorporated in the investment valuation. Dixit and Pindyck (1995) reformulate the NPV rule by incorporating this opportunity cost as follows: "Instead of just being positive, the NPV of the expected cash flows of the project must exceed the cost of the project by an amount equal to the value of keeping the investment option alive."

Real options can be classified in two major categories: (1) single options that can be analyzed in isolation (such as the option to defer an investment or the option to alter the scale of operations) and (2) multiple options presenting interdependencies. In particular, if the investment opportunity leads to further discretionary opportunities, then the option is embedded in a set of *nested* or *compound options* (i.e. each option provides upon exercise another option) and must be analyzed as part of a chain of investments. Geske (1979) valued compound options, which can be applied to value sequential investments or growth opportunities that become available only when earlier investments took place.

Another distinction must be drawn between proprietary options, for which the firm is the only one to possess the investment opportunity, and shared options, for which the firm shares the exercise rights with other players. A detailed classification of real options along with examples and references is proposed by Trigeorgis, 1996.

The valuation of the optimal exercise of real options builds on the valuation of financial options, which has been studied extensively by academics over the past three decades (see Cox and Rubinstein 1985, Hull 2001). The quantitative origins of options theory derives from the seminal work of Black and Scholes (1973) and Merton (1973). The practice of valuing options was later simplified by Cox and Ross (1976) who recognized that an option can be valued using an equivalent dynamic portfolio of traded securities (replicating portfolio) and arbitrage-free pricing. This synthetic duplication enables risk-neutral valuation that is, discounting certainty-equivalent cash flows (expected future cash flows weighted by risk-neutral probabilities) at the risk-free rate of interest, rather than the expected cash flows at the risk-adjusted discount rate.

Real options may be valued with the same techniques as financial options even though they are not traded. The existence of a replicating portfolio of traded securities perfectly correlated with the underlying asset in a complete market is sufficient to value any contingent claim on an asset traded or not (Trigeorgis, 1996).

4.1.2 Options in Capital Investment and Capacity Expansion

The option approach to capital investment has been the center of particular attention. Pindyck (1988a) applied contingent-claims analysis to electricity-generating assets by comparing two fictive investment programs: one in a large plant with low unit capital cost and one in a small plant with high unit capital cost and the option to add capacity as demand grows. He showed that under price uncertainty, the value gained by delaying substantial capital outlay offered by the smaller plant made the investment in a smaller plant preferable to a larger one. On the other hand, demand uncertainty has two opposite effects. First, it creates an option of waiting to invest, and second it increases the value of the underutilized capacity by making it more likely that this capacity will be needed in the short term. The latter effect dominates in Pindyck's analysis. This model can be used in investments presenting large demand uncertainty.

Madj and Pindyck (1985) proposed a general model for projects that take "time to build". The project is analyzed using compound options: each dollar invested buys an option to invest the next dollar. The analysis is structured as an optimal control problem, where the maximum rate of investment is the control variable. The decision to invest or delay depends on the value that the project would have if completed today.

Using a model based on the same general idea, Pindyck (1988b) shown that the value of a firm can be split into the value of its installed capital and its options to expand its production capacity in the future. We use this idea in Section 4.2 to show how the value of a modular nuclear power plan is driven not only by the value of the installed capacity by also by the option to add future increments of capacity.

Pindyck (1993) examined investments in projects that take time to complete and are subject to cost uncertainty. The model is particularly suitable for the analysis of long construction programs. Two sources of cost uncertainty are examined: (1) technical uncertainty, which is resolved as the investment proceeds (such as geotechnical conditions) and (2) input cost uncertainty, such as external uncertainty over the price of construction material, the labor cost and the effect of governmental regulations among others. The model is used to analyze the decision to start and then continue or abandon construction of a nuclear power plant. The model brings a justification for the abandonment of nuclear power plant construction programs in the 1980s.

Some capital investments, such as oil and gas exploration and production, require a sequence of capital outlays and are well suited for an analysis using compound options. Paddock *et al.* (1988) studied the case of offshore petroleum leases using a series of two compound options corresponding to exploration, development and extraction. Each phase requires an irreversible capital expenditure and upon completion provides the owner of the lease with the possibility to proceed to the next phase. Upon exercise of the exploration option, the owner receives the value of the undeveloped reserve and the option to develop it. Upon exercise of the development option, the owner receives the right to exploit a developed reserve and produce oil. The values of the underlying undeveloped and developed reserves are determined using a petroleum market equilibrium model.

Thomas (1992) applied some contingent-claims models to nuclear economics. He considered several operating options, time-to-build option and a valuation for two compound options for capacity expansion in continuous time. He compared three fictive investment programs in nuclear power plants with various operating and capital costs but presenting the same Busbar cost. Thomas demonstrated that the Busbar cost of electricity is not an appropriate measure of the economic value of a nuclear plant when significant operating options or construction modularity is present.

4.1.3 Binomial Model

Dynamic programming solves optimal decision problems by rolling out all possible values of the underlying asset during a given limited time frame and folding back the value of the optimal investment decision in the current period. The rational for this approach is expressed by the Bellman Principle: "Given the choice of an initial strategy, the optimal strategy in the next period is the one that would be chosen if the entire analysis were to begin in the next period."

Cox, Ross and Rubinstein's (1979) binomial approach enables a simplified valuation of the optimal exercise of options in discrete time. The binomial valuation model is based on a simple representation of the evolution of the value of the underlying asset. Starting at the value V at time zero at the beginning of the lattice, the underlying asset can only take two possible values in the next period: up with probability p, or down with probability $q=(1-p)$. In the *multiplicative* or *geometric binomial model*, the values in the next period can be either uV in the up case or dV in the down case[1] (with $u>1$ and $d<1$). In the next period, the set of possible values of the underlying asset is: u^2V, udV, d^2V. This random

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[1] This representation assumes no cash payout (similar to no dividend in the case of a stock). This assumption is later relaxed.

walk is illustrated in the value tree of the underlying asset in Figure 4.1. The entire set of possible asset values is obtained by progressing forward along the tree.

The random walk represented by the geometric binomial model is a discretization of a geometric Brownian motion described in Equation 4.1. This process contains two components: and exponential growth rate (or drift) characterizing the long-term expected return on the asset, and a stochastic term describing random variations of the value of the asset around the long-term trend. This process yields a lognormal distribution of relative changes in the asset value.

$$\frac{dV}{V} = \mu\, dt + \sigma\, dz \tag{4.1}$$

where μ is the expected return on the asset V, σ is the standard deviation of the expected returns on V or volatility[2], and $dz = \varepsilon \sqrt{dt}$ is an increment of a Weiner process (or Brownian motion), ε is a normally distributed random variable, with mean zero and standard deviation 1.

In the binomial discrete approach the respective amplitude of an up event and a down event are estimated using:

$$\mathrm{u} = \mathrm{e}^{\sigma\sqrt{\Delta \mathrm{t}/\mathrm{n}}} \quad \text{and} \quad \mathrm{d} = 1/\mathrm{u} \tag{4.2}$$

where *n* is the numbers of steps used to simulate a one-period event. For instance, if $\sigma=10\%$ is the annual volatility, and we use 12 steps per year, then $\Delta t = 1$ year, $n = 12$ steps per year, then u = 1.02929, and d = 0.9715.

The risk-neutral probabilities of an up event and a down event are given respectively by[3]:

$$p = \frac{r-d}{u-d} \quad \text{and} \quad q = 1 - p \tag{4.3}$$

where r = 1 + risk-free rate of interest, *u* is the one-period asset price change for an up event, *d* is the one-period asset price change for an down event. Note that the condition $d < r < u$ must apply to avoid arbitrage opportunities.

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[2] Refer to Cox and Rubinstein 1985 for the methodology in estimating the parameters σ and μ.

[3] The expected return on the asset is: (probability of an up event)×u +(probability of a down event)×d. If p is the risk-neutral probability, then p is the probability of an up event that makes the return on the asset equal to the risk-free rate. Therefore, p×u + (1-p)×d ≡ r, and p = (r-d)/(u-d).

The American call option with two periods to maturity on the asset modeled by the two period-binomial tree in Figure 4.1 is valued using a backward recursion from boundary conditions. At the end of the second period (terminal nodes A, B and C, Figure 4.1), since there are no more periods remaining, the optimal exercise of the option is written as follow:

$$C_{uu} = Max\ \left[u^2V - k, 0\right]$$

$$C_{ud} = Max\ \left[udV - k, 0\right]$$

$$C_{dd} = Max\ \left[d^2V - k, 0\right]$$

where *C* is the value of the option and *k* is the exercise price.

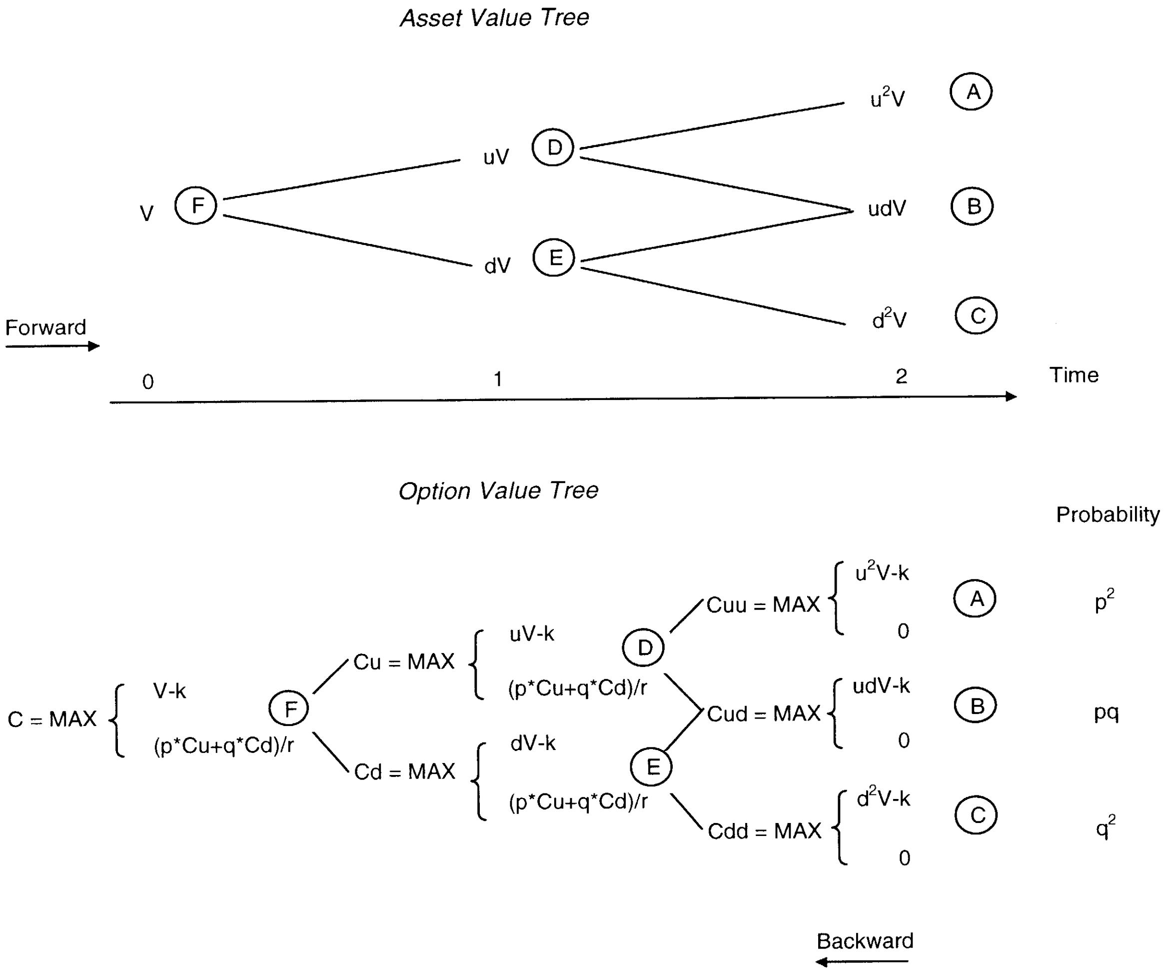
Working backward along the tree and using a recursive procedure the value of the option is obtained at each node. The value of the option at the end of the first period (nodes D and E, Figure 4.1), is obtained by comparing the value of the option if exercised now with the value of the unexercised option or *continuing value*. The continuing value is obtained by discounting the certainty-equivalent cash flows (expected future cash flows weighted by risk-neutral probabilities) at the risk-free rate of interest:

$$C_u = Max\ \left[uV - k, \left(pC_{uu} + qC_{ud}\right)/r\right]$$

$$C_d = Max\ \left[dV - k, \left(pC_{ud} + qC_{dd}\right)/r\right]$$

The value of the option in the current period (node F, Figure 4.1) is obtained in the very same way:

$$C = Max\ \left[V - k, \left(pC_u + qC_d\right)/r\right]$$



Asset Value Tree

Option Value Tree

Where: V is the value of the asset in the current period,k is the exercise price, r = 1 + risk-free rate of interest, u is the one-period asset price change for an up event, d is the one-period asset price change for an down event. p is the probability of an up event, q = 1-p is the probability of a down event. Assuming no cash payout.

Figure 4.1: Option valuation binomial model.

There is no problem in incorporating cash payout (i.e. cash flows from the asset to the owner similar to dividends on a stock) in a multiplicative tree, *assuming that cash flows are proportional to the value of the underlying asset* (Figure 4.2). Again, the value of the option at each decision node is obtained by comparing the value of the option if exercised now with the continuing value.

If exercised now, the payoff of the option is the value of the asset pre-dividend; if unexercised, the continuing value is based on the asset value ex-dividend. For instance, given a constant payout rate δ, and assuming V is the value of the asset pre-dividend in the current period, the value of the asset in the next period in the up state (node D in Figure 4.1) is $uV(1-\delta)$ pre-dividend, and $uV(1-\delta)^2$ ex-dividend. Then the value in node A is $u^2V(1-\delta)^2$ pre-dividend and $u^2V(1-\delta)^3$ ex-dividend. In node D, the option value if exercised now is $uV(1-\delta)-k$ and the continuing value is:

$$\left\{ p.Max\left[u^2V(1-\delta)^2,0\right]+qMax\left[udV(1-\delta)^2,0\right]\right\}/r$$

When there is no dividend, it is never optimal to exercise the option early (i.e. the continuing value is always greater than the immediate exercise value). However, this is not the case for a dividend-paying asset, and the higher the payout rate, the higher the probability of early exercise.

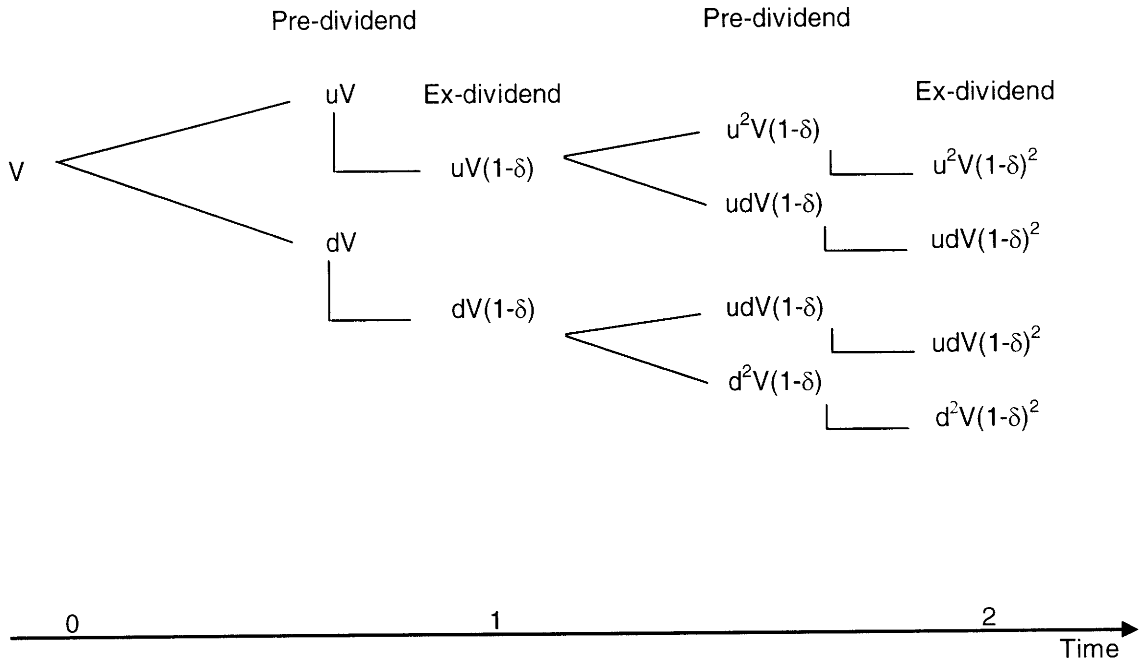


Figure 4.2: Asset value tree showing values pre- and ex-dividend.

The valuation procedure in continuous time is not exposed in this study as our model is based on a discrete-time valuation. The interested reader can refer to Dixit and Pindyck (1994) and Trigeorgis (1996).

4.2 Option Nature of the Investment Program

Consider a generation company, which holds the modular nuclear technology and plans on building a power plant with *N* units of capacity (one unit of capacity is one 110MWe MPBR module). The final size of the plant, *N*, is determined exogenously. Modules are built sequentially, adding capacity as needed.

At any point during the life of the project, the value of the investment program has two components: the value of installed capacity (i.e., the value of the expected flow of profits generated by the capital currently in place[4]) and the value of the firm's option to add capacity in the future (Pindyck, 1988b).

Letting *K* be the amount of capacity [MWe] in place, *P* the price of electrical energy [$/kWh], the *current value*[5] of the project *W* can be written as the sum of two parts:

$$W = V(K,P) + F(K,P) \tag{4.4}$$

where *V(K,P)* is the value of the capacity in place, that is, the present value of expected flow of profit that this capacity will generate given the expected evolution of prices; *F(K,P)* is the value of the firm's "*expansion option*", that is, the option to expand capacity given the capacity in place at any point in the future. *F(K,P)* represents an additional source of value, which is not captured by the traditional DCF approach, nor by the Busbar cost analysis.

The investment program is a contingent asset, whose payoff depends on the value of a more basic asset, namely the *incremental unit of capacity* (i.e. one 110MWe MPBR module). Thus we can derive the value of the project as a contingent claim for a given level of installed capacity. To solve the investment problem, we need to determine the value of an incremental unit of capacity on the one hand, and the value of the option to add capacity in the other hand.

Noting that capacity is added *incrementally* (one module at a time), *sequentially* (one module after another) and in a *lumpy* fashion (sizeable amount of capacity in each increment), we can view the project as a sequential investment program and rewrite Equation (4.4) for any given stage corresponding to a *discrete addition of capacity.*

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[4] In the general case of the valuation of a productive asset, the firm's operating options, i.e. the option to utilize or not the installed capacity depending on the level of price, should be incorporated in the valuation of the capital in place. However, such options are not readily available in the case of nuclear power, as nuclear plants operate generally at full capacity whenever they operate (see Chapter 2).

[5] W is the *current value* of the project. To obtain the *net value*, the incurred capital cost must be subtracted.

Consider units 1 to $n < N$ have been installed so far, the current value of the project is given by:

$$W_n = \sum_{i=0}^{n} \Delta V(K_i, P) + \Delta F(K_{n+1}, P) \qquad (4.5)$$

where $\Delta V(K_i,P)$ is the value of the i th unit of capacity, that is, the present value of expected flow of *incremental* profit attributable to this unit; $\Delta F(K_{n+1},P)$ is the value of the option to add the n + 1st unit of capacity, provided that n units have already been installed. Note that for $n = N$, $\Delta F = 0$.

When the firm exercises the n + 1st option it receives an asset worth $\Delta V(K_{n+1},P)$ and an option to build the n + 2nd unit of capacity. Hence the opportunity to add capacity incrementally provided by the modularity of the technology can be described as a series of *sequential compound options* and must be valued as such.

4.3 Binomial Approach for Modular Nuclear Technology: Practical Methodology

A discrete-time formulation enables to account for the lumpiness of capacity addition and the discrete nature of firm's decisions, which are effectively revised on a periodic basis. Moreover, intermediate values and decision points are made visible, which enables the analyst to build strong intuition about the source of value of the option and thus better communicate the results of the model.

4.3.1 Assumptions

To keep the size and complexity of the model manageable a number of simplifying assumptions are required. Nonetheless, we intend to preserve the basic nature of the investment problem and capture the value generated by modularity. Assumptions are grouped in three categories: (1) structure of the investment program and characteristics of the asset, (2) characteristics of the firm making the investment, (3) financial market.

1. We consider a capital investment program with the following structure:
   - Investment is irreversible: capital invested may not be costlessly recovered and the asset in place has no other use and no salvage value.
   - Capacity may be expanded and is added incrementally (one unit at a time), sequentially (one unit after another) and in a lumpy fashion (sizeable amount of capacity in each increment).
   - The final size of the plant is fixed. Capacity can be expanded up to a maximum capacity.

- The technical risk is uncorrelated to market risk; it is unsystematic and thus can be diversified entirely.

- Construction takes time. The capital cost corresponding to the construction of one unit of capacity is incurred at the time the decision to build the unit is taken. Indirect construction costs are assumed to be negligible until construction begins. There is no possibility to defer or abandon or defer the construction of a unit once it started.

- A single good is produced: electricity sold on the spot market.

- Operating costs are uncorrelated with the market and assumed constant.

- Cash payout is assumed proportional to the value of the underlying asset. The cash payout rate is constant over time.

- The firm may not temporarily shut down production.

- The market value of the completed project is determined by the present value of the stream of future profits it generates over its operating life discounted at the owner's cost of capital.

- The investment opportunity may not be deferred indefinitely.

- The plant has a fixed operating life. Capital does not depreciate until the end of the operating life, at which point the value of the capital drops to zero.

These assumptions require some additional comments in the context of the MPBR technology:

The capital cost of a unit of capacity (i.e. the exercise price of the option) corresponds to the overnight specific capital cost (defined in Section 3.1.1), which is defined as the cost of the asset as if it could be constructed instantaneously, excluding of financial charges. This definition fits with the assumption of an instantaneous cash outlay for the construction of a unit of capacity.

Constant operating costs are justified by the constant level of personnel required to operate the plant and the small volatility of nuclear fuel prices. We used constant operating costs determined using lifetime levelized operating costs presented in Chapter 3.

Given the nature of nuclear power (Chapter 2), an installed unit of capacity is assumed to produce at maximum capacity (corresponding to a 90% capacity factor, see Chapter 3) for its entire lifetime, and production cannot be temporarily stopped.

The assumption of a limited life of the investment opportunity is restrictive but necessary for a discrete-time analysis. It is realistic nonetheless for a large enough timeframe. Thus, we assume that the first five (5) units must be installed before the end of a ten (10) year period, and that the last five (5) units must be installed the before the end of a twenty (20) year period. This assumption limits the life of the first five options to ten (10) years and the life of the last five options to twenty (20) years. This is necessary because discrete-time binomial model cannot handle perpetual options. However, the planning time horizon is reasonable given an expected three year construction time per module and provided that several modules can be under construction at the same time.

Moreover, we need to assume that the supporting industry for the MPBR system is fully developed.

2. We shall assume that this firm possessing the investment opportunity has the following characteristics:

   - The capital structure of the firm is 100% equity[6].
   - The firm's goal is to maximize expected profit.
   - The firm is a price-taker. Demand uncertainty is ignored.
   - There is no depreciation of capital.

3. The financial market is modeled as follows:

   - The market is complete, i.e. any market-correlated risk may be spanned by a portfolio of existing assets.
   - The market competition is perfect. There are no arbitrage opportunities.
   - The market is frictionless, i.e. there are no taxes, no transaction costs, no restriction on long or short sales.
   - The riskless rate of interest is known with certainty at time zero and is assumed constant.
   - Inflation is ignored.

Assumption regarding depreciation and taxes can be easily relaxed and depreciation and taxes can conveniently be incorporated into the analysis of the free cash flows generated by the asset. However, given the precision of the estimates of costs available at this point in the MPBR development process, this refinement would not add much useful information.

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[6] See Masson and Merton (1985) for the application of contingent claims analysis for firms with leveraged capital structures.

4.3.2 Choice of the Underlying Asset

The choice of underlying asset for the option is a fundamental step in application of real option valuation methods. The application of options theory to value real options requires (1) that a replicating portfolio must be identifiable and (2) to identify the evolution in time of the value of the underlying asset (Section 4.1.1).

Because a unit of capacity produces only electricity, which is sold on the spot market, the value of the plant at time zero is the present value of its future free cash flows resulting form the sale of electricity discounted at the firm's cost of capital. Assuming that operating costs are uncorrelated with the market, the non-diversifiable risk component of the rate of return on the plant is thus perfectly correlated with electricity prices. We choose the value of a unit of capacity (i.e. one 110MWe MPBR module) as the underlying asset and assume a complete market. This is a sufficient condition for the application of option theory in the valuation of the investment opportunity (Section 4.1.1).

All sources of uncertainty concerning operating costs, demand and prices can be combined in a Monte Carlo simulation to generate the present value of the underlying asset at time zero. In particular, this simulation procedure allows us to incorporate any stochastic model for the price of electricity. As the goal of this study is to demonstrate the use of option analysis to value modularity in nuclear technology, we used a *simplified approach* based on the following assumptions:

- Fixed operating costs calculated using the lifetime levelized operating cost estimate as presented in Table 3.4;
- Constant price of electricity of $0.04/kWh;
- 10% annual cost of capital for the firm;
- 30 year operating life

Furthermore, we assume without justification, that the value of the asset evolves according to a *geometric Brownian motion*[7]. The volatility of the asset is entered as a parameter subject to sensitivity analysis (Section 5.4). The resulting static present value of the underlying asset at time zero is $\Delta V =$ \$356 million.

Each module has the same present value, i.e. each unit has the same operating costs and we neglect economies of scale in operation. Consequently, each module has the exact same market value at any point in time. This assumption can be relaxed by considering a different underlying asset for each option, but would increase substantially the size of the model.

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[7] More elaborated models, incorporating stochastic variations of electricity prices, can be found in Skantze and Ilic (2001).

4.3.3 Binomial Model

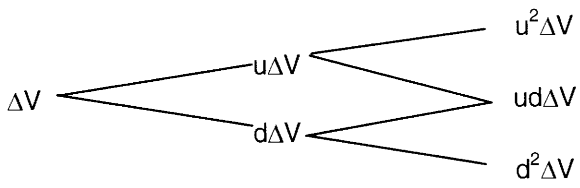
Figure 4.3 presents a matrix formulation of the binomial process for the asset value of a single module, where the column index *j* describes the time evolution and the line index *i* describes the state evolution (up or down events). Using this triangular matrix form we can write a general recursive formula providing the value of the a single unit of installed capacity pre-dividend, $\Delta V(i,j)$, in state *i* and time *j*:

For integers
$i, j \in [0,h],\ i \leq j$

$$\Delta V(i,j) = u^{j-i} d^{i}\ \Delta V(1-\delta)^{j} \qquad (4.6)$$

where ΔV is the value of unit of a installed capacity pre-dividend at time zero, $\Delta V(i,j)$ is the value of a unit of installed capacity pre-dividend in state *i* and time *j*, *h* is the maximum number of periods in the binomial tree, *u* is the one-period asset price change for an up event, *d* is the one-period asset price change for an down event, δ is the constant cash payout rate.

Asset Value Tree



Matrix Representation

$$\begin{array}{cc} & \begin{array}{ccc} \text{Time, j} \; 0 & 1 & 2 \end{array} \\ \text{State, i} & \\ \begin{array}{c} 0 \\ 1 \\ 2 \end{array} & \begin{bmatrix} \Delta V & u\Delta V & u^2\Delta V \\ & d\Delta V & ud\Delta V \\ & & d^2\Delta V \end{bmatrix} \end{array}$$

Figure 4.3: Matrix representation of the binomial process, no dividend.
ΔV is the value of a single module at time zero.

The timeframe for the analysis is 20 years (Section 4.3.1). We fixed the time steps arbitrarily to four (4) per year. This quarterly basis for the evaluation was chosen to keep the size of the trees manageable and considering that corporate investment decisions are revised every quarter. Time steps could be refined further (e.g. weekly) without more difficulty and decision points could be introduced in every time step or at more distant intervals (e.g. quarterly).

As a result, the underlying asset binomial lattice presents *h = 80* periods, corresponding to a 80x80 triangular matrix.

An American option on one unit of capacity is valued using the following recursive formulas:

- Terminal tree nodes:

For integers $i \in [0,h], j = h$

$$C(i,h) = Max[\Delta V(i,h) - k, 0] \tag{4.7a}$$

- Intermediate tree nodes:

For integers $i, j \in [0,h], i \le j$

$$C(i,j) = Max[\Delta V(i,j) - k, (pC(i,j+1) + qC(i+1,j+1))/r] \tag{4.7b}$$

4.3.4 *Compound Options and Conditional Exercise*

Let us now turn to the evaluation of the compound options by considering first that we can build two modules sequentially. Upon exercise of the second option (OPT2), the owner receives the second unit of capacity. Upon exercise of the first option (OPT1) the owner receives the first unit of capacity and the right to build the second module, i.e. the owners receives the first unit of capacity and the second option. The first and the second module of capacity have the exact same market value at the same time. Equation 4.7 needs to be modified as follows to value OPT1:

- Terminal tree nodes:

For integers $i \in [0,h], j = h$

$$C^1(i,h) = Max\left[\Delta V(i,h) + C^2(i,h) - k, 0\right] \tag{4.8a}$$

- Intermediate tree nodes:

For integers $i, j \in [0,h]$, $i \le j$

$$C^1(i,j) = Max\left[\Delta V(i,j) + C^2(i,j) - k, \left(pC^1(i,j+1) + qC^1(i+1,j+1)\right)/r\right] \tag{4.8b}$$

where $C^1(i,j)$ is the value of OPT1 and $C^2(i,j)$ is the value of OPT2 in state *i* and time *j*.

However, the construction of the second module cannot start before the beginning of the construction of the first module. Standing at time zero, we can value the compound options by recognizing that we can either exercise OPT1 or keep it alive and wait for the next period. If OPT1 is exercised at time zero then the second option can be exercised in the next period. It is said that *the exercise of OPT1 uncovers OPT2*. In other words, the starting date of OPT2 is *conditional to the exercise* of OPT1. If in state i and time $j < h$, OPT1 has been exercised, then OPT 2 can be valued using Equation (4.7.b). If in state i and time $j < h$ OPT1 has not been exercised, then OPT2 cannot be exercised and its value lies only in the continuing value. It must be valued using:

For integers $i, j \in [0,h], i \leq j$

$$C^2(i,j) = Max\left[0\, ,\left(pC^2(i,j+1) + qC^2(i+1,j+1)\right)/r\right] \qquad (4.8c)$$

The series of possible exercise dates of OPT1 has to be determined proceeding forward in time in the binomial tree. The exercise of OPT1 is therefore a path-dependent problem and consequently, the starting date of OPT2 is also a *path-dependant problem*. Because the binomial valuation algorithm proceeds backwards, it is not possible standing in state i and time j to know which path would be followed to arrive in $(i,,j)$ and thus it is not possible to know for the collection of state histories up to an including time j that leads to state i if OPT1 has been exercised in the previous period(s). Such path-dependant problems can be solved numerically using Monte Carlo simulation[8].

We solve this path-dependant problem in a binomial setting using the following approximation:

> If in state i and time j there exists at least one path for which OPT1 has never been exercised in the previous period, then OPT2 cannot be exercised in state i and time j.

This approximation yields a lower bound for the option value, because it disregards potential paths where OPT1 could have been exercised in the previous period. However, given that the time lag is only one period, this approximation has little influence on the exact value of the option.

Consider now a series of sequential compound options. The algorithm for valuation of the $n+1^{st}$ option conditional upon the exercise of the n^{th} option with maturity M_n is given in Figure 4.4. This algorithm contains two logical tests:

- This first test says that if time j is greater than the maturity of the n^{th} option, then the $n+1^{st}$ option can be exercised immediately and is valued using the greater of the immediate exercise value and the continuing value; else proceed to the second test.

- The second test says that if the n^{th} option has been exercised in the previous period (here "exercised" refer to the simplified condition defined in the box above), then the $n+1^{st}$ option is valued using the greater of the immediate exercise value and the continuing value; else the $n+1^{st}$ option is valued using the greater of the continuing value and zero.

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[8] See Hull (2001) for the use of Monte Carlo simulation in option valuation.

Thus, our binomial algorithm requires a backward induction and a conditional exercise algorithm (Figure 4.4) that requires a forward induction. Coupling the two algorithms, our valuation requires both backward and forward iterations along the binomial trees paths. We speak therefore of a "backward-forward algorithm"[9].

4.3.5 *Investment and Construction Lags*

The above analysis assumes that a unit of capacity can be build instantaneously. The holder of the option to invest could thus receive immediately upon exercise the full value of the asset and the full option value to invest in the next unit.

In fact, the holder of the option receives the asset only after a time lag corresponding to the construction time[10] of the unit. Moreover, even though the owner receives the option to build the $n + 1^{st}$ unit of capacity immediately upon exercise of the n^{th} option, the firm might not be able to start the construction of the n^{th} unit immediately because of limited resources (physical constraints on the building site, limited production capacity, maximum rate at which the firm can invest productively...). Construction and investment lags have two distinct effects on the valuation. These two constraints however both tend to decrease the value of the investment opportunity (by limiting flexibility).

1. *The construction lag reduces the value of the stream of profits from the asset.*

Let T be the construction time lag. By beginning construction at time j, the firm has a claim to receive the value of the unit of installed capacity at time $j + T$. The value at time j of the claim to receive a unit of installed capacity at time $j + T$ is simply its present value (Paddock *et al.* 1988). Let ρ be the required rate of return to the owner, the present value at time j of one unit of installed capacity received at time $j + T$, $\Delta\hat{V}(j)$, is:

$$\Delta\hat{V}(j) = e^{-\rho T} E[\Delta V(j+T)]$$

where $E[.]$ denotes the expectation operator, $E[\Delta V(j+T)]$ is the expected value of the asset at time $j + T$, and ρ the required rate of return on ΔV to the owner.

The expected value of the asset at time $j + T$ is given by its expected future value:

$$E[\Delta V(j+T)] = e^{(\rho-\delta)T} \Delta V(j)$$

---

[9] The term "backward-forward algorithm" was used by Professor Copeland to describe the valuation of another type of path-dependant problem (switching options) during the MIT Sloan Proseminar on Real Options (15.976), on April 4th, 2002.

[10] We define the construction time as the time necessary to bring one unit of capacity in production. This includes prefabrication, site preparation, site assembly, fueling, and testing.

Thus, the present value of one unit of installed capacity is:

For integers $j \in [0,h]$
and $T \in [0,h-j]$
$$\Delta\hat{V}(j) = \Delta V(j)\, e^{-\delta T} \tag{4.9}$$

The actual asset underlying the series of compound options is the present value of one unit of installed capacity received after the construction lag. However, $\Delta\hat{V}$ follows the same evolution process as ΔV, so that we can simply replace ΔV by $\Delta\hat{V}$ to value the investment program. Thus, the binomial recursive formulation in Equation 4.6 is adjusted as follows:

For integers
$i, j, \in [0,h], i \leq j$
and $T \in [0,h-j]$
$$\Delta\hat{V}(i,j) = u^{j-i} d^{i}\, e^{-\delta T} \Delta V (1-\delta)^{j} \tag{4.10}$$

where ΔV is the value of one unit of capacity at time zero if it could be constructed overnight and $\Delta\hat{V}(i,j)$ is the value of one unit of capacity at time zero considering a construction lag, *t*.

2. The investment lag restricts the exercise of the option to invest incrementally and reduces its value.

Let *t* be the investment lag, t integer and $t \in [0,j]$. The option to invest in the next unit cannot be exercised immediately after it is received. Instead, there is a period during which exercise is restricted. In that sense, the option to invest becomes an exotic American option similar to the one fund in warrants issued by a company on its own stock limiting exercise during the first years of the life of the option and sometimes used in employee incentive schemes. Such an option is called a *forward start option*[11].

To incorporate the investment lag into the binomial value tree of the option, we used a restrictive condition on the early exercise of the option. We face the same path-dependent problem as exposed in Section 4.3.4, and we use a similar approximation. Considering again two compound options for sake of simplicity:

> If in state *i* and time *j* there exists at least one path for which OPT1 has never been exercised at time *j* - *t*, then OPT2 cannot be exercise in state *i* and time *j*.

---

[11] Hull (2001) provides a simple analytic solution for the value of the option in the case of a European call.

This approximation also yields a *lower bound for the option value*, because it disregards potential paths where OPT1 could have been exercised in previous periods. The influence of this approximation on the option value increases as the investment lag increases; i.e. as more and more paths are disregarded. However, the investment time lag in our analysis is kept small relative to the maturity of the option.

Considering now a series of sequential compound options the algorithm for the valuation of the $n+1^{st}$ option conditional upon the exercise of the n^{th} option with maturity M_n taking into account the construction T and investment lag t is given in Figure 4.5. This algorithm is an extension of the one presented in Figure 4.4 and contains two logical tests:

- This first test says that if the time j is greater than the sum of the maturity of the n^{th} option and the investment lag, then the $n+1^{st}$ option can be exercised immediately and is valued using the greater of the immediate exercise value and the continuing value; else proceed to the second test.

- The second test says that if the n^{th} option has been exercised in the period $j-t$ (here "exercised" refer to the simplified condition exposed in the box above), then the $n+1^{st}$ option is valued using the greater of the immediate exercise value and the continuing value; else the $n+1^{st}$ option is valued using the greater value of the continuing value and zero.

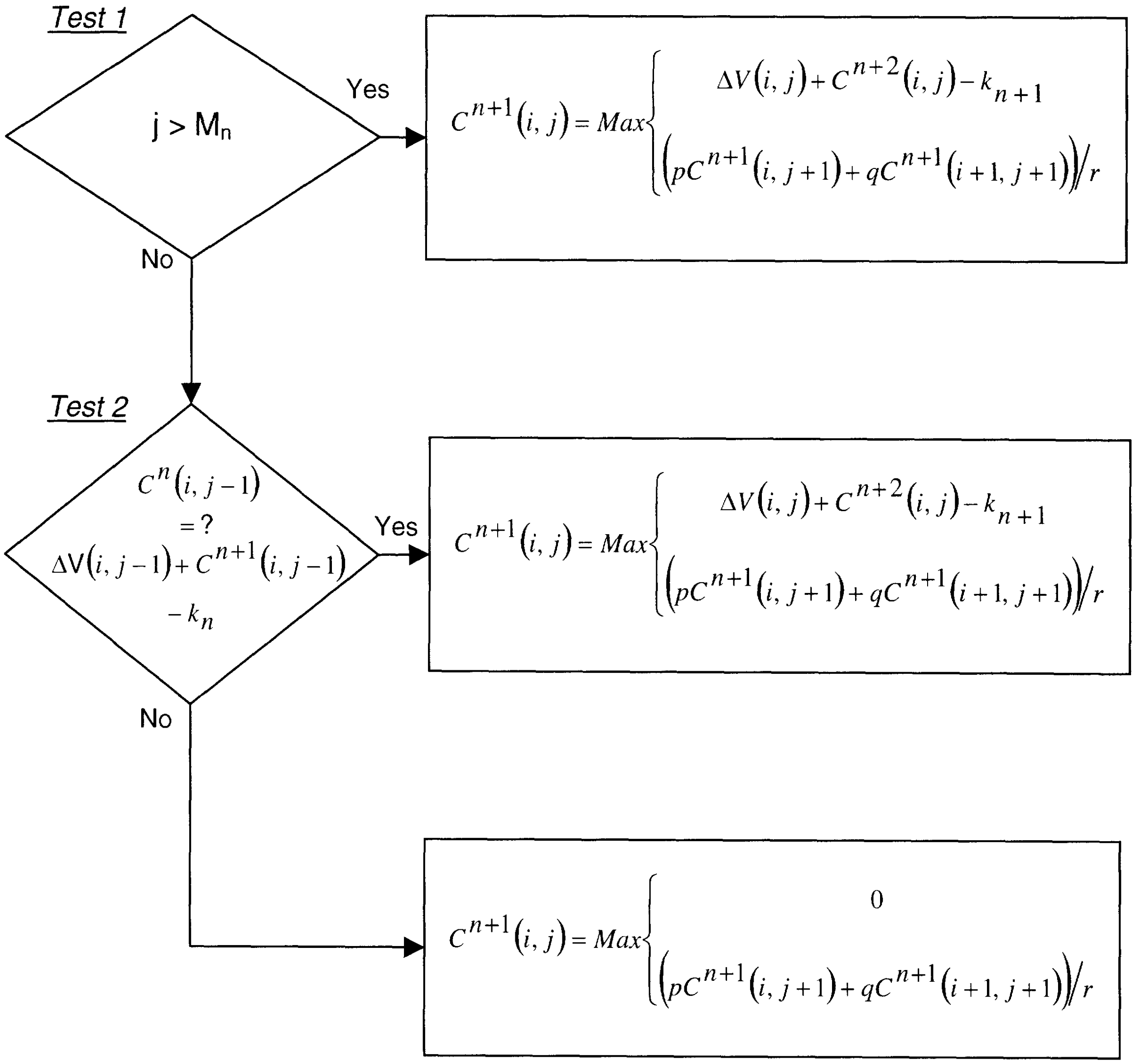

Figure 4.4: Algorithm for conditional exercise of sequential compound options.

Valuation of n +1st option in state i and time j, C^{n+1} (i,j),
conditional to the exercise of nth option in state i and time j - 1 C^{n} (i,j-1).

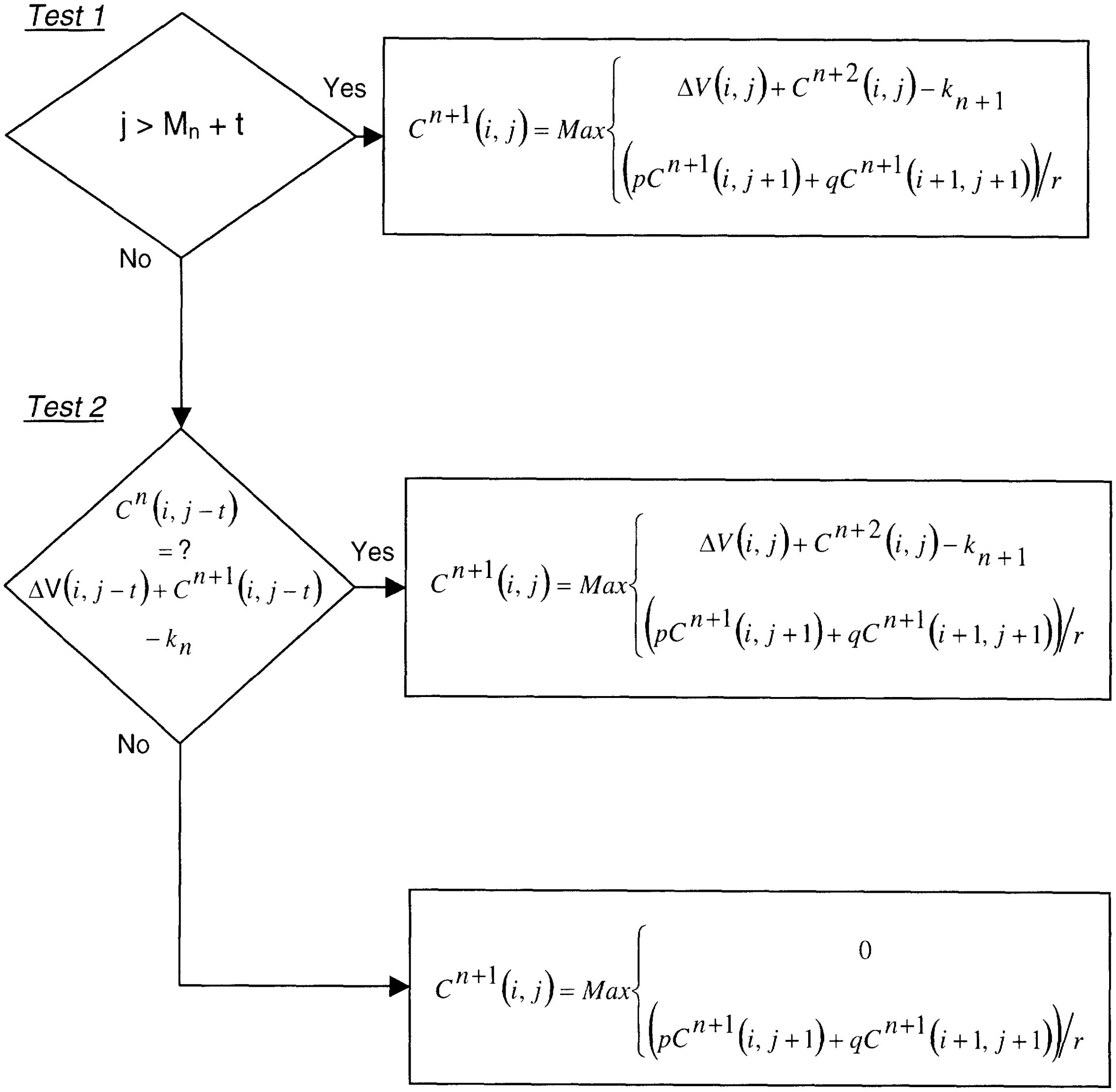

Figure 4.5: Algorithm for conditional exercise of sequential compound options when there is an investment lag, t.

Valuation of n +1st option in state i and time j, $C^{n+1}(i,j)$, conditional to the exercise of nth option in state i and time j - t $C^n(i,j\text{-}t)$.

Chapter 5 Characteristics of the Solution to the Investment Problem

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This Chapter presents and interprets the results of the numerical simulations done using the model in Chapter 4. As exposed in Sections 4.3.4 and 4.3.5, the model yields a *lower bound* for the compound option value. We limit our analysis to three scenarios for the potential capital cost of each individual module. These scenarios are defined in Section 5.1 along with base case parameters. We present three sets of results. Section 5.2 discusses the effects of compounding on the relative value of each option for the base case parameters. Section 5.3 explains the interdependence of construction and investment lags. Finally, Section 5.4 presents a sensitivity analysis on some key parameters with a particular emphasis on the unexpected influence of volatility.

5.1 Base Case Scenarios

5.1.1 Definition of the Scenarios

To the best of our knowledge, no cost analysis of the exact construction sequence for an nth-of-a-kind (NOAK) plant has been performed to date. In particular, we found no information on the size of the common facilities necessary to start operation and how many modules these initial facilities could support before extension is needed. Hence, the capital cost incurred for the construction of each individual module has not yet been established. This information is however required for a real option analysis because the capital cost of the nth module represents the exercise price of the option to invest in the nth unit of capacity. As discussed in Section 4.3.1, the exercise price of each option in the sequence is the overnight specific capital cost of the corresponding module.

Thus, we generated three scenarios; each is based on a different allocation of capital costs to each individual module. In order to do so, we performed the cost segregations presented in Tables 5.1 and 5.2, based on the original plant cost breakdown shown in Table 3.3. Our cost segregation for the first and second scenarios is based on the following assumptions that we believe to be a reasonable proxy for the actual capital costs: The common facilities initially built are sufficient to support operation up to the 5th module. Then, the common facilities that are built to support the 6th module are sufficient to support operation up to the 10th module.

We believe these three scenarios cover a wide range of possible cases and provide good insights into the investment problem. Moreover, they represent three different starting points for the value of the first option: in the first scenario OPT1 starts deep-out-of-the-money[1], in the second scenario OPT1 starts in-the-money (near-the-money), and in the third scenario OPT1 starts deep-in-the-money. These scenarios are described below and summarized in Table 5.3.

Scenario 1. We allocate the cost of the common facilities and the indirect costs among the 10 units as shown on Table 5.1. Reactors and turbines equipments, field office supervision and services and owner's costs are spread evenly through the ten units. Land cost is charged entirely to the first module. Other costs (mainly for the common facilities) are allocated as follows: 31% is charged for the 1st unit, 19% for the 6th unit and 50% evenly to the remaining units. In this way, the cost of the 1st module is estimated to $346million, the cost the 6th module to $269million and the cost of units 2 to 5 and 7 to 10 to $179 (Table 5.1).

Scenario 2. We modify Scenario 1 to allocate the costs of common facilities as follows: 15% is charged for the 1st unit, 10% for the 6th unit and 75% evenly to the remaining units. In this way, the cost of the 1st module is estimated to $249million, the cost the 6th module to $217million and the cost of units 2 to 5 and 7 to 10 to $198 (Table 5.2).

Scenario 3. We assume that all costs could be evenly spread among all units, resulting in an estimated cost of $205million per module (divide by 10 the total overnight capital cost in Table 3.3).

---

[1] An option is said to be *in-the-money* (respectively *out-of-the-money*) when the value of its underlying asset is greater (lower) than its exercise price. It would pay to exercise immediately. An option is said to be *deep-in-the-money* when the value of its underlying asset is much greater than its exercise price.

Table 5.1: Scenario 1 - Capital Cost Estimate per module for a MPBR 110MWe module. Segregation based on the cost estimates for a 10 module plant in Table 3.3. Millions of January 1992 US dollars.

Account No.	**Description**	**Cost Estimate**			
		Module 1	**Modules 2-5**	**Module 6**	**Modules 7-10**
20	Land & Land Rights	2.5	0	0	0
21	Structures & Improvements	60.0	12	36.0	12
22	Reactor Plant Equipment	62.8	62.8	62.8	62.8
23	Turbine Plant Equipment	31.6	31.6	31.6	31.6
24	Electric Plant Equipment	20.0	4	12.0	4
25	Miscellaneous Plant Equipment	15.0	3	9.0	3
26	Heat Reject System	12.5	0	12.5	0
	TOTAL DIRECT COSTS	204	113	164	113
91	Construction Service	34.7	6.9	20.8	6.9
92	Home Office Eng. & Service	19.7	3.9	11.8	3.9
93	Field Office Supv. & Service	5.4	5.4	5.4	5.4
94	Owner's Cost	14.7	14.7	14.7	14.7
	TOTAL INDIRECT COSTS	74	31	53	31
TOTAL BASE CONSTRUCTION COST		279	144	217	144
Contengency [24%]		67	35	52	35
TOTAL OVERNIGHT SPECIFIC COST		**346**	**179**	**269**	**179**
UNIT CAPITAL COST [$/kWe]		**3,144**	**1,628**	**2,442**	**1,628**
AFUDC		42	22	33	22
TOTAL CAPITAL COST PER MODULE		**388**	**201**	**301**	**201**
TOTAL CAPITAL COST FOR THE PLA		**2,296**			

AFUDC: Allowance for Fund Used During Construction (See Section 3.1.1).

Table 5.2: Scenario 2 - Capital Cost Estimate per module for a MPBR 110MWe module. Segregation based on the cost estimates for a 10 module plant in Table 3.3. Millions of January 1992 US dollars.

Account No.	**Description**	**Cost Estimate**			
		Module 1	**Modules 2-5**	**Module 6**	**Modules 7-10**
20	Land & Land Rights	2.5	0	0	0
21	Structures & Improvements	48.0	12	48.0	12
22	Reactor Plant Equipment	62.8	62.8	62.8	62.8
23	Turbine Plant Equipment	31.6	31.6	31.6	31.6
24	Electric Plant Equipment	16.0	4	16.0	4
25	Miscellaneous Plant Equipment	12.0	3	12.0	3
26	Heat Reject System	12.5	0	12.5	0
	TOTAL DIRECT COSTS	185	113	183	113
91	Construction Service	27.8	6.9	27.8	6.9
92	Home Office Eng. & Service	15.8	3.9	15.8	3.9
93	Field Office Supv. & Service	5.4	5.4	5.4	5.4
94	Owner's Cost	14.7	14.7	14.7	14.7
	TOTAL INDIRECT COSTS	64	31	64	31
TOTAL BASE CONSTRUCTION COST		249	144	247	144
Contengency [24%]		60	35	59	35
TOTAL OVERNIGHT SPECIFIC COST		**309**	**179**	**306**	**179**
UNIT CAPITAL COST [$/kWe]		**2,807**	**1,628**	**2,779**	**1,628**
AFUDC [12%]		38	22	37	22
TOTAL CAPITAL COST PER MODULE		**346**	**201**	**343**	**201**
TOTAL CAPITAL COST FOR THE PLANT		**2,296**			

AFUDC: Allowance for Fund Used During Construction (See Section 3.1.1).

5.1.2 Base Case Parameters

Unless otherwise noted, we set the parameters of the investment program as presented in Table 5.3. We fixed the time steps in the binomial model to four (4) per year. Options values and exercise prices are in January 92 million dollars.

Table 5.3: Base case parameters.

Input parameters

Current value of the underlying	356
Annual risk free rate	3.5%
Annual payout rate	10.0%
Annual standard deviation	12.0%
Number of steps per year	4
Number of years	20
Construction lag [steps]	12
Investment lag [steps]	1

Scenario 1

Option	**OPT 1**	**OPT 2 to 5**	**OPT 6**	**OPT 7 to 10**
Exercise price [$million]	346	179	269	179
Maturity [periods]	40	40	80	80

Scenario 2

Option	**OPT 1**	**OPT 2 to 5**	**OPT 6**	**OPT 7 to 10**
Exercise price [$million]	249	198	217	198
Maturity [periods]	40	40	80	80

Scenario 3

Option	**OPT 1**	**OPT 2 to 5**	**OPT 6**	**OPT 7 to 10**
Exercise price [$million]	205	205	205	205
Maturity [periods]	40	40	80	80

5.2 Relative Value of Each Option and Compounding Effects

In the first scenario, the value of the option to build the first unit of capacity (OPT1) is \$23million (Figure 5.1a). This value can be interpreted as the net present value at time zero of the investment program, whose first phase (only) has a present value of \$356million and a standard deviation of 12% per year, and requires investment in ten stages. Because of construction lag (see Equation 4.9) the present value of the asset is reduced to \$264million. Consequently, without the option component, the first phase of the investment program would have a negative \$82million NPV[2] if the firm were to invest now.

On the other hand, if the firm were to invest today, it would exercise the option to build the first unit of capacity and give up the possibility of waiting for new information. This lost value of the option represents an *opportunity cost* that must be taken into account in the investment decision. Hence, for the firm to invest today, the value of the first module should exceed its capital cost by an amount at least equal to keeping the first option alive, i.e. \$23 million in this case. The firm should only invest when the value of the payoff of the option if exercised now is larger than the continuing value. Critical values of the asset for which it is optimal to invest now are readily available in the option binomial tree and can be revised each period.

As discussed in Section 4.2, at any point during the life of the project, the value of the investment program has two components: the value of installed capacity and the value of the firm's option to add capacity in the future. For instance, if at time zero, three modules have already been installed, the option component of the remaining investment program is the value of the fourth option. This option to expand capacity incrementally still has a significant value: \$17million, for the first scenario (Figure 5.1a).

The critical value of the underlying asset that triggers the exercise of each option is readily available in the binomial tree. This is illustrated in the abstract from the binomial model presented in Figure 5.2. This abstract shows the value tree of the underlying asset and the value trees of the first and second options up to ten periods in the future for the second scenario. Shaded areas in the options value trees show the value of the option when it is exercised. The corresponding value of the asset can be read directly in the asset value tree. The value of the first option (as well as the value of the other options in the sequence) evolves in time as shown in Figure 5.2.

The relative value of each option is shown in Figure 5.1 for 12% annual volatility and 10% payout rate. The downward sloping curves resulting from the second and third scenarios correspond to what we would expect intuitively (Figures 5.1b and c): the value of the investment program grows as the number of embedded expansion options increases. Indeed, in the third scenario all options in the sequence have the same exercise price. The option to invest in the last module (OPT10) is the option to acquire one unit of installed capacity for an exercise price EX10, and the option to invest in the ninth module (OPT9) is the option to acquire one unit of installed capacity <u>and</u> OPT10 for an exercise price EX9 = EX10. Thus the value of OPT9 is greater than the value of

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[2] $\text{Value module 1} \times e^{-\text{constr. lag} \times (\text{payout rate}/4)} - \text{capital cost module 1} = 356e^{-12\times(0.10/4)} - 346 = -82$

OPT10. The same argument holds for all options in the sequence and the value of the option increases gradually as we move from OPT10 to OPT1. This is the *compounding effect*.

In the first scenario however, the relatively higher exercise prices of OPT6 and OPT1 disrupt this compounding effect and reduce significantly the value of each option in the sequence and consequently reduce the value of the option to invest in the first module. The large difference between the exercise prices of the first and the second options causes the value of OPT1 to be lower than OPT2, hence the change in slope between the first and second options in Figure 5.1a.

The value of the investment program is thus highly sensitive to the relative cost of the first module as compared with the next ones. In particular, the value of the incremental expansion option reaches its highest value when the cost of each individual module is the same (scenario 3, Figure 5.1c). However, even if the first phase of the project exhibits a large negative NPV (in the first scenario), the possibility to add capacity incrementally confers the investment program with a positive present value, and the project should therefore be undertaken whenever the value of the payoff of the option is larger than the continuing value.

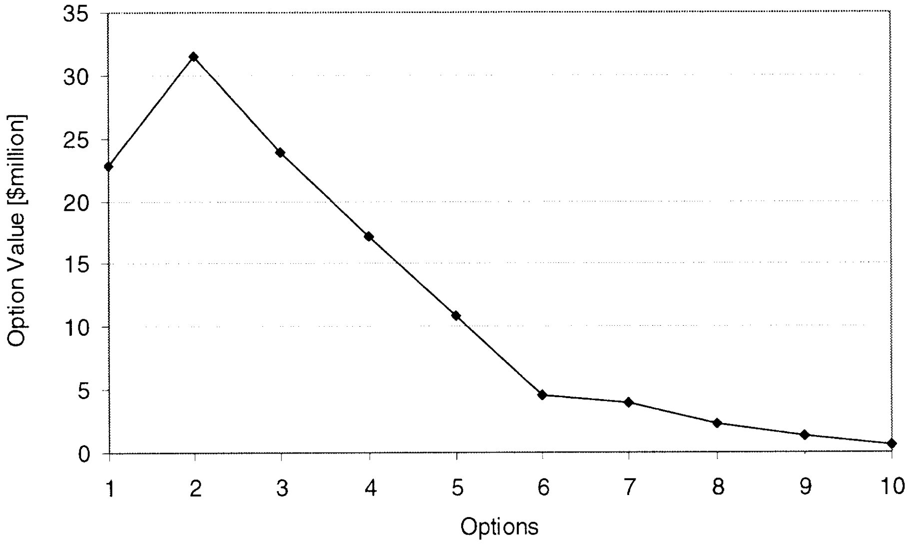

Figure 5.1a: Scenario 1. Options value as a function for $\sigma = 12\%$ and $\delta = 10\%$ per annum.

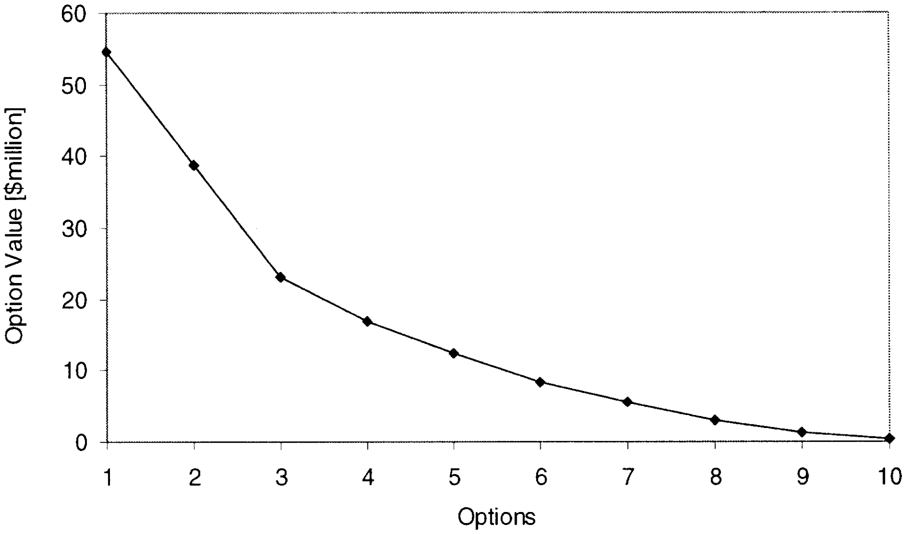

Figure 5.1b: Scenario 2. Options value as a function for σ = 12% and δ = 10% per annum.

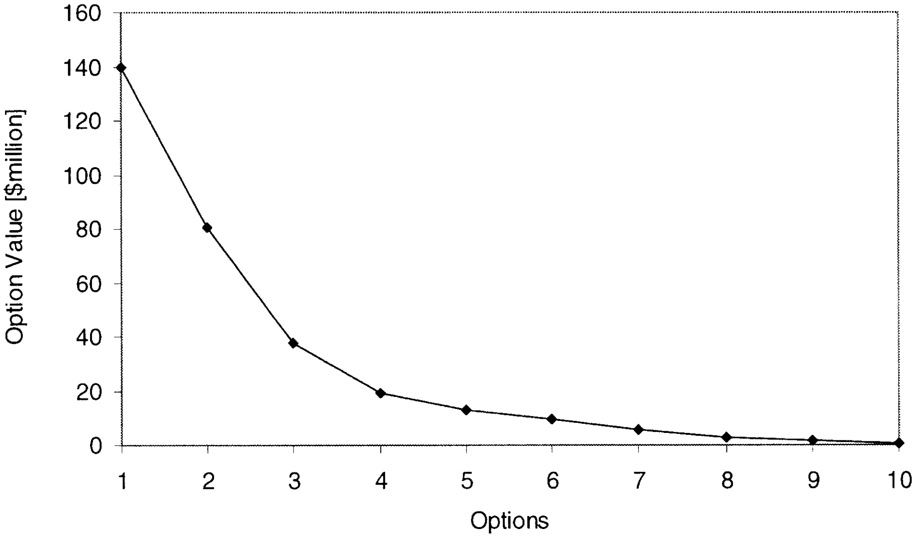

Figure 5.1c: Scenario 3. Options value as a function for σ = 12% and δ = 10% per annum.

5.3 Construction and Investment Lags

The dependence of the options values to the construction time is highlighted in Figure 5.3. As expected, increasing construction time decreases the options values by diminishing the present value of the underlying asset and thus delaying the exercise of the options (see Equation 4.9). The general shape of the curve describing the relative value of each option in the sequence discussed in Section 5.2 still holds. However, the difference in value between two consecutive options gets smaller as the construction time increases. Note that the value of the first three options decreases sharply as the construction time increases: this slope is determined by the payout rate. A six month construction delay (from 12 to 14 quarters) reduces the value of the first option by approximately one-third in each scenario (respectively from $23million to $16million, from $55million to $34million and from $140million to $100 million in scenarios 1, 2 and 3).

The interdependence of construction and investment lags is illustrated for the first option in Figure 5.4. On the one hand, the investment lag restricts the possibility of early exercise, resulting in lower option value. On the other hand, longer construction times decrease the value of the underlying asset, consequently delaying the decision to invest in the next increment of capacity. Hence, as the construction time grows, the waiting time between two investment decisions increases and the influence of the investment lag on the option value decreases. For long enough construction times, the waiting time between two sequential capital outlays becomes larger than the investment lag, which has no influence on the option value anymore. Note that the investment lag affects all the more the value of the option as the probability of early exercise is high, that is as the first option is deeper-in-the-money (compare Figures 5.4a, b and c). In other words, the deeper-in the-money the option, the more its value is affected by the investment lag.

Value Tree for the underlying asset pre-dividends with construction lag

State i \ Time j	0	1	2	3	4	5	6	7	8	9	10	11
0	264	273	283	293	304	315	327	338	351	363	376	...
1		242	251	260	270	279	290	300	311	322	334	...
2			223	231	239	248	257	266	276	286	296	...
3				205	212	220	228	236	245	253	263	...
4					188	195	202	209	217	225	233	...
5						173	179	186	192	199	207	...
6							159	165	171	177	183	...
7								146	151	157	163	...
8									134	139	144	...
9										123	128	...
10											113	...
11												...

Investment threshold for OPT1

Investment threshold for OPT2

Value Tree for Option 2

State i \ Time j	0	1	2	3	4	5	6	7	8	9	10	11
0	39	54	75	105	149	**212**	**254**	**306**	**373**	**458**	**570**	...
1		21	28	39	53	72	99	136	187	**257**	**310**	...
2			11	16	21	29	40	55	75	102	140	...
3				6	9	12	16	23	31	42	57	...
4					3	5	6	9	13	17	24	...
5						2	2	3	5	7	10	...
6							1	1	2	2	3	...
7								0	1	1	1	...
8									0	0	0	...
9										0	0	...
10											0	...
11												...

OPT2 execise region

Value Tree for Option 1

State i \ Time j	0	1	2	3	4	5	6	7	8	9	10	11
0	55	**78**	**109**	**150**	**204**	**278**	**331**	**395**	**474**	**572**	**697**	...
1		26	37	52	**74**	**103**	**140**	**187**	**249**	**330**	**395**	...
2			13	18	26	36	51	72	**102**	**139**	**187**	...
3				6	9	13	18	26	36	51	72	...
4					3	5	6	9	13	19	26	...
5						1	2	3	5	7	9	...
6							1	1	1	2	3	...
7								0	0	1	1	...
8									0	0	0	...
9										0	0	...
10											0	...
11												...

OPT1 execise region

Figure 5.2: Scenario 2. Compound options binomial model. Underlying asset value tree and value trees for the first and second option out of ten compound options in the series for the first ten periods, with construction and investment lags.
Definition of the investment thresholds and options exercise region.

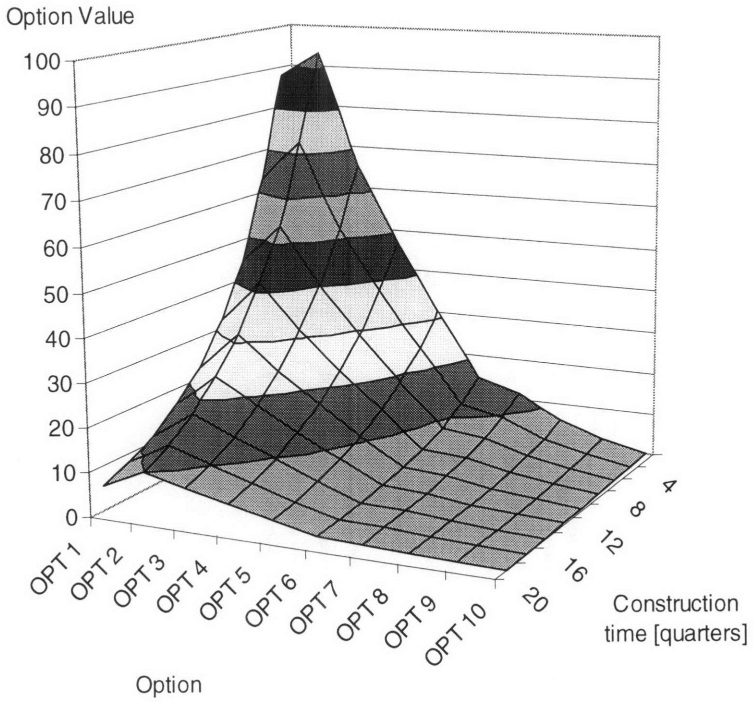

Figure 5.3a: Scenario 1. Options value as a function of construction time.

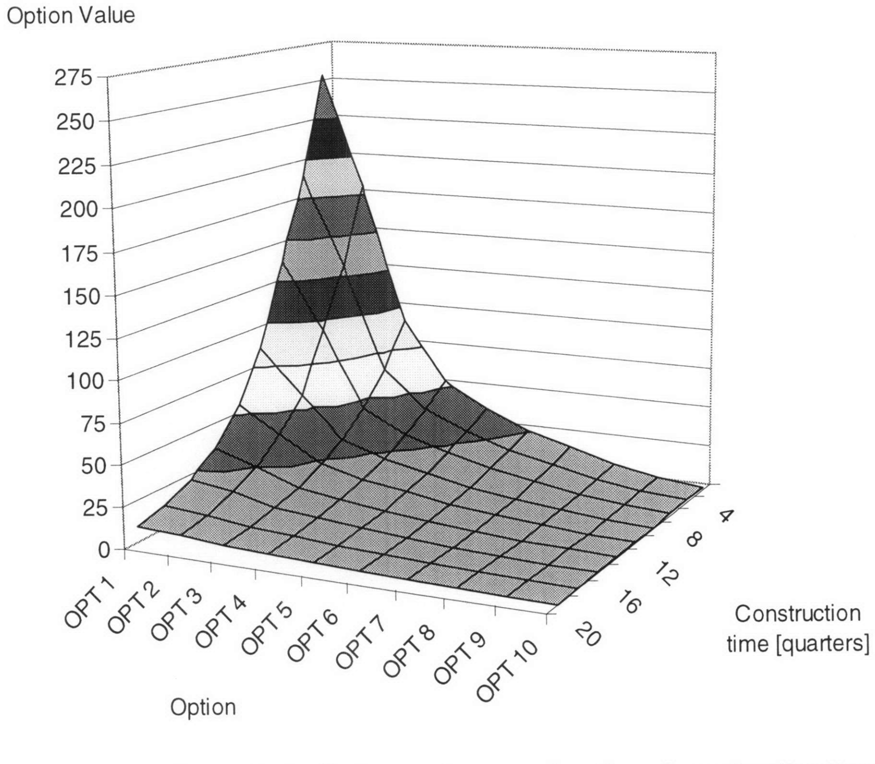

Figure 5.3b: Scenario 2. Options value as a function of construction time.

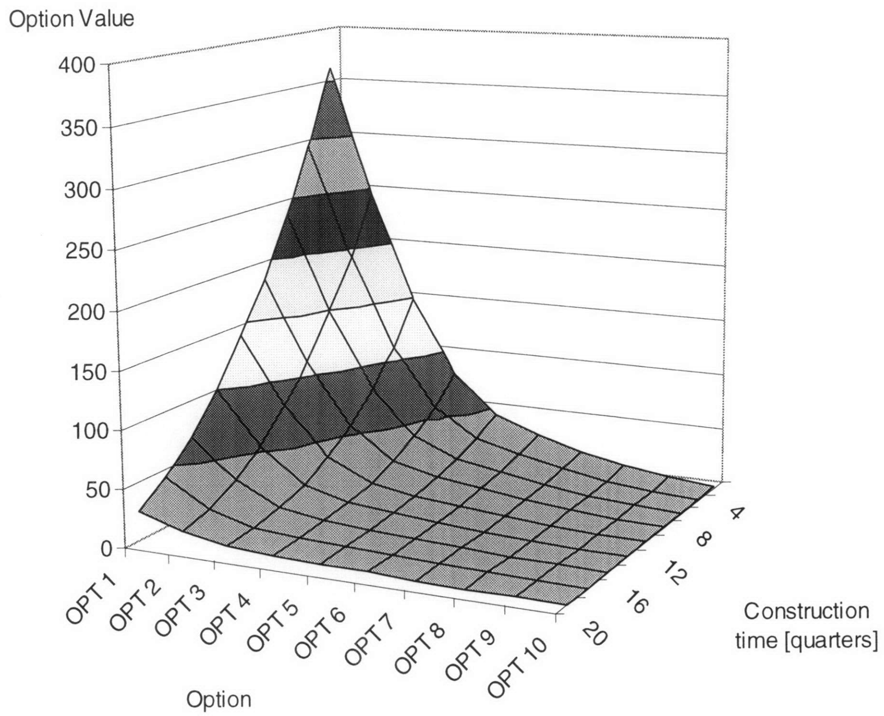

Figure 5.3c: Scenario 3. Options value as a function of construction time.

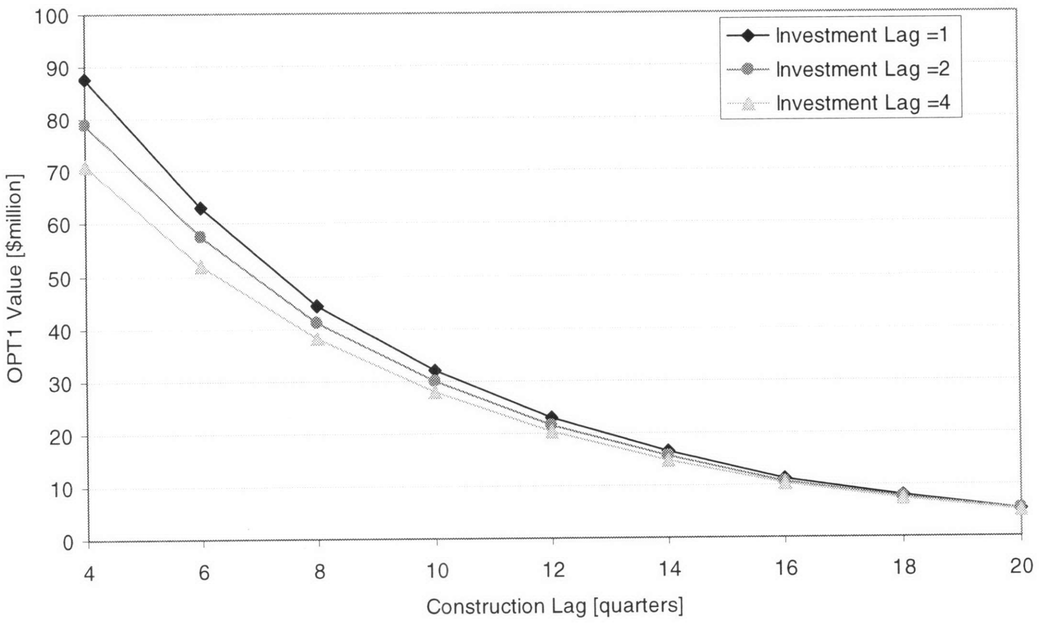

Figure 5.4a: Scenario 1. Value of option 1as a function of construction and Investment lags.

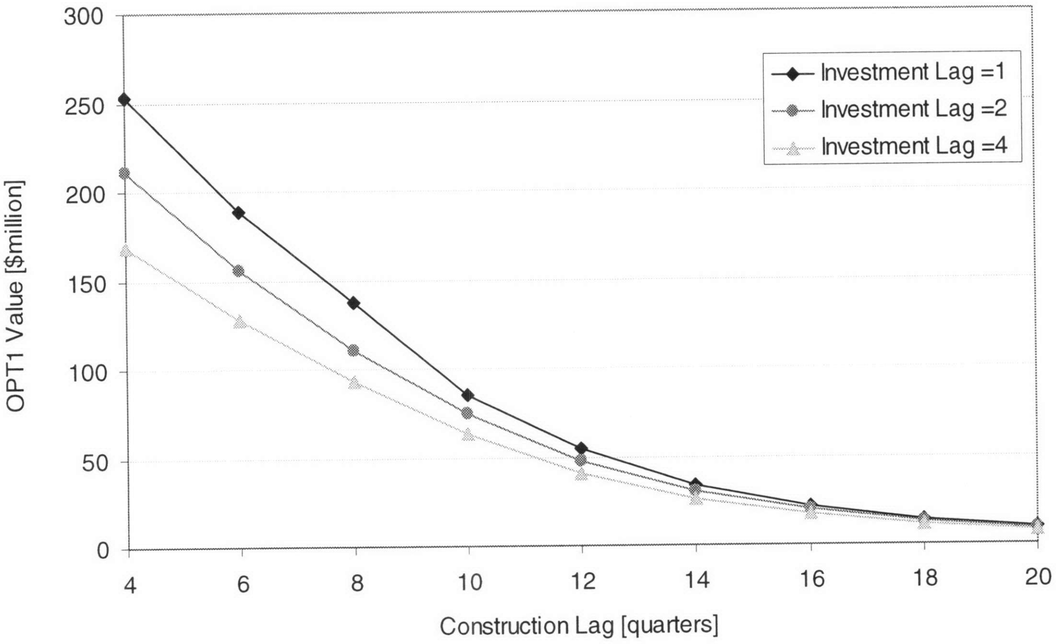

Figure 5.4b: Scenario 2. Value of option 1as a function of construction and Investment lags.

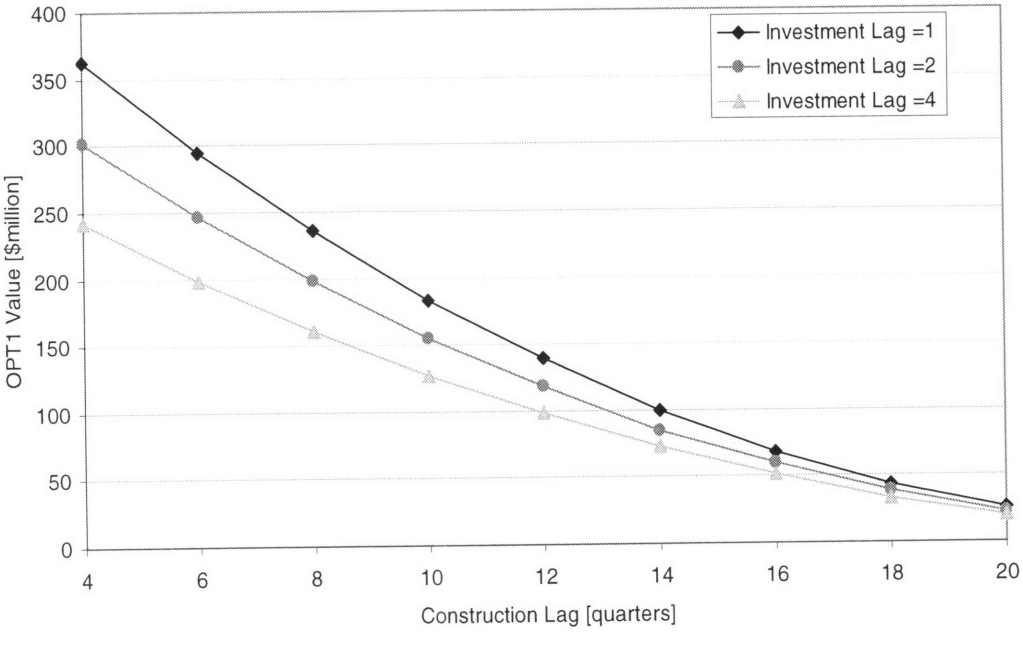

Figure 5.4c: Scenario 3. Value of option 1as a function of construction and Investment lags.

5.4 Sensitivity Analysis

This section discuses the influence on the valuation of the base case parameters, namely the volatility, the payout rate, the initial value of a unit of installed capacity, and the risk free rate of interest.

- *Volatility*

The value of the compound option is highly sensitive to the volatility in the value of a unit of installed capacity (irrespective of investors or managers risk preference). This dependence is shown in Figures 5.5 and 5.6. The first scenario exhibits expected increasing option value for increasing volatility (Figures 5.5a and 5.6a). Note again the relative value of OPT1, OPT2 and OPT3: as volatility increases, the compounding effect is reinforced and the value of each individual option in the sequence tends to be higher than the next option.

The third scenario however exhibits unexpected and counterintuitive results. Figure 5.5c presents a "U" shape: option values decreases with increasing volatility for relatively low volatilities (below 10%); then option value increases with increasing volatility for high volatilities (between 10 and 20%). We offer the following plausible explanation to this behavior:

> In the third scenario, the first option at time zero is *deep-in-the-money* and is exercised immediately for high payout rates. The remaining options are also deep-in-the-money but cannot be exercised immediately because of the sequential investment condition and the investment lag: sequential options are not active before the previous option has been exercised. Hence, for a two period investment lag, the second option is uncovered after two periods; the third option is uncovered after four periods, and so on.
>
> For low level of volatility and high payout rate ($\delta = 10\%$ in the base case) the asset value tree exhibits slowly increasing asset values in time or even decreasing asset values in time (see Figure 4.2). Small increase in volatility generates larger amplitude of the up and down movements in the asset value in time, increasing the value of the asset in up events and decreasing the value of the asset in down events. However, this results in fewer cases in which the options are being exercised: options are still exercised in an up event but are not exercised in a down event. Consequently, the continuing value of the inactive options decreases and the compounding effect decreases the value of all options in the sequence. This effect is attenuated for large enough volatility and we observe increasing option value for increasing volatility in this case. We believe this effect might be created by the approximation we use to model the sequential exercise of the options and the investment lag (Sections 4.3.4 and 4.3.5).

As $\delta \rightarrow \infty$, the value of the compound option goes to zero and volatility has no influence on it; the only choices are invest now or never. As $\delta \rightarrow 0$, the options are exercised only at maturity (it is never optimal to exercise early an American option on a non-dividend paying stock), and the compound option behaves as European options. Thus increasing volatility increases the compound option's value.

Moreover, we assumed that the payout rate δ was independent of other parameters in the model; i.e. notably independent of the volatility σ. In fact, this might not be the case (see Dixit and Pindyck 1994 for a discussion of the dependence of δ and σ). A more thorough analysis of the combined effect of δ and σ on the options values is warranted.

In the second scenario, the first option starts in-the-money and near-the-money: this represents a case somewhere between the first and third scenarios. Hence, the second scenario (Figure 5.5b) shows patterns observed in the two other scenarios. OPT1 and OPT2 follow the same pattern as observed in the third scenario: decreasing compound option value with increasing volatility for volatilities below 6%, and then increasing compound option value with increasing volatility. Values of the other options (from OPT3 onward) exhibit increasing options values with increasing volatility.

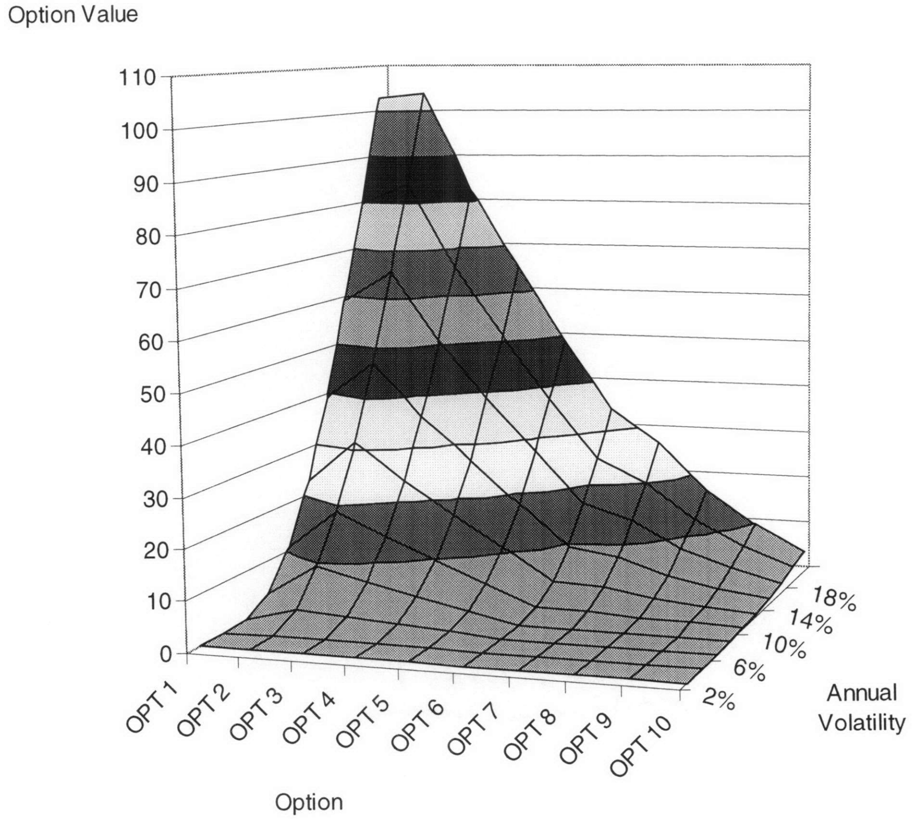

Figure 5.5a: Scenario 1. Options value as a function of volatility.

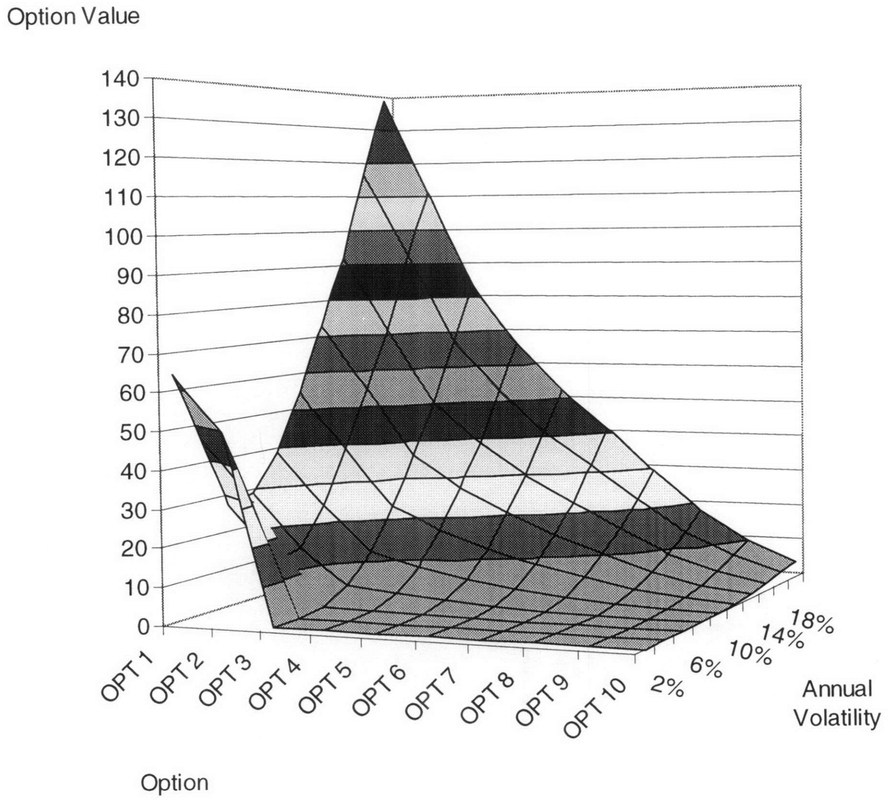

Figure 5.5b: Scenario 3. Options value as a function of volatility.

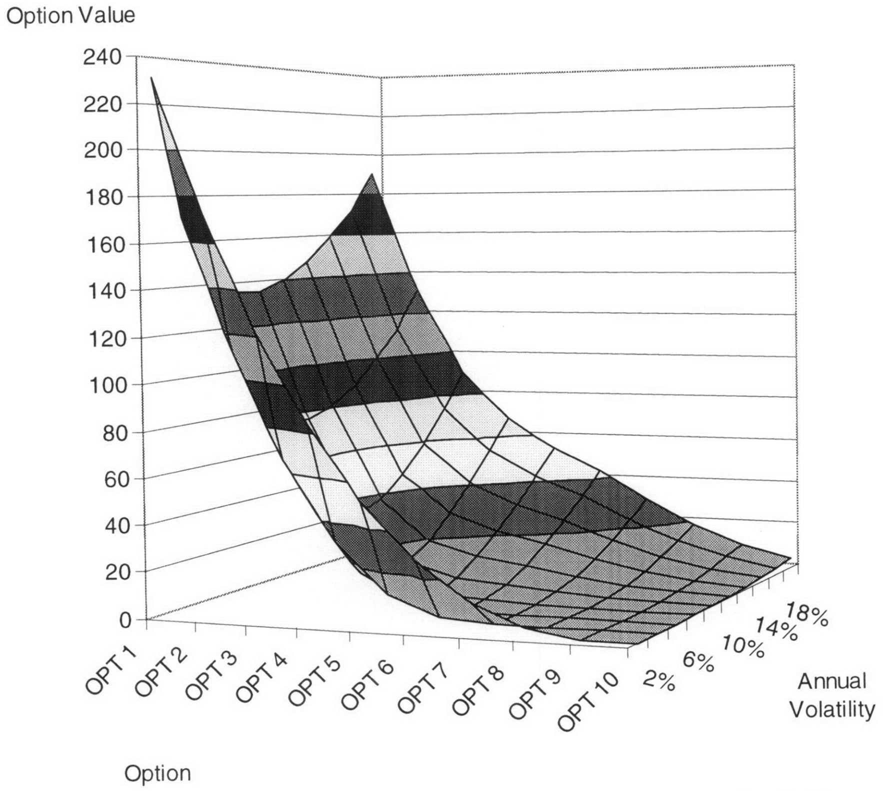

Figure 5.5c: Scenario 3. Options value as a function of volatility.

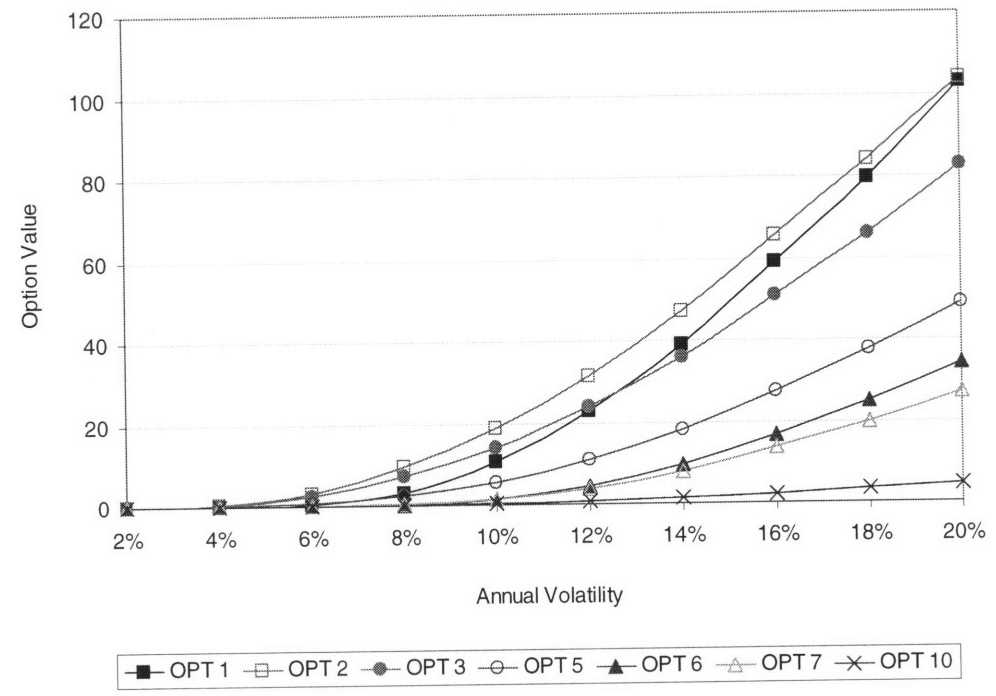

Figure 5.6a: Scenario 1. Options value as a function of volatility.

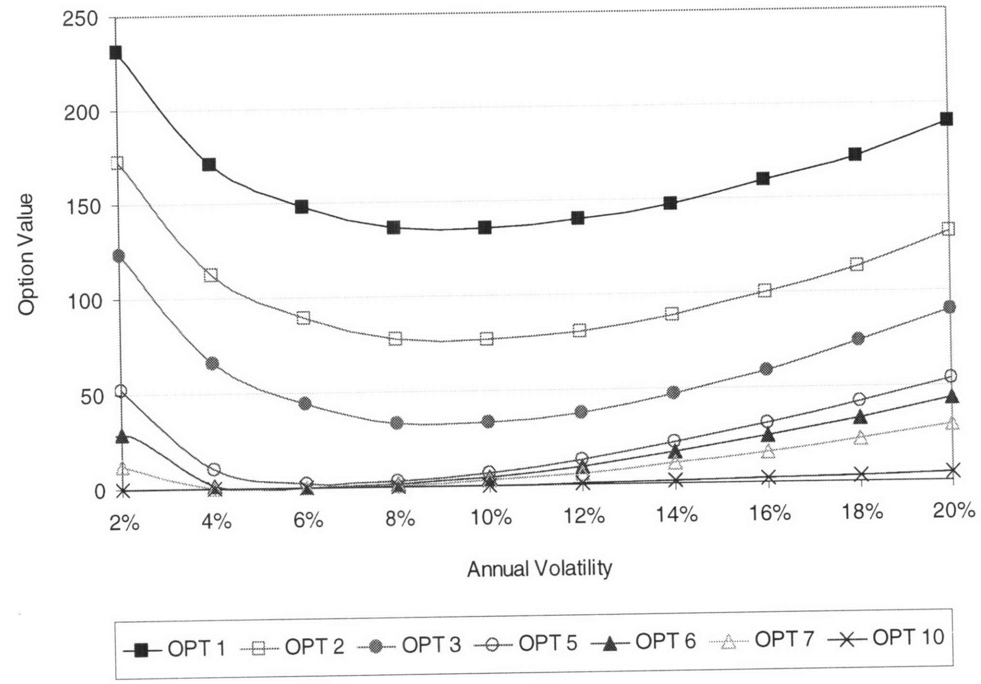

Figure 5.6b: Scenario 3. Options value as a function of volatility.

- *Risk free rate of interest*

Figure 5.7 shows option value as a function of the risk free rate for the first scenario (similar curves are observable for the other scenarios). As explained in Section 4.1.3, in the binomial model the condition $d < r < u$ must apply to avoid arbitrage opportunities. Therefore, for a 12% annual volatility, our analysis is limited to a 6% annual risk free rate.

If the risk free rate of interest, r, increases, the options values increase. Dixit and Pindyck (1994) provide the following rational to explain this variation: The present value of the capital expenditure k made at time j is ke^{-rj}, but the present value of the one unit of capacity, ΔV, received at time j is $\Delta Ve^{-\delta j}$. Hence, if the payout rate δ is fixed, increasing r reduces the present value of the cost without affecting the present value of the underlying asset. On the other hand, we note that for sequential compound options, increasing r reduces the present value of the inactive options (Section 4.1.3). Those two opposing effects result in the convex curves in Figure 5.7.

Dixit and Pindyck (1994) further note that while an increase in the risk free rate raises the value of the firm's option to invest, it also results in fewer of these options being exercised. As a result, higher interest rates reduce actual investment by increasing the opportunity cost of investing now. In the standard NPV valuation model, higher risk free rate also reduces the amount of investment by increasing the cost of capital.

- *Initial value of the underlying asset*

As expected, increasing value of the underlying asset at time zero increases the value of the firm's investment opportunity (Figure 5.8). Moreover, for the first scenario, a high enough initial value of a unit of capacity pushes the first option in-the-money and above the value of the third and second options (compare Figure 5.8a with Figure 5.1a).

Finally, irregularities in the curves and surfaces presented in this Chapter are due to the discrete nature of the investment decisions and modeling approximations. In particular, the change in slope occurring at OPT6 observable in Figures 5.1a, 5.2a and 5.5a is due to the change the options maturity (10 years for OPT1 to OPT5 and 20 years for OPT6 to OPT10). This change is more sensitive for the first scenario: on the one hand, the options are deep-out-of-the-money, which tends to delay investment decisions; on the other hand the exercise is forced after ten years, which increases the value of OPT 5 to OPT1 (hence the change in slope).

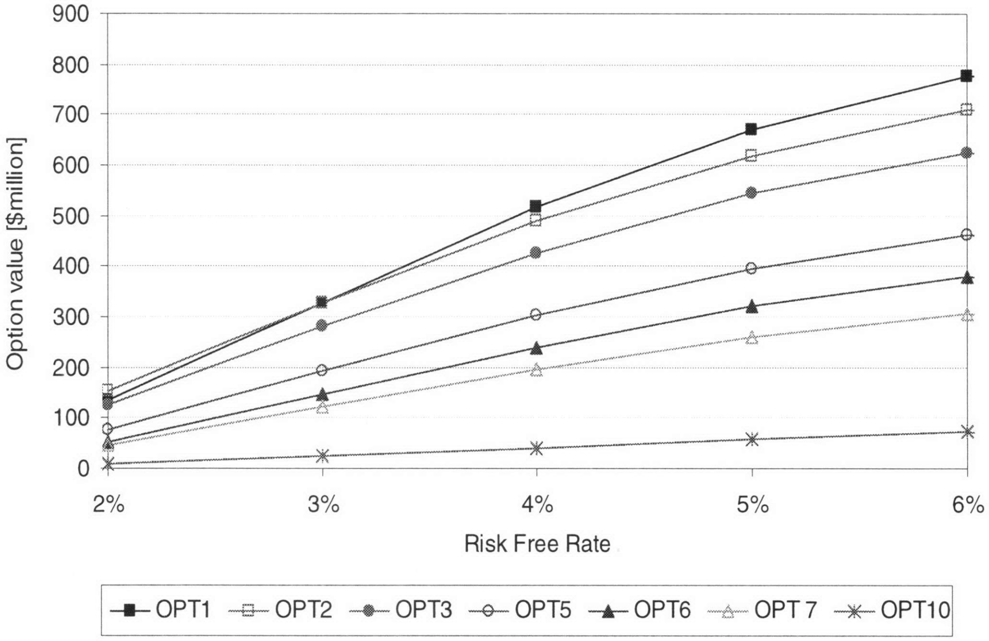

Figure 5.7: Scenario 1. Options value as a function of the risk free rate of interest, $\sigma = 12\%$, $\delta = 10\%$.

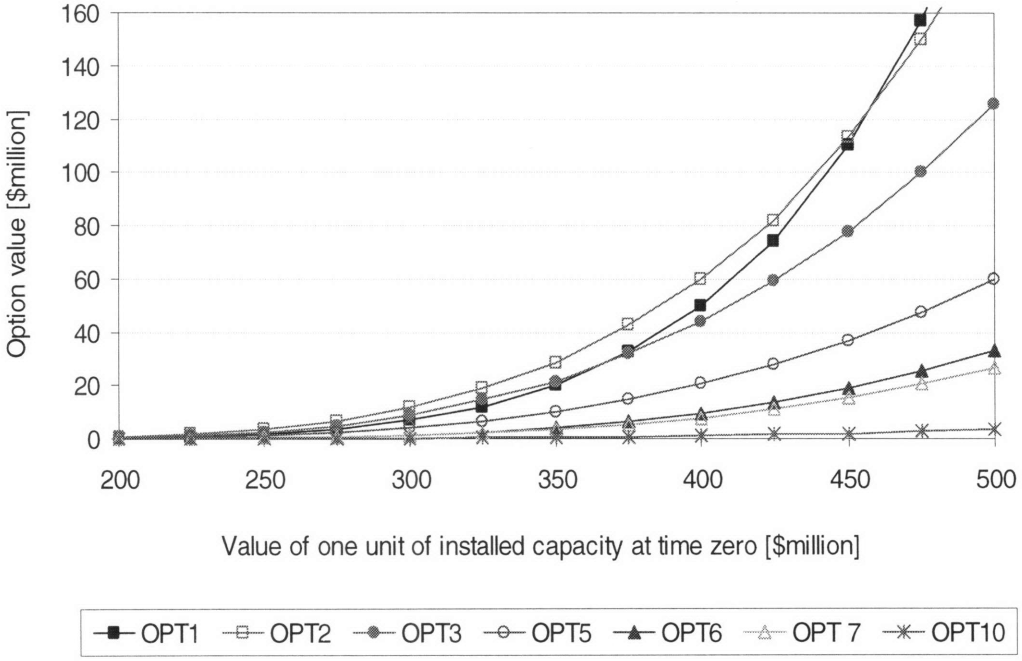

Figure 5.8a: Scenario 1. Options value as a function of the initial value of one unit of installed capacity, $\sigma = 12\%$, $\delta = 10\%$.

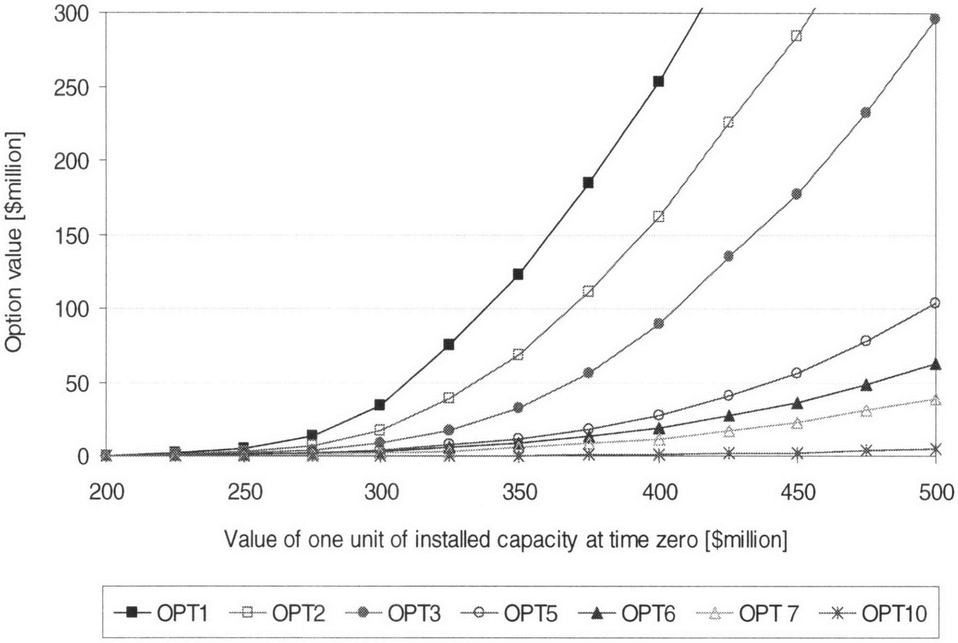

Figure 5.8b: Scenario 3. Options value as a function of the initial value of one unit of installed capacity, $\sigma = 12\%$, $\delta = 10\%$.

Chapter 6 Conclusions and Recommendations

The opportunity provided by the modularity of the Modular Pebble Bed Reactor (MPBR) technology to add incremental capacity is analyzed and valued in this Thesis as a series of *sequential compound options*. Our contribution is twofold. First, we demonstrated that, at any point in time, the value of a modular nuclear power plant has two components: the value of the installed capacity and the value of the firm's option to add capacity incrementally in the future. Second, we contributed to the real options literature by developing an algorithm that simplifies the analysis of sequential compound options using binomial trees.

The additional source of value given by the option to add capacity incrementally cannot be captured by a standard discounted cash flow (DCF) valuation. The traditional Busbar cost approach used in the power industry relies on a static DCF analysis of the costs of producing electricity averaged over the life cycle of the plant. Therefore, the Busbar cost analysis is inappropriate to value modular electricity-generating capacity because it simply ignores the expansion option, which can represent a significant source of economic value and affect investment decisions. A real option analysis constitutes a better tool to value the flexibility to expand capacity incrementally offered by the modular technology.

We demonstrated that the value of the firm's option to incrementally add capacity is particularly sensitive to the cost of the first module relative to the following ones. In particular, we showed that the value of the expansion option is higher if the cost of each module is the same. For example building oversized peripheral support facilities significantly increases the capital cost the first module as compared with the following ones and, therefore reduces the value of the firm's option.

This result has the following important implication for the future development of the MPBR system. As noted in Section 5.1.1, the design of the peripheral support facilities and the construction sequence of a MPBR plant are still under consideration and no prevailing solution has been developed yet. Nevertheless based on the numerical simulations presented in Chapter 5 we recommend that the concept of modularity, which is already applied to the nuclear and electric components of the plant, be extended to the design of the peripheral facilities. These facilities should be developed by stages to support the installed capacity following the construction schedule of the modules regardless of future eventual additions. Then by adopting a modular design for the peripheral facilities the costs of these facilities will be spread among the modules with the tendency of equalizing the per module capital cost. Moreover, the overall plant layout should also be designed to allow for timely and low cost capacity expansion. All those recommendations are to reduce the cost of the first module and to equalize the per module capital cost, therefore increasing the value of the option to add capacity incrementally In addition from a financing perspective, minimizing initial capital investment also decreases financial charges and reduces the capital at risk, making the investment more attractive.

In this respect, the sequential compound options model developed in Chapter 4 provides a tool to compare different design scenarios: the best design being the one that maximizes the value of the firm's expansion option.

The analysis of sequential compound options is a path-dependant problem particularly difficult to resolve using a binomial model. Our approach suggests a simplified algorithm to deal with the path-dependent problem with the advantage of yielding a lower bound for the options value. However, we must point out here that some results in our analysis are controversial; in particular, the effect of the underlying asset's volatility should be analyzed more closely before the proposed algorithm be used in practice[1].

Real option analysis is independent of personal risk preference and especially suitable for electricity-generating assets as market information is readily available. Practical use of real option analysis requires however careful valuation of the underlying asset and proper estimate of its volatility. We took a simplified approach that is sufficient to demonstrate the value of incremental capacity expansion but would not be suitable for an applied valuation. In particular, a more precise approach would require an appropriate stochastic model to describe the evolution of electricity prices.

Finally, we would like to extend the conclusions of this study to some notable policy implications. First, we reiterate the argument made by Thomas (1992) that real options analysis should be considered as a relevant tool for the selection of electric power systems, and more particularly for the evaluation of the next generation of nuclear power technologies. We also recommend that real options analysis be incorporated in the regulatory framework that governs technology selection and capacity expansion decisions in the electric power industry. In particular for the MPBR technology, the flexibility to add capacity on a timely basis is highly dependant upon the nuclear regulatory framework. We emphasize that it is essential for the Nuclear Regulatory Commission (NRC) to recognize that the MPBR design concept requires new regulations that ultimately will lead to standard design certification. The recent steps taken by the NRC go in this direction and should be continued.

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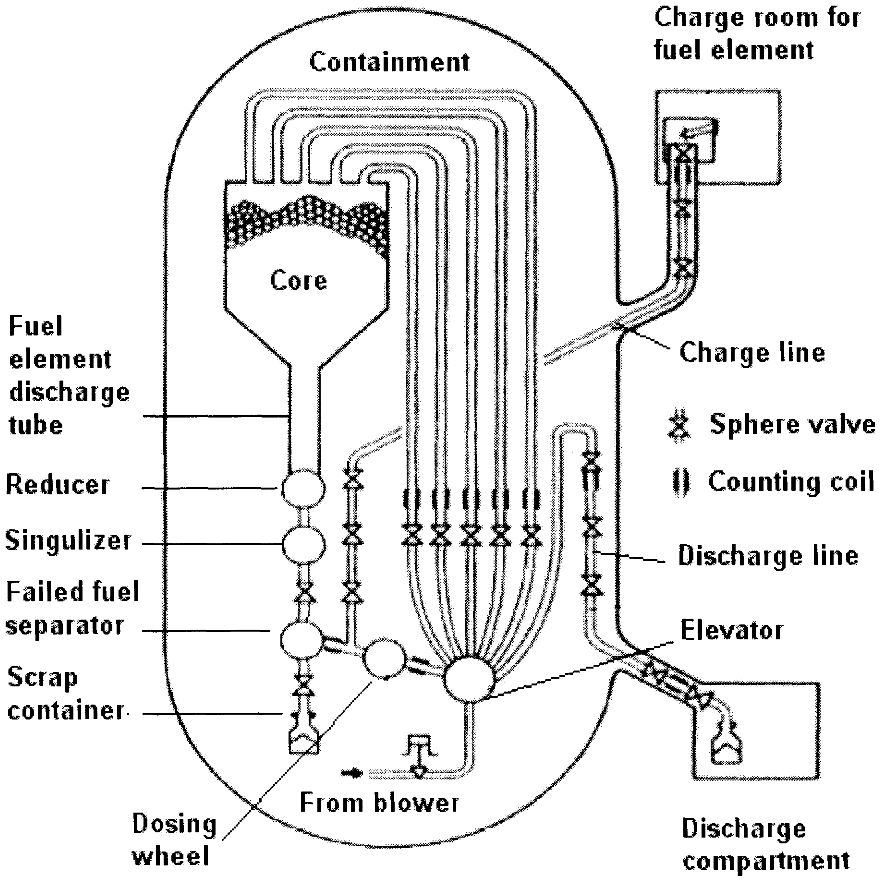
[1] See Section 5.4, sensitivity analysis on the volatility.

Appendix

Modular Pebble Bed Reactor – MIT-INEEL Design

- Reactor design

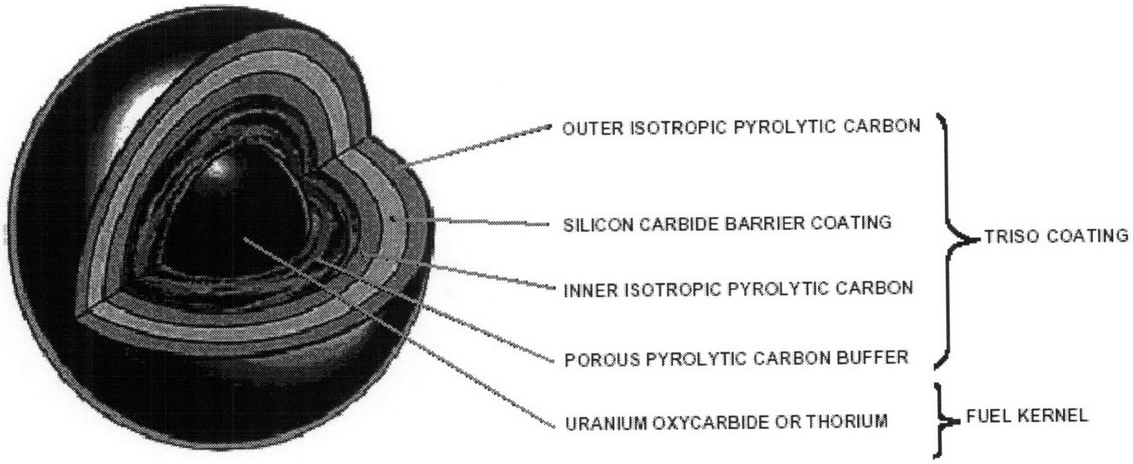


- Main design specifications:

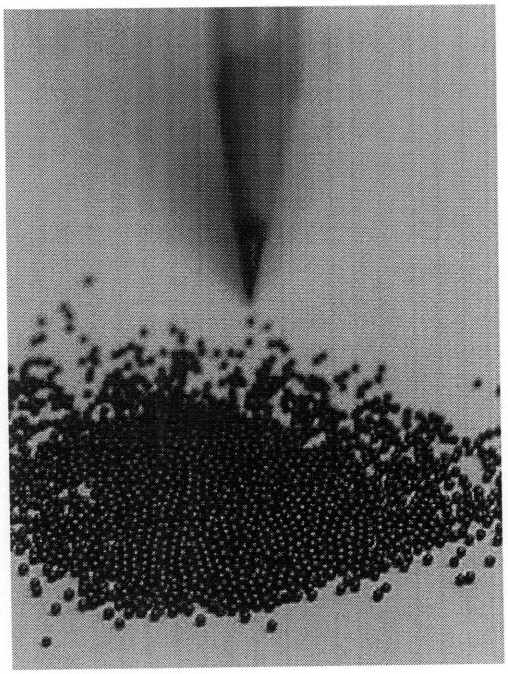
Thermal Power	250	MWt
Net electrical Rating	110	Mwe
Core Height	10	m
Core Diameter	3	m
Pressure Vessel Height	16	m
Pressure Vessel Diameter	5.6	m
Number of Fuel Pebbles	360,000	
Fuel Pebble Diameter	60	mm
Fuel	UO_2	
Fuel Enrichment	8	%
Uranium Mass per Fuel Pebble	7	g
Coolant	Helium	
Coolant Flow Rate (100% power)	120	kg/s
Helium Entry/Exit Temperatures	450/850	°C
Helium Pressure	80	bar
Mean Power Density	3.54	MW/m^3
Number of ControlRods	6	
Numer of Absorber Ball Systems	18	

- Current estimates for major components size:
  - Reactor core: 10.0m x 3.0m
  - Reactor Pressure vessel: 16.0m x 5.6m
  - IHX: 3.5m 6.0m
  - Precooler: $8.5m^3$
  - Gas turbine HP turbine 3 stage, maximum tip diameter 0.9m, 3m long
  - LP turbine 6 stage, maximum tip diameter 1.71m, 0.86m long
  - Compressor 15 stage, maximum tip diameter 0.73m, 1.3m long
  - Generator: rotor diameter 1.24m, 3.5m long.

- Fuel pebbles



- Size of the uranium fuel elements embedded in the pebbles.



Sources: Kadak 2001, a, b and c, and Kadak 1998b.

Modular Pebble Bed Reactor:

Construction Flow Path for a Standard Unit

Step	Event	Description	Timeline [weeks]
0	Initial interest	The clock starts	0
1	Negotiation	It is estimated that standard negotiations will take three months from the time the potential buyer indicates interest in purchasing a plant.	12
2	Construction order	Construction order is placed within one month of the completion of negotiation.	15
3	Site selection	It is assumed that the buyer already knows where he would like to build the plant.	18
4	Unit specific design work	It is assumed that 80% of the design is complete (standard design). The remaining design work is only for siting conditions such as soil conditions.	31
5	License Application	The standard design has previously obtained NRC design certification.	31
6	License Approval	A three-month period for public opposition is required by law. In case of opposition, the license approval process could be prolonged.	43
7	Purchase order	Because the design is standard and pre-negotiated contracts with vendors are in place, it is assumed that it will take two weeks to place the order with the vendor.	45
8	Components fabrication	This represents the longest time required for any of the plant component being fabricated in parallel. Turbines and reactor vessels take 9 months to fabricate. Any fabrication delay past 9 months will create an overall delay in the delivery of the plant.	84
9	Module assembly	It is assumed that once all components have been fabricated, a module can be assembled and tested in 6 months. It is also assumed that the factory is capable of having two modules in progress at the same time, completing the n+1st module within three months of the nth.	110

10	Site preparation	This represents the time for the longest activity required to support initial module assembly. Foundation work is the limiting item and is assumed to take a minimum of 1 year and a maximum of 2 years. Site preparation is conducted in parallel with components fabrication.	112
11	Shipment	It is assumed 1 month (after activity 9) for shipments within the continental U.S. (3 months outside the U.S.)	114
12	Site Assembly	Once the site is ready, it is assumed that a unit can be moved into place and connected within 9 months.	
13	Permanent staffing	Staffing includes hiring and training of workers that will operate and maintain the plant. Reduced design and regulatory complexity enables staff preparation in 18 months.	119
14	Construction time	Time between beginning of construction and start of operation of the unit.	121
15	Testing & Fuel loading	Because most components can be tested in factory, the only site testing required are an operability test and a core test after fuel load. The pebble bed also makes fueling much faster. This step is assumed to take 3 months.	162
16	Operation	An additional one-month period is added to account for eventual adjustments after testing and production ramp-up.	166

Source: Kadak (1998b).

Steps 0 to 16 are required for the first unit, corresponding to a total construction time of 166 weeks. For the following modules, only steps 7 to 16 are required corresponding to a construction time of 123 weeks.

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