A Systems Analysis of Spent Nuclear Fuel Management and Storage

使用済核燃料管理・貯蔵のシステム分析

２００２年１１月

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CONTENTS

Executive Summary

Spent nuclear fuel discharged from nuclear power reactors has accumulated to a considerable amount in Japan and the other countries with nuclear power generation stocks, which will lead to risks of their overflow beyond the existing management capacities at those nuclear power plants. If such overflow happens, the power plant has to be shut down until appropriate measures have been taken. Meanwhile, uncertainties have accumulated surrounding final treatment facilities, either reprocessing or geological disposal, reflecting difficulties to find appropriate sites caused by oppositions of local and/or general public and other factors. As a result, spent nuclear fuel has to be stored for the time being in interim devices for a certain time period, e.g. 20 years to 40-50 years, until such time that they can be moved to their final destination.

The objective of this dissertation is to review theoretical background and thoughts relevant to policy considerations on spent nuclear fuel management and storage ranging from their discharge to final treatment, to obtain quantitative images, and ultimately to present desirable policies and their implications in medium and long range in Japan. Essential key questions to be addressed here include the following, to which the dissertation presents first the theoretical framework to obtain answers and then answers at the moment while encompassing underlying uncertainties:

- When and to what extent spent nuclear fuel storage will be required, and which type of technology options should be applied?
- How long should it be the appropriate storage duration? How does it connect to the overall nuclear fuel cycle program?
- Which should be chosen, AR (At Reactor) storage, AFR (Away From Reactor) storage or a combination of both?
- How will it cost?
- How will the price for storage services be determined?

After presenting these objectives and key questions in Chapter 1, the dissertation first discusses in Chapter 2 the present status of spent nuclear fuel management in Japan, which clarifies where the dissertation stands at this moment. As spent nuclear fuel accumulates at all the nuclear power plants in Japan, enhancement measures of the management capacity, such as re-racking, have already been implemented by now where available. Since opportunities for further enhancement are narrow and scarce, implementation of AFR storage is justifiably needed in an appropriate time range. In fact, relevant institutional developments, namely policy formulation, such as statements

in the Long-term Program of Research, Development and Utilization of Nuclear Energy, as well as legislation, especially the amendment of the Law for Regulation of Nuclear Reactors, Nuclear Facilities and Nuclear Materials, have already been completed and implemented. This clearly justifies the needs for the policy analyses in this dissertation, such as strategic planning of storage projects and their economic assessments.

Chapter 2 also deals with the historical evolutionary patterns of spent nuclear fuel storage technologies. Various types of storage technique have been developed and are now available. Recently, new dry storage techniques, which are characterized as a combination of metal canisters and concrete blocks including concrete cask storage and horizontal silo storage, are receiving higher shares in the market. The analysis of the historical patterns of worldwide market penetration of various techniques, however, has found no clear sign of retirement of any technology from the global market, while each technique has comfortably found its own "*niche*" with its own strength and special features to form cohabitation of all. This may reflects the very characteristics of spent nuclear fuel storage market with limited number of projects for long lifetimes. This observation at this moment, meanwhile, does not rule out possibilities of different patterns of market evolution to take place in the future, since the world market will expand whilst choices of techniques will be put more on invisible hands of market economy.

Chapter 3 presents the energy and nuclear fuel cycle modeling frameworks, with which the author attempts to describe optimal patterns of nuclear fuel cycle management in harmony with nuclear energy utilization pathways. Chapter 3 starts with the development of Fuel Cycle Optimization Model (FCOM) and extends to its integration with the LDNE21 global energy model, in order to analyze spent nuclear fuel management in an overall framework of nuclear fuel cycle and the global energy system. FCOM solves a long range (90 years) cost minimization problem of the LWR (light water reactor) – FBR (fast breeder reactor) symbiotic system based on linear programming. The optimal solution provides a desirable evolutionary pattern of plutonium (Pu) economy with Pu supply from reprocessing of spent LWR fuel as its key parameter. FCOM's superb feature is, despite a compact model, to obtain an optimal solution of management of spent LWR fuel integrated with reactor mix patterns. Through numerical experiments, it is concluded that spent LWR fuel storage is chosen to adjust future uncertainty as it gives flexibility to the whole nuclear fuel cycle to allow spent LWR fuel reprocessing according to Pu demand. The illustrative simulation runs showed that, while reprocessing of spent LWR fuel is undertaken in accordance with Pu demands, storage of spent LWR fuel provides the adjustment function between Pu supply and demand. This means that storage of spent nuclear fuel should be chosen actively as a measure to cope with uncertainty towards future as it gives flexibility to the management and operation of the whole nuclear fuel cycle.

Chapter 3 further extends to the integration of FCOM with the long-range global energy model LDNE21 (Linearlized Dynamic New Earth 21). In this application, FCOM serves as a nuclear energy sub-model within the LDNE21 framework, which analyzes optimal global energy pathways in terms of minimum discounted total system costs up to the year 2100 under a certain set of global environmental and other constraints. The illustrative simulation runs showed that, under a constraint of atmospheric concentration of carbon dioxide (CO_2) to be kept below 550ppm in the year 2100, the optimal global energy strategy will be chosen under competition between nuclear power generation and combined cycle generation by coal. This underscores the importance of nuclear fuel cycle and spent nuclear fuel management modeled in FCOM against global energy pictures. Meanwhile, necessity of global shift towards Pu economy does not necessarily maintain.

Chapter 4 presents a theoretical analysis of optimal choice of storage duration. In this analysis, the fundamental roles and benefits of storage are understood as twofold; 1) postponement of subsequent processes, which leads to a decrease of present value of those costs, and 2) gains through R&D by earning time with storage. As the result, there could appear an optimal storage duration, which equalizes the following two indices; a) the incremental storage cost for 1 more year, in other words the marginal cost, and b) the increase of the sum of above mentioned benefits, or the marginal utility, through 1 year extension of storage. In the case of uncertainty, this optimal storage duration is prolonged accordingly through a risk-averse attitude. These findings stand also in the case of direct disposal of spent nuclear fuel. This analysis, however, omits certain factors such as specific lifetimes of storage containers and/or facilities, or societal anxieties, which may lead to additional costs when storage duration is prolonged.

Chapter 5 deals with the methodologies of material balance calculation ranging discharge, storage, transportation and final processing of spent nuclear fuel. They are categorized into the following two kinds; 1) a microscopic accounting for each power station site or each power utility company, and 2) a macroscopic analysis, either simulation or optimization, in a region-wide or nationwide scale. In Chapter 5, development of a Japan-wide simulation tool SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System) is discussed. SFTRACE is mainly based on the 2nd methodology while taking the 1st microscopic accounting aspect fully into account. The illustrative simulation runs revealed various trade-off relations, such as the one between storage capacity to be installed and transportation requirements, the other among geographic coverage of AFR storage facilities as to whether to construct one to serve all over Japan or several to serve segmented regions. These trade-offs clearly demonstrate the necessity and usefulness of integrated analytic tools such as SFTRACE.

Chapter 6 discusses the framework of economic analyses of spent nuclear fuel storage. Based on the methodological review of the following three categories, numerical applications are presented for each of them; 1) an engineering-economic cost calculation to assess levelized unit costs, 2) a total cost assessment with strategic planning, and 3) a project financing appraisal and storage price induction. Based on latest sets of data and information, the levelized unit storage costs lay in a reasonable range of 30-70 kJPY/kgU, which corresponds to 0.07-0.17 JPY/kWh at burnup of 49,000MWd/tU with no discounting applied between power generation and storage. With the strategic planning application, several key parameters are identified such as the geographic coverage of AFR centralized storage devices, economy of scale and others. Finally, the project financing appraisal method is applied to explore viable storage pricing schemes which maintain the project of 5,000MTU metal cask storage facility as healthy enough against financial criteria. Because of the highly investment intensive nature of the project, a combinatory pricing scheme of storage service is highly recommended with an initial payment upon receipt of spent nuclear fuel at the storage facility and annual fee payments per unit of spent nuclear fuel stored for each year of storage duration.

As the conclusion of the analyses described in these Chapters, policy recommendations are presented in Chapter 7 for planning and implementation of spent nuclear fuel management in Japan. The demand of spent nuclear fuel storage will increase steadily and rapidly, to reach 7,000-10,000MTU by the year 2020 to 2030. In 2050, uncertainties surrounding spent nuclear fuel management will also accumulate. In a most likely scenario, the storage demand will level off at around 10,000MTU after 2020-30 to 2050, which suggests storage capacity of 10,000MTU must be installed by the year 2020. As concerns to the storage duration as well as the long-term planning of spent nuclear fuel management, unless utility values of Pu uses will improve significantly, processes after storage should be planned with reference of lifetime expiration of the storage facility.

要旨

日本をはじめとして、原子力発電を行っている多くの国々においては、個々の原子力発電所サイトでの使用済燃料蓄積の増大により既存の管理貯蔵容量の逼迫を来たし、ある時点で原子炉の運転停止を余儀なくされるリスクを生じている。その一方で、一般公衆の反対や立地点の確保が不可能なことなどにより、使用済燃料の最終処理施設（再処理施設ないし最終処分場）の円滑な建設、運転の困難や不確実性を増しており、このことにより、使用済燃料はその最終処理方法の如何によらず、その最終処理が可能となるまでの間、たとえば20年から40-50年程度、中間的に貯蔵することを迫られている。

本論文の目的は、使用済燃料の発生から消滅に至る管理・貯蔵に関わる様々な政策検討を構成する理論的背景を整理し、定量的描像を構築することによって、日本として中長期的な使用済燃料管理・貯蔵戦略立案と、その実施に向けた政策上の留意点を明らかにすることにある。使用済燃料管理問題に関わる本質的な論点には、以下が挙げられる。本論文は、これらの問いに対する解答を得るための理論的枠組みを示した上で、現時点での解答を、介在する不確実性に留意しつつ提示する。

- 使用済燃料貯蔵は、どの時点から、どの程度の規模で必要となるか。また、どのような技術が採用されるべきか。
- 適切な貯蔵期間はどの程度か。また、核燃料サイクル計画全体との関連はどうか。
- 敷地内(At Reactor, AR)貯蔵、敷地外(Away From Reactor, AFR)貯蔵のいずれ、またはそれらの組み合わせを選択すべきか。
- 貯蔵コストはどの程度か。
- 貯蔵サービス提供価格はどのように定められるべきか。

本論文は、最初に日本における使用済燃料管理の現状について述べ、本論文の位置付けを明らかにする。日本の原子力発電所各サイトでは使用済燃料が蓄積する一方で、発電所の既存の管理貯蔵容量の増強措置（リラッキング等）がすでに採られてきており、新たな貯蔵施設の設置を含むAR貯蔵増強措置を実施できる余地は極めて限られているため、AFR貯蔵の着実な整備が求められている。実際に、所要の政策（原子力の研究・開発及び利用に関する長期計画での明文化）及び立法措置（とりわけ原子炉等規制法の改正）が採られた結果、現在までに、敷地外貯蔵事業の実施へ向けた制度の整備が完了している。このことから、本論文が対象とする政策研究、とりわけ使用済燃料貯蔵事業の戦略立案、経済性評価などの研究の必要性が明らかである。

使用済燃料貯蔵技術は、これまでに各種の方式が開発されている。最近では、

乾式新技術（金属キャニスタとコンクリート躯体の組み合わせによる貯蔵方式、コンクリートキャスクやサイロ貯蔵など）が徐々に市場シェアを伸ばしつつある傾向が観察され注目されるものの、過去の施設設置の実績を分析した結果、世界の市場においてはある技術方式が淘汰され市場から退出する現象は観察されず、これまでのところ各方式ともに独自の特徴を活かしつつ、各々の“*niche*”市場を確保する形での「棲み分け」が形成されている。これは、技術の寿命が長く、また市場規模が比較的限られているという使用済燃料貯蔵技術分野の特質を反映したものと考えられる。しかしながら、将来的には市場の世界的拡大も予想され、技術の選択が市場に委ねられた結果、従来の競合過程と異なる新たな状況が出現する可能性も否定できない。

次に、核燃料サイクル全体との関連を考察するため、プルトニウム(Pu)リサイクル利用評価が可能なモデルを開発し、これを長期世界エネルギーモデルと組み合わせて分析・評価した。まず、燃料サイクル最適化モデル FCOM (Fuel Cycle Optimization Model)は、長期間（90 年間）の軽水炉(LWR)－高速増殖炉(FBR)の共生システム（L-F 共生系）の費用最小化問題を線形計画法に基づいて解くモデルであり、Pu 経済の本格化の過程を、軽水炉使用済燃料の再処理による Pu 供給を鍵として描き出す。FCOM の特長は、コンパクトなモデルでありながら、使用済燃料貯蔵（AR 及び AFR）と再処理から成る軽水炉使用済燃料管理問題を明示的かつ炉型構成問題と一体として扱って最適解を得ることにある。評価の結果、Pu 需要に応じた軽水炉使用済燃料再処理が実施される一方で、使用済燃料の貯蔵が Pu 需給調整の機能を発揮することが明らかになり、使用済燃料貯蔵は燃料サイクル全体の運用に柔軟性を与える重要な意義を持ち、将来の不確実性への対処のための手段として積極的に選択されるべきことが示された。併せて、FCOM を世界エネルギーモデル LDNE21 と統合したモデル分析を試みたところ、たとえば 2100 年時点の大気中 CO_2 濃度を 550ppm 以下にしなければならないという制約条件の下での世界のエネルギー戦略において、原子力は 21 世紀後半に石炭コンバインドサイクル発電との競合関係の下に置かれ、上述の意味での燃料サイクル整備や使用済燃料管理の重要性が世界のエネルギー情勢の展望からも明らかとなった。一方、モデル分析によれば、世界的な Pu 経済への移行は必ずしも必要とされていない。

貯蔵期間の最適選択に関わる理論的考察においては、貯蔵の根本的な意義と役割を以下の 2 点に集約的に着目して分析した。1) 貯蔵以降のプロセスの実施を遅延することによる、同費用現在価値の低減、2) 貯蔵の実施により獲得した時間における研究開発の実施。解析結果によれば、ある貯蔵期間において、貯蔵をさらに 1 年延長する増分費用と、1 年延長に伴う上述の 2 つのベネフィットの増分の和が等しくなるとき、すなわち限界費用と限界効用が等しくなるときに貯蔵期間は最適となり、また、不確実性の介在により貯蔵期間の長期化とい

うリスク回避的対応が発生することが明らかとなった。なお、この事実は再処理をしないで直接処分をする場合でも変わらない。ただし、貯蔵容器や施設の寿命、また、社会的不安の拡大など、貯蔵の長期化によって新たな費用が発生することも考えられるが、本解析では考慮されていない。

使用済燃料の発生、貯蔵、輸送、消滅に関わる物量評価の方法論は、大別して次の2種に分類される。1) 発電所サイト、あるいは電力会社単位のミクロ評価、2) 全国大のマクロ評価（シミュレーション及び最適化)。本論文では、日本全国を対象とする評価ツール SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System)を開発した。これは、主として第2の全国大マクロ評価の考え方に立ちつつ、第1のミクロ評価の視点も十分に取り入れたものである。モデル検証のための試算では、使用済燃料管理問題における種々のトレードオフ関係、たとえば所要の貯蔵設備容量と輸送必要量のトレードオフ、AFR 貯蔵施設の地理的対象範囲（日本全体をカバーする集中型施設を一つだけ設置するか、地域的に分割した複数の施設を設置するか）と貯蔵容量のトレードオフなどが存在することが示され、SFTRACE のような統合型評価ツールの有効性が明らかになった。

使用済燃料貯蔵の経済性評価手法は、大別して以下の3種に分類される。1) 技術経済的積み上げ手法に基づく均等化コスト評価、2) 戦略評価に基づく総システム費用評価、3) プロジェクト収支評価と貯蔵費用算定。最新の情報に基づいた試算によれば、均等化貯蔵コストは貯蔵方式や貯蔵規模によって異なるが概ね 30-70 千円./kgU の範囲と評価されており、これは燃焼度 49,000MWd/tU 及び発電時点と貯蔵時点の時間差に伴う割引を考慮しない条件で、0.07-0.17 円/kWh に相当する。戦略評価に基づく総システム評価から、たとえば AFR 貯蔵の地理的対象範囲と規模の経済性などの重要なパラメータの存在が示唆された。最後に、プロジェクト収支評価においては、貯蔵規模 5000MTU の敷地外金属キャスク貯蔵施設を想定した試算により、貯蔵事業として成立し得る貯蔵料金設定について評価した。貯蔵事業は優れて設備投資集約的な事業であり、事業初期に支出が集中する。この性質のため、財務的制約条件を満たしつつ合理的な経営を実現する上で、貯蔵料金設計においては使用済燃料の貯蔵施設受け入れ時一括払い、貯蔵期間中の年あたり一定額払いの双方を加味した混合料金制が望ましいことが示された。

以上の分析を総合して、今後の日本の使用済燃料管理において念頭におくべき政策提言を示せば、以下のとおりである。使用済燃料貯蔵需要は今後急激に増大し、2020-30 年までに 7,000-10,000MTU 程度に達する。2050 年にかけて、貯蔵需要を巡る不確実性もまた増大するが、最尤度シナリオにおいては 10,000MTU 程度で貯蔵需要が高止まりすると想定されるため、2020 年までに 10,000MTU 程度の貯蔵施設設置を目指すべきである。貯蔵期間及び核燃料サイ

クルの長期計画については、Pu 利用の効用に大きな好転がない限り、貯蔵施設の設計寿命（40-50 年）を目安として、貯蔵以降の過程への移行を計画することが現実的である。

CHAPTER 1

Background and Objectives

1. Background and Objectives.

Spent nuclear fuel discharged from nuclear power reactors has accumulated to a considerable amount in Japan and the other countries with nuclear power generation stocks, which will lead to risks of their overflow beyond the existing management capacities at those nuclear power plants. If such overflow happens, the power plant has to be shut down until appropriate measures have been taken. Meanwhile, uncertainties have accumulated surrounding final treatment facilities, either reprocessing or geological disposal, reflecting difficulties to find appropriate sites caused by oppositions of local and/or general public and other factors. As a result, spent nuclear fuel has to be stored for the time being in interim devices for a certain time period, e.g. 20 years to 40-50 years, until such time that they can be moved to their final destination.

The objective of this dissertation is to review theoretical background and thoughts relevant to policy considerations on spent nuclear fuel management and storage ranging from their discharge to final treatment, to obtain quantitative images, and ultimately to present desirable policies and their implications in medium and long range in Japan. Essential key questions to be addressed here include the following, to which the dissertation presents first the theoretical framework to obtain answers and then answers at the moment while encompassing underlying uncertainties:

- When and to what extent spent nuclear fuel storage will be required, and which type of technology options should be applied?
- How long should it be the appropriate storage duration? How does it connect to the overall nuclear fuel cycle program?
- Which should be chosen, AR (At Reactor) storage, AFR (Away From Reactor) storage or a combination of both?
- How will it cost?
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After presenting these objectives and key questions in Chapter 1, the dissertation first discusses in Chapter 2 the present status of spent nuclear fuel management in Japan, which clarifies where the dissertation stands at this moment. Chapter 2 also deals with the historical evolutionary patterns of spent nuclear fuel storage technologies, which are intended to be useful to explore dynamics of choices among storage techniques in the future.

Chapter 3 presents the energy and nuclear fuel cycle modeling frameworks, with which the author attempts to describe optimal patterns of nuclear fuel cycle management in harmony with nuclear energy utilization pathways. Chapter 3 starts with the development of Fuel Cycle Optimization Model (FCOM) and further extends to the integration of FCOM with the long-range global energy model LDNE21 (Linearlized Dynamic New Earth 21). In this application, FCOM serves as a nuclear energy sub-model within the LDNE21 framework, which analyzes optimal global energy pathways in terms of minimum discounted total system costs up to the year 2100 under a certain set of global environmental and other constraints. Through sets of illustrative runs, these tools will reveal themselves to be useful for analyzing roles and requirements of nuclear fuel cycle in broader pictures of national and global energy systems.

Chapter 4 presents a theoretical analysis of optimal choice of storage duration. In this analysis, the fundamental roles and benefits of storage are understood as twofold; 1) postponement of subsequent processes, which leads to a decrease of present value of those costs, and 2) gains through R&D by earning time with storage. The theory the author has found suggests that there could appear an optimal storage duration, whose end point is the best to move to subsequent processes, either reprocessing or final disposition. In the case of uncertainty, this optimal storage duration is prolonged accordingly through a risk-averse attitude.

Chapter 5 deals with the methodologies of material balance calculation ranging discharge, storage, transportation and final processing of spent nuclear fuel. After a review of methodologies, development of a Japan-wide simulation tool SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System) is discussed. The illustrative simulation runs reveal various trade-off relations in spent nuclear fuel management systems, which clearly underscore the necessity and usefulness of integrated analytic tools such as SFTRACE.

Chapter 6 discusses the framework of economic analyses of spent nuclear fuel storage. Based on the methodological review, numerical applications are presented for each of the type of methodologies. In particular, the project financing appraisal method is applied to explore viable storage pricing schemes, in which a combinatory pricing scheme of storage service is highly recommended with an initial payment and annual fee, due to highly investment intensive nature of spent nuclear fuel storage projects.

As the conclusion of the analyses described in these Chapters, policy recommendations are presented in Chapter 7 for planning and implementation of spent nuclear fuel management in Japan. By those recommendations, the author wishes to present proper answers to those relevant questions presented above.

The study presented in this dissertation is indeed an interdisciplinary one, combining

engineering expertise with policy orientation, in which there are found little preceding studies. For example, the author participated in an international collaborative study of nuclear fuel cycle back-end policies of member states of IAEA held during 1999-2000, whose results are summarized in IAEA (2002). Most of the inputs tend to have been compilations of factual data and information, lacking capabilities of projecting future scenarios and their sensitivities against key parameters. In particular, spent nuclear fuel management was considered just as practical needs, projected by simple extrapolation of past trends while little attention was paid for future uncertainties and capability to analyze them. It is true that this does not cause any serious problem to a country where the national program is being promoted as a routine with 100% certainty, but it does not quite apply for Japan with the plan to expand nuclear energy output, introduce new types of nuclear reactors and fuel cycle technologies, and yet suffer from social and other difficulties and obstacles time to time.
Such analytical capabilities are usually provided by energy system models, whose history is found long and rich with numerous references, such as "Edmonds and Reilly Model" in Edmonds and Reilly (1985) and Global-2100/MERGE Model in Mann and Richels (1992). Among others, the two most important ones are the WEC (World Energy Congress) 1998 global scenarios presented in Nakićenović et al. (1998) and the IPCC (Intergovernmental Panel for Climate Change) Special Report on Emission Scenarios in IPCC (2000). The analytical tools in these two works, however, dealt with nuclear energy as 'black box' which takes money in and generates energy output accordingly, neglecting technological details of, especially, its fuel cycle. Attempts to incorporate such technical features of nuclear energy are summarized in an IAEA joint study in IAEA et al. (2002), particularly LANL (Los Alamos National Laboratory) Model in Krakowski (1996) and NE21 Model in Fujii and Yamaji (1995), the latter is taken by the author for further extension in Section 3.2. These model analyses adequately took technical aspects and nuclear material balance consideration into account, but not necessarily in sufficient precision or scope so as to allow dynamic nature of nuclear reactor mix and spent nuclear fuel management to be analyzed in a realistic sense and fully integrated in the whole energy system.

In conclusion, appropriate bridging among imaginary model analyses, factual information and policy development has been lacking. This clearly reveals the motive to promote this study, which to provide the missing link in policy analysis of nuclear energy, both analytic tools and policy implications from numerical results obtained from the tools, namely of spent nuclear fuel management as a key aspect in the technology chain of nuclear energy activities.

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CHAPTER 2

The Status and Circumstances of Spent Nuclear Fuel Management

2. The Status and Circumstances of Spent Nuclear Fuel Management.

2.1. Spent Nuclear Fuel Management in Japan.

With years of nuclear energy production and utilization, increasing pressure of spent nuclear fuel arising is receiving a serious attention in Japan in order for those plants keep their operation without causing an overflow of built-in storage pools. There are other key constraints with spent nuclear fuel management, such as the schedule of Japan's first spent nuclear fuel reprocessing plant construction and operation. In a more general context, several accidents in the nuclear facilities, such as sodium leak at Monju fast reactor, asphalt explosion at PNC Tokai reprocessing plant and the latest criticality accident at JCO uranium conversion plant, have made the public increasingly suspicious and distrustful of nuclear power establishment in general. We should clearly recognize such conceptual gaps between the nuclear power establishments and the general public as a crucial constraint to influence nuclear technology development pathways.

This section first discusses about the present situation of spent nuclear fuel management

Table 2.1.1-1: The Spent Nuclear Fuel Stored in NPSs in Japan.

As of March 2001

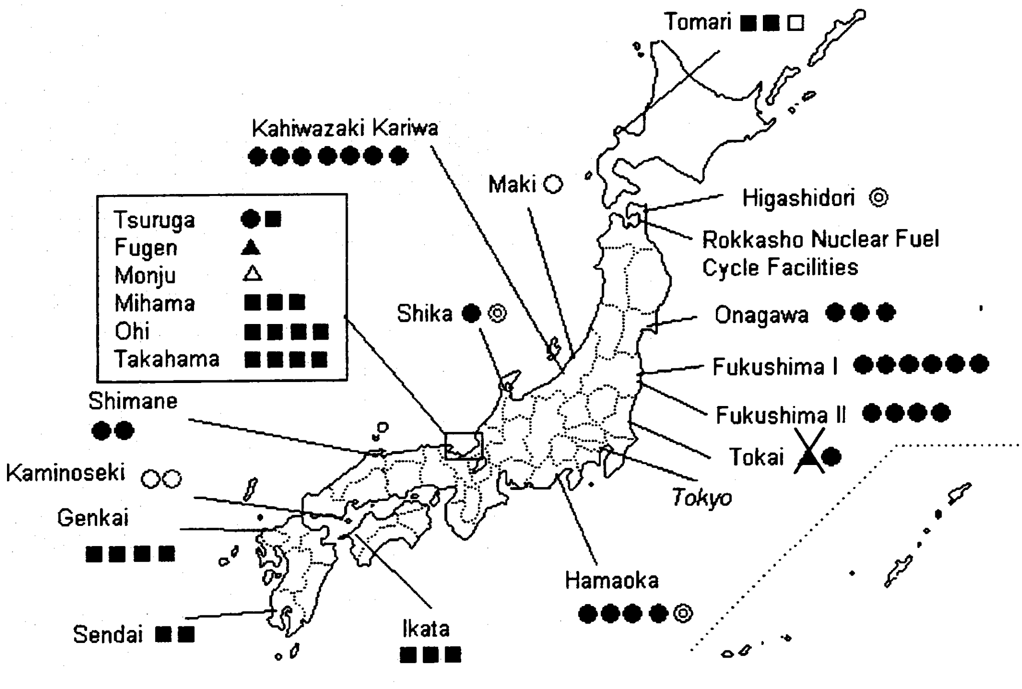
Utility Company	NPS	Loading in Core	Fuel per Batch	SF in Store	Storage Capacity
Hokkaido	Tomari	100	30	250(+10)	420
Tohoku	Onagawa	160	40	200(+10)	370
Tokyo	Fukushima-1	580	150	1140(+40)	2100
	Fukushima-2	520	140	1280(+30)	1360
	Kashiwazaki-Kariwa	960	250	1470(+100)	1890
Chubu	Hamaoka	420	110	730(+10)	860
Hokuriku	Shika	60	20	50(+20)	100
Kansai	Mihama	160	50	280	300
	Takahama	290	100	850(+50)	1100
	Ohi	360	120	740(+70)	1370(+530) *1
Chugoku	Shimane	170	40	340(+70)	440
Shikoku	Ikata	170	60	330	980(+450) *2
Kyushu	Genkai	270	100	420	1060
	Sendai	140	50	580(+10)	900(+200) *3
JAPCo	Tsuruga	140	40	440(+10)	870
	Tokai-2	130	30	220	260
Total		4630	1330	9290(+380)	14380(+1190)

(Source) Federation of Electric Power Companies (FEPC): http://www.fepc.or.jp
- Changes (in parentheses) are from September 2000.
  *1: Re-racking of Unit No.3 and 4.
  *2: Re-racking of Unit No.3.
  *3: Re-racking of Unit No.1 and 2.

in Japan. It continues to review analytic tools of economic analyses of spent nuclear fuel storage, with specific numerical examples of each under the present context of Japanese spent nuclear fuel management. The paper further extends to guidelines for potential users on choice of methodology depending on their specific purposes.

2.1.1. Present Status of Spent Nuclear Fuel Management.

Table 2.1.1-1 shows the present status of spent nuclear fuel accumulation at all the nuclear power stations (NPSs, hereafter) as of March 2001, with changes in 6 months from September 2000. Japan's current nuclear power generation, with a total capacity of 45.9 GWe with 53 reactor units (see Figure 2.1.1-1), discharges about 900 MTU (metric ton of uranium) of spent nuclear fuel per year. This spent nuclear fuel arising primarily accumulates in the reactor pools built-in at those power reactor units. As spent nuclear fuel accumulation approaches to the capacities of those reactor pools, some nuclear power stations are forced to supplement storage capacity in order to avoid

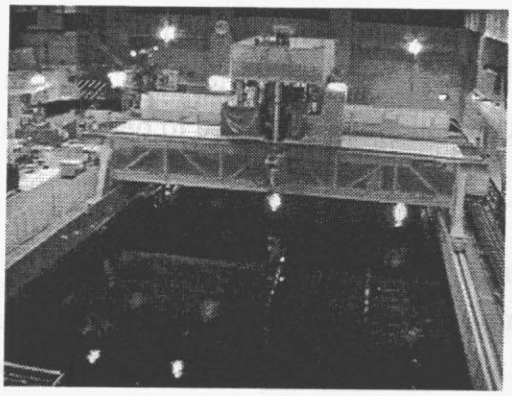


Reactor Type	In Operation	Under Construction	Under Construction Preparation
PWR	■	◇	□
BWR	●	◎	○
GCR, FBR	▲	△	

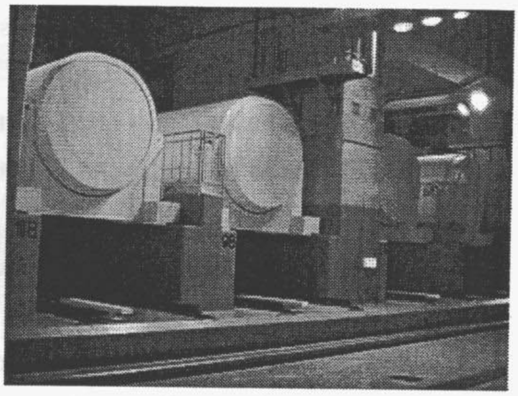
Total Capacity	In Operation		Under Construction		Planned		Total	
	Units	GWe	Units	GWe	Units	GWe	Units	GWe
Sep. 1991	41	32	11	12	3	2	55	36
Dec. 1996	51	43	4	3	2	2	57	48
Jan. 2002	53	45.9	4	4.12	6	7.24	63	57.26

Figure 2.1.1-1: Nuclear Power Stations in Japan as of January 2002, with Illustration of Changes since 1991.

(Note: The No.1 Unit of Tokai NPS was shut down on March 31, 1998.)



(a) Water pool storage.



(b) Dry metal cask storage.

Photo 2.1.1-1: AR storage devices at Fukushima Dai-ichi NPS.

Photo 2.1.1-2: Dry Metal Cask Storage Facility under Construction at Tokai Dai-ni NPS, as of March 2001.

overflow of the reactor pools. At Fukushima Dai-ichi NPS of Tokyo Electric Power Company (Tokyo EPCo), a 1,120MTU water pool storage facility has been implemented in 1997, as well as a dry metal cask storage capability. These facilities are shown in Photo 2.1.1-1. At Tokai Dai-ni NPS of Japan Atomic Power Company followed the line to construct a dry metal cask storage device with its capacity of 260MTU (24 casks), also shown in Photo 2.1.1-2. Several other stations are also found with additions of storage capacity by re-racking of storage pools, some of which are found in Table 2.1.1-1.

It is clear that opportunities for enhancing existing AR storage capacity is almost exhausted, which strongly suggests urgent needs for AFR (Away From Reactor) storage measures. In November 2000, Mutsu City in Aomori Prefecture announced to invite Tokyo EPCo for site investigation for AFR storage in its territory. As the site characterization has already been started, this initiative is expected to open up ways for the other EPCos to follow in the direction.

2.1.2. Institutional Developments in Spent Nuclear Fuel Management.

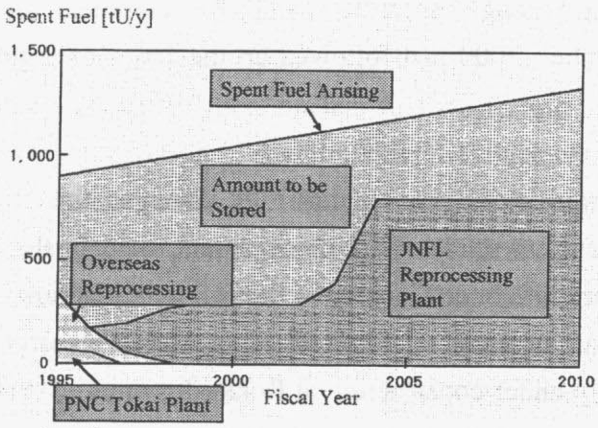
Spent nuclear fuel storage was first mentioned in the 1987 Long-term Program for Development and Utilization of Nuclear Energy, which has been the most fundamental document of nuclear policy in Japan. In the 1994 Long-term Program for Research, Development and Utilization of Nuclear Energy, special words were added for future methods of spent nuclear fuel storage, as well as ways to manage spent MOX (mixed oxide) fuel.

The Steering Committee for Nuclear Energy under the Council for Comprehensive Energy Policy for then-Ministry of International Trade and Industry, which is the primary 'engine' to formulate Japan's energy policy, published an interim report on spent nuclear fuel storage in January, 1997, which urged preparedness for possible prolongation of spent nuclear fuel storage, and actual deployment of AFR storage in about 2010. The Cabinet supported the report in February 1997.

In order to plan steps to realize conceptual views in the interim report, The Working Group for Spent nuclear fuel Storage Measures were formed with representatives from the government and major EPCos. The Working Group, after series of intensive discussion during March 1997-March 1998, submitted its final report, revealing the idea of "storage of recycle fuel resources", as well as possible regulatory schemes for storage service providers and related legal framework. The Steering Committee for Nuclear Energy (1998) published in June 1998 was primarily an endorsement of the Working Group's report, with emphasis on legal procedure and site selection principles.

One should not overlook the fact that it was emphasized in both of these reports that, because spent nuclear fuel storage is a safe and static process, virtually any business ventures may be able to enter into the market of storage services. While this statement was intended partly for better public acceptance, it is still worth paying attention to the fact that such competitive atmosphere was already anticipated positively by those representatives from the government and power utility industry.

The law for regulation of nuclear power reactor and other nuclear related operations (The Regulation Law, hereafter) was amended in June 1999, as a follow-up to the interim report. In this amendment, "operation of storage of recycle fuel resources"



Assumptions:

Fiscal Year	1995	2000	2010
Nuclear Power Generation Capacity [GWe]	4150	4500	7000
Annual Discharge of Spent Fuel	900 – 1300 tU/y		
PNC Tokai Reprocessing Plant	Receipt of spent fuel ends in 1996.		
JNFL Reprocessing Plant	Receipt of spent fuel is started in 1997. Operation starts at 800tU/y in 2003.		

Figure 2.1.3-1: Prospects of Spent nuclear fuel Arising and Management. (source: MITI)

Table 2.1.3-1: The Official Prospect of Spent nuclear fuel Management [tU]. (source: Agency of Natural Resources and Energy "On the Interim Storage of Spent nuclear fuel," 1999.)

	1997-2010	2011-2020
Cumulative Arising (a)	15200	16000
Shipment to JNFL/Rokkasho Repro. Plant (b)	5900	8000
Shipment to Overseas Reprocessers (c)	70	-
AR storage Capacity (d)	5300	4200
Requirements for AFR storage (a-b-c-d)	3900	3800
Cumulative AFR Requirements	3900	7700

was identified and introduced[1], which opened up ways for new business ventures to be allowed of this service provider operation. Related regulatory schemes such as safety design criteria of facilities are under preparation accordingly.

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[1] In The Regulation Law, those entities licensed for specific "operations" for various activities related to nuclear energy and nuclear materials are regulated, such as power reactor operation, fuel fabrication, material transportation, spent nuclear fuel reprocessing and radioactive waste disposal. This "regulation by operational entity" principle shows clear contrast with those "regulation by materials" in US, for example, where nuclear materials are put under regulation regardless of who owns or handles. As there was no specification of "storage of spent nuclear fuel," virtually no one was allowed to stay as such situation possessing stocks of spent nuclear fuel for the purpose of their storage. The Regulation Law amendment in 1999 meant that such an operation of spent nuclear fuel storage became recognized and put in the normal regulatory formula.

The latest Long-term Program for Research, Development and Utilization Program published in December, 2000 just followed up the series of arguments and discussions described above.

2.1.3. Future Prospects of Spent Nuclear Fuel Management.

Future prospects of spent nuclear fuel management, namely the demand for additional storage measures, are influenced largely by the following factors:

1) The JNFL (Japan Nuclear Fuel Limited) reprocessing plant of 800MTU/year design capacity, currently under construction at Rokkasho-mura of Aomori Prefecture; when it starts its operation and at which capacity factor.
2) One-time full-core discharge upon decommissioning of reactor units foreseen from 2010, while built-in storage pool is also dismantled at a certain stage of decommissioning.

Even if the Rokkasho reprocessing plant is successfully operated at its design capacity, it cannot receive the whole discharge of Japan's NPSs every year, neither the past discharges. While the government's official views are shown in Figure 2.1.3.-1 and Table 2.1.3-1, those underlying assumptions, especially the schedule of the reprocessing plant, are already obsolete, since the JNFL Rokkasho reprocessing has been rescheduled to start its operation in July 2005. This clearly illustrates the importance to repeat projections with any changes of the above mentioned factors.

In the long run, it is obvious that large-scale storage devices are needed. This is particularly true after 2010 when the first commercial LWR plant expires its 40-year lifetime. After then, series of LWR plants would be shut down, which mean on one

Table 2.1.3-2: Projected Spent nuclear fuel Storage Needs in 2050 in Japan. (same as Table 5.2.1-1)

Simulation Cases	Spent Low Burnup UO2 Fuel	Spent High Burnup UO2 Fuel	Spent MOx Fuel	Total Amount to Manage (A)	Total AR Storage Capacity (B)	Needs for Additional Storage (C=A−B)	2nd Reprocessing Plant to Commence in 2020	Range of Needs for Storage
O	0	39,000	10,000	49,000	24,000–27,000	22,000–25,000		0–25,000
N	7,000	30,000	11,000					
O+2Rep	0	21,000	13,000	34,000		7,000–10,000	Δ8000	
N+2Rep	0	23,000	11,000					

Assumptions for Projection Cases.
Case O: No 2nd reprocessing plant. The 1st reprocessing plant receives older spent fuel as prioritized.
Case N: No 2nd reprocessing plant. The 1st reprocessing plant receives newer spent fuel (higher burnup) as prioritized.
Case O+2Rep: The 2nd reprocessing plant starts in 2030. No MOx fuel is reprocessed. Older spent fuel prioritized.
Case N+2Rep: The 2nd reprocessing plant starts in 2030. Spent MOx fuel and older spent fuel prioritized.
The total nuclear power generation capacity is 70GWe in 2010 and 80GWe in 2050, respectively.
AR capacity is assumed at 300MTU/GWe, slightly larger than the current average (270MTU/GWe).
The 2nd reprocessing plant is assumed with capacity of 800MTHM/year to commence in 2030.
UO2 fuel for reload is of low burnup (33,000MWd/MTU at average) until 1992, and thereafter of higher burnup at 45,000MWd/MTU.

hand a large amount of one-time discharge of spent nuclear fuel, and at the same time loss of storage capacity of the reactor pools, would come out.

Based on the existing amount of spent nuclear fuel stocks and projections to the future, Nagano (2001a) gave a projection of spent nuclear fuel balances in Japan up to the year 2050, using an integrated tool SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System) discussed in the Chapter 5. One of the main results is shown in Table 5.2.1-1, which is photocopied here as Table 2.1.3-2, which reveals that the Japanese nuclear industry should prepare a storage capacity at around 10,000 to 15,000 MTU in the medium term, e.g. by 2030. Then, in a long-run up to 2050, the storage needs would defer significantly, from decrease to none to continuous increase up to the level of 25,000 MTU. For more details, see Section 5.2.1.

Special attentions should be given to the plutonium utilization in LWR plants. Spent MOX fuel will have to be stored, as the Rokkasho reprocessing plant is not licensed for the type of spent nuclear fuel with higher generation of heat and radiation. Significant uncertainty has been overcast on this MOX fuel utilization because of local oppositions, which was vividly demonstrated by the negative results of public vote of Kariwa villagers[2] on May 27, 2001. Up to now, no MOX fuel has been eventually loaded to any NPS units in Japan.

2.2. Historical Evolution of Spent Nuclear Fuel Storage Technologies.[3]

2.2.1. Introduction.

The technology options of spent nuclear fuel storage are categorized, by methods of cooling in general, into two major groups, such as wet (water pool) and dry (metal casks, vault, concrete silos and concrete casks). Various methods are implemented according to specific circumstances and conditions worldwide. In some cases, technological inertia and/or site-specific binding conditions may predetermine one particular option to be chosen, while in a more general context one among other options has been chosen under competitive market conditions. By examining past tendencies which options have been chosen and thereby how technological paradigm has evolved, we can explore future directions of technological transitions.

In this section, the author attempts a theoretical analysis of paradigm shifts among number of technological options of spent nuclear fuel storage. After describing the model to be applied, such paradigm shifts in spent nuclear fuel storage are analyzed to derive implications towards future.

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[2] Among the electorate, 88.2% voted, of which negative votes for MOX fuel loading were 1925, supportive 1553, reserved 131, and invalid 16.

[3] This section is based on Nagano (2001).

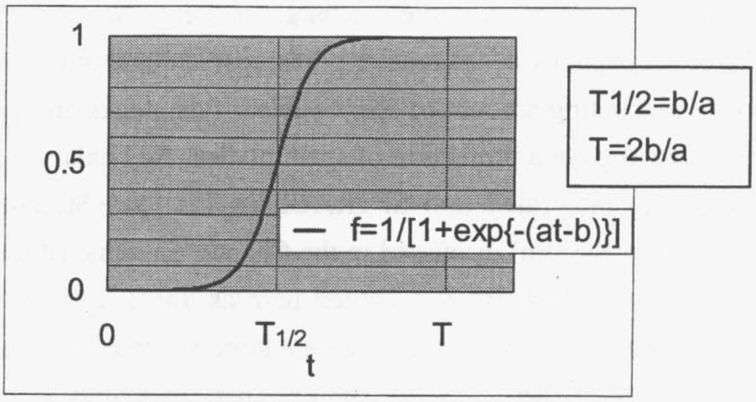

Figure 2.2.2-1: The Logistic Curve.

2.2.2. A Paradigm Shift Model.

Marchetti and Nakićenović (1979) proposed a theoretical model for market penetration and retirement processes of multi-goods or multi-technology options. According to the model, time trajectory of a given new good to penetrate into market is described by the logistic curve, which is shown in the following formula as well as Figure 2.2.2-1.

$$\frac{f}{1-f} = \exp(\alpha \cdot t + \beta) \qquad (1)$$

where, f: market share.

Thus, by plotting a diagram in which time represents the horizontal axis and $\log(f/1-f)$ for the vertical axis, the market penetration trajectory of the good is represented as linear function. Marchetti and Nakićenović (1979) also applied the formula (1) for market retirement process and also for multi-goods problems. Here, behavior of a given good or technology option is modeled as linear function with positive slope in its penetration phase to kink at the time when the maximum market share is obtained to another linear function in its retirement phase with negative slope. Figure 2.2.2-2 is the best known example among many other attempts to justify the theory, the patterns of sources of world primary energy consumption.

In the following sections, the author attempts to apply the model for spent nuclear fuel storage facilities installed worldwide.

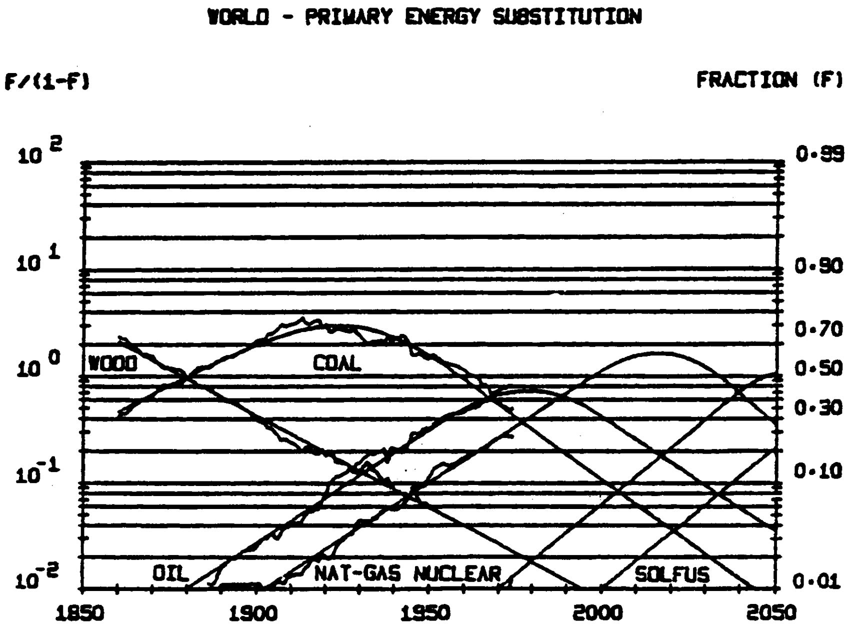

Figure 2.2.2-2: The Historical Evolution of Primary Energy Consumption of the World.
(ref: Marchetti and Nakićenović (1979).)

2.2.3. Installed Spent Nuclear Fuel Storage Facilities Worldwide.

There are available a number of technology options in spent nuclear fuel storage, each of which can be chosen with suitable characteristics against specific conditions for location or fuels to be stored. The following conditions are referred to when making a choice of options:

- Confinement of radioactive nuclides; metal canisters, metal casks or pool water.
- Cooling method; wet (forced or natural convection) or dry (natural convection or forced).
- Radiation shielding; pool water, container or building.
- Structural integrity; building or container.
- Wet or dry,
- Characteristics of fuels to be stored; heat generation, radiation and physical configuration,
- Roles and purposes of the store to install; storage capacity, storage duration, processes before and after the storage,
- Natural, societal and other factors; land availability, weather and climate, acceptability.

Figure 2.2.3-1 shows the cumulative capacity of installed storage facilities worldwide

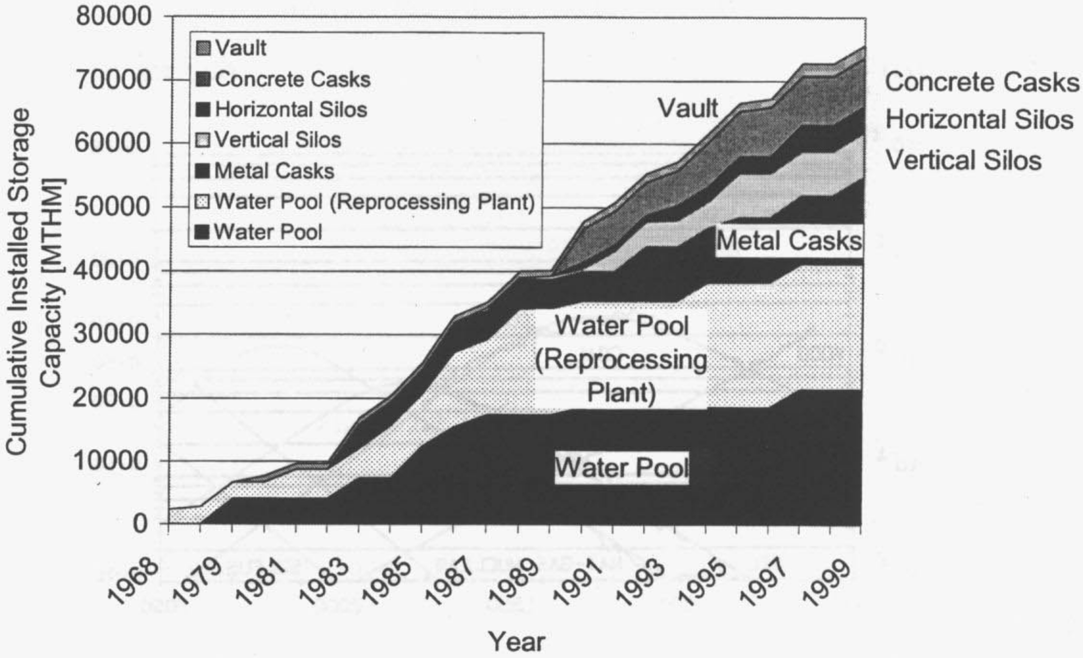

Figure 2.2.3-1: The Cumulative Installed Capacity of Spent nuclear fuel Storage Worldwide.
(ref: Yagishita et al. (2000))

by technology options. Here, the options are categorized into seven kinds as follows;

- Water pool, as adjunct to reprocessing facilities,
- Water pool as independent store,
- Metal Casks,
- Vault,
- Vertical silos,
- Horizontal silos, and
- Concrete casks.

In the following analysis, new additions of storage capacities are taken as basic data. Since the data are quite dispersed over time, it is inevitable to take 10-year moving average of installation for each of the above 7 storage options to get smooth enough time series data. This shortcoming of data limitation will have to be better addressed.

2.2.4. Results and Observations.

Figure 2.2.4-1 shows the results to fit the data of Figure 2.2.3-1 for the plot similar to Figure 2.2.2-2. From these results, it is observed that except the water pool storage in earlier stages, none of the seven technology options has never monopolized nor retired from the market, but each of them has found its own "*niche*" market to survive, possibly

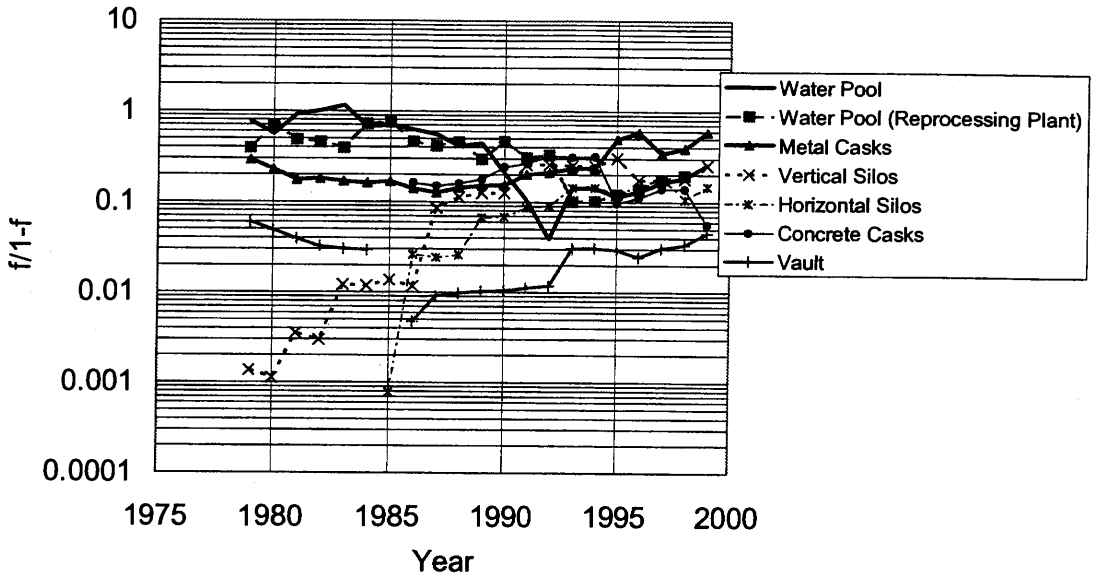

Figure 2.2.4-1: Technological Transitional Patterns of Spent nuclear fuel Storage.

based on their own specific strength such as economy of scale or modular features. In short, all of the options 'cohabitate' in the global market.

In Figure 2.2.4-1, there are found breaking-offs as the share f=0 although moving average is taken over as long as 10 years. Another drawback is noticed as insufficient capability to explain behavior of each of the options.

Figure 2.2.4-2 is an attempt to get over these shortcomings, where those "new dry methods" other than metal casks are integrated into one category for comparison among

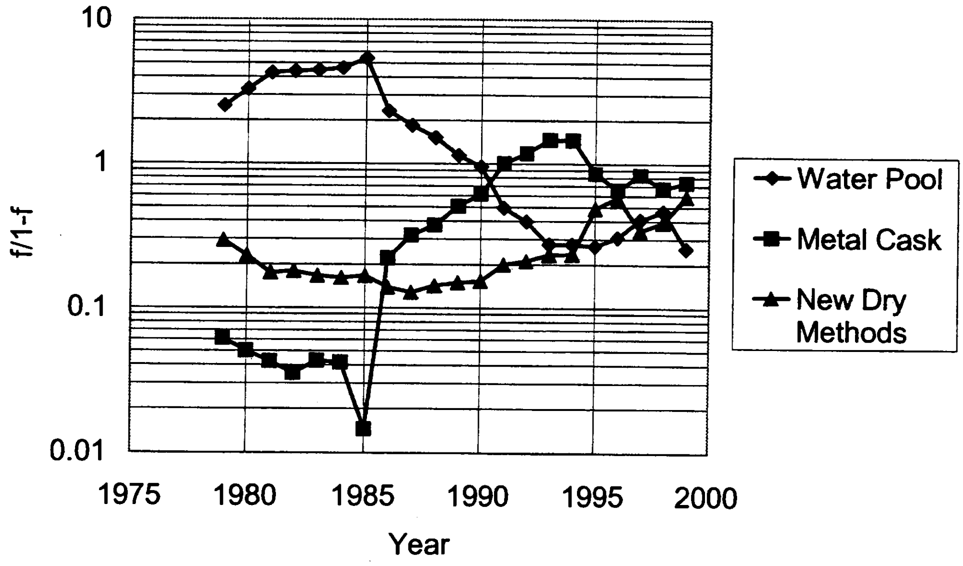

Figure 2.2.4-2: The Technological Transitional Patterns of Spent nuclear fuel Storage: New Dry Storage Methods Grouped as One Category.

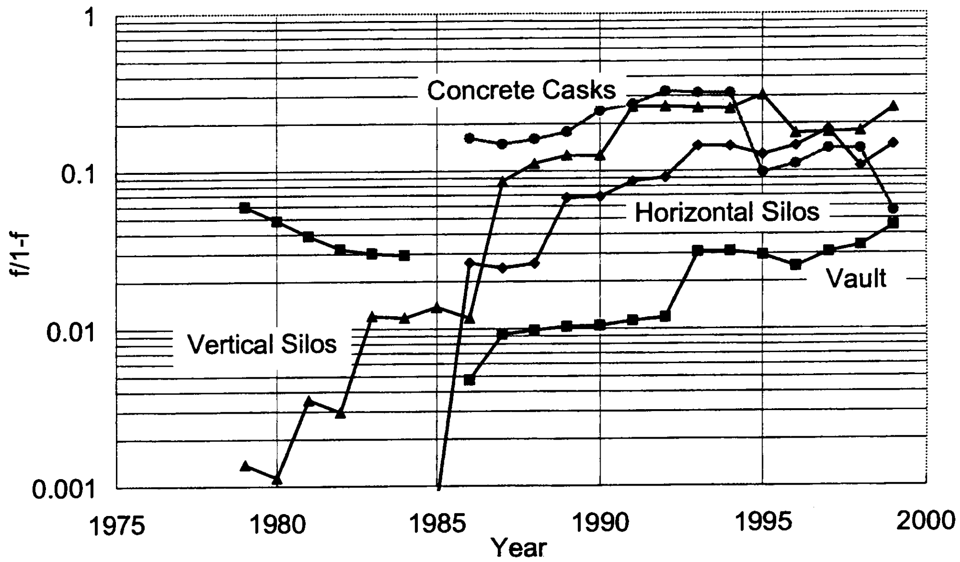

Figure 2.2.4-3: The Market Penetration Patterns of New Dry Options.

two others; water pool and metal casks. The metal casks option has surged its share in late 1980s, while the new dry options in 1990s. The water pool has lost its share almost throughout the time horizon.

Figure 2.2.4-3 is the result of analyzing among the new dry options by the same analysis. None of those options has yet shown any clear signs of either expansion or shrinkage of their shares, which would be translated as those options are yet to build their positions in the market.

2.2.5. Summary.

In this section, a model of market penetration patterns of multiple goods is applied for spent nuclear fuel storage technology options. The analytical method is yet to be improved, as data used in the analysis, i.e. new installation of storage capacities, are dispersed over time, etc. The results and observations are also not clear enough. Among all, while the model has a certain explanatory power for the past behavior, it is limited in capability for future projection, such as technological breakthrough. This attempt should be repeated periodically to assess whenever any typical patterns are found.

Up to now, the author has found no clear signs of any options to retire or eradicate. The growth of new dry methods may imply possibilities of other options, namely water pool, to phase out. In order to keep track, the analysis needs to repeat.

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CHAPTER 3

Energy and Nuclear Fuel Cycle Modeling - Spent Nuclear Fuel Storage as Flexibility Measure in Optimal Strategies -

3. Energy and Nuclear Fuel Cycle Modeling: Spent Nuclear Fuel Storage as Flexibility Measure in Optimal Strategies.

3.1. Fuel Cycle Optimization Model.[4]

In order to analyze the needs of storage of spent nuclear fuel from the light water reactors, FCOM (Fuel Cycle Optimization Model) was developed, which is a linear programming model which can optimize nuclear power reactor strategy as well as nuclear fuel cycle strategy at the same time. In this section, the basic structure of FCOM and the results from case studies by the model are described.

3.1.1. Outline of the Model.

(1) Basic Structure of FCOM.

The basic structure of FCOM is shown in Figure 3.1.1-1. FCOM is formulated as a linear programming model with 90 years of planning time horizon, 1966-2055, divided into nine ten-year periods.

The objective function of FCOM is the total cost discounted over the time horizon, and FCOM finds an optimal composition of nuclear power reactors ("optimal reactor strategy") and a corresponding optimal nuclear fuel cycle profile ("optimal fuel cycle strategy"), which minimize the objective function.

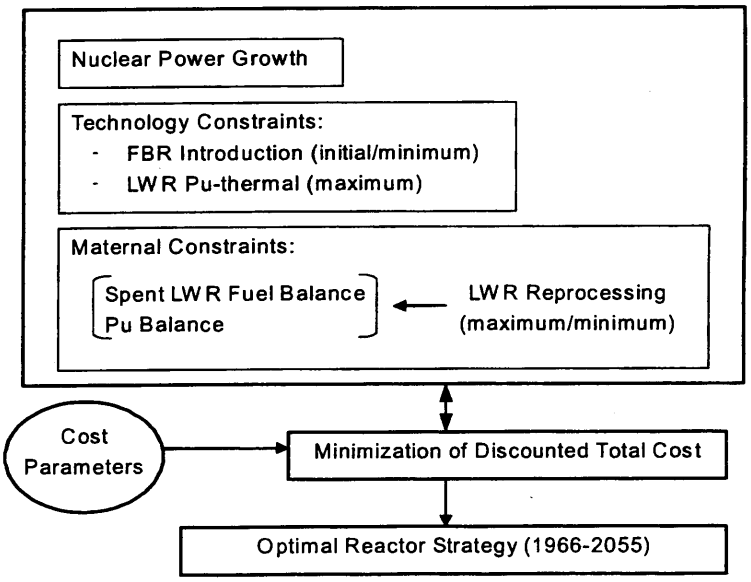

Fig. 3.1.1-1: The Outline of FCOM.

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[4] This section is based on Nagano and Yamaji (1989a) and Nagano and Yamaji (1989b).

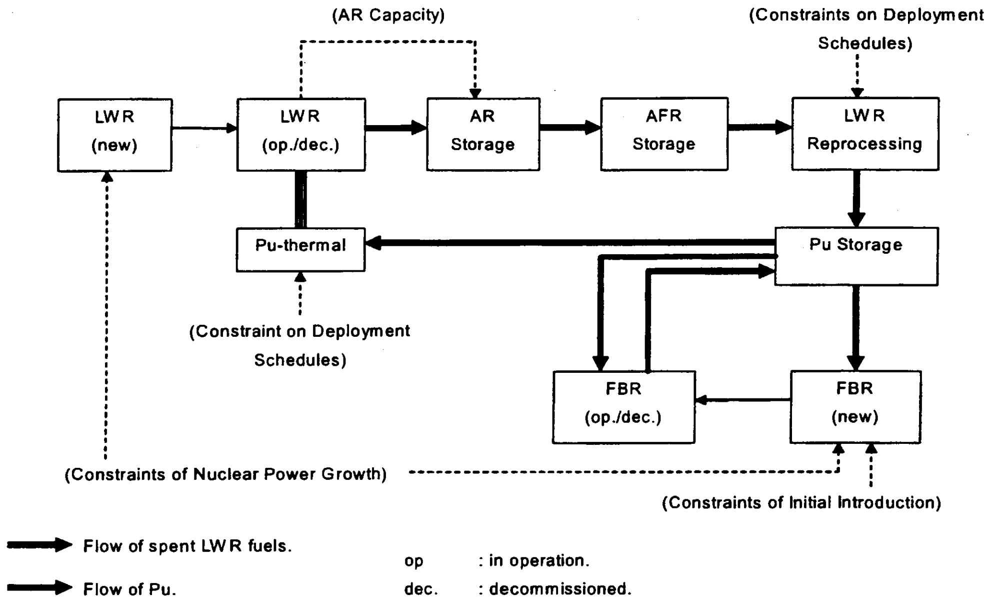


Fig. 3.1.1-2: Flow of Nuclear Fuel Materials in FCOM.

The nuclear fuel cycle modeled in the FCOM is shown in Figure 3.1.1-2. Nuclear power reactors, conventional light water reactors (LWRs, hereafter) or more advanced fast breeder reactors (FBRs, hereafter) are installed so as to meet the constraint of total nuclear power generation capacity. From the operating and decommissioning capacities of each reactor, corresponding amount of spent nuclear fuels are discharged with certain time lags. Spent nuclear fuels from LWRs are transferred through at-reactor (AR) storage and away-from-reactor (AFR) storage to reprocessing. The timing of reprocessing of LWR spent nuclear fuels and their storage duration in AR and AFR are selected as optimal, while FBR spent nuclear fuels are assumed to be reprocessed with some constant cooling time after discharge. The plutonium (Pu) recovered through the reprocessing of spent nuclear fuels both from LWRs and FBRs is recycled to FBRs or LWRs through storage, duration of which is also optimized.

FCOM has been implemented on a personal computer. The linear programming matrix of FCOM in standard case calculation of this section is about 280 columns and 120 rows with about 1,000 non-zero element.

(2) Objective Function of FCOM.

The objective function of FCOM is the discounted total cost. Discount calculation are done assuming that costs are incurred at the central point of each time period. It is possible to set the values of cost parameters for each period. All cost parameters are assumed to be expressed in real terms. The cost components are grouped into the following three categories:

- Capital costs. The capital expenditure in each period is expressed as levelized capital charge during the physical life of each plant. Levelization is employed for eliminating the end effect of planning horizon.
- Operating and maintenance costs.
- Fuel cycle costs.
  - LWR fuel cycle costs include the following items; natural uranium ore (including conversion and transportation), uranium enrichment services, fuel fabrication for UO_2 and MOX, reprocessing of spent nuclear fuels, and storage of spent nuclear fuels.
  - FBR fuel cycle cost is counted as a lump sum in terms of JPY/kWh.
  - Storage cost of Pu.

Table 3.1.2-1: The Assumed Nuclear Power Generation Capacities.

year	Capacity [GWe]
1970	2.5
1980	15.0
1990	32.0
2000	53.0
2010	70.0
2020	85.0
2030	100.0
2040	116.0
2050	132.0

Table 3.1.2-2: The Assumed Fueling Characteristics.

	Unit	LWR	LWR-Pu	FBR
Initial Core				
U	t	76.70	76.70	76.466
Enrichment	%	2.60	2.60	0.300
Pu-fiss	t	0.00	0.00	3.286
Heavy Metal	t	76.70	76.70	81.030
Equilibrium Loading				
U	t	25.40	23.80	25.417
Enrichment	%	3.20	0.71	0.300
Pu-fiss	t	0.00	0.96	1.154
Heavy Metal	t	25.40	25.49	27.020
Equilibrium Discharge				
U	t	24.30	23.22	24.408
Enrichment	%	0.90	0.44	0.234
Pu-fiss	t	0.17	0.67u	1.337
Heavy Metal	t	24.50	24.47	26.255
Decommissioned Core				
U	t	74.40	70.19	74.217
Enrichment	%	1.49	0.53	0.253
Pu-fiss	t	0.42	2.23	3.836
Heavy Metal	t	74.90	74.01	79.523

3.1.2. Conditions and Parameters.

Nuclear power projection shown in Table 3.1.2-1 is used for the case studies described later. The projection is based on "The Long-term Nuclear Power Development and Utilization Program" (Atomic Energy Commission of Japan (1987)).

For the reactor fueling characteristics used in the case studies, Table 3.1.2-2 is assumed. The other technical constraints are based on the following assumptions:

- FBRs are technically available after the year 2006.
- Full core Pu loading is possible for LWRs.
- 200MTU of AR storage capacity is available for each 1,000MWe of LWR capacity.

In the reference setting, no constraint is imposed on the reprocessing capacity, which means any amount of spent nuclear fuels can be reprocessed whenever needed. In the alternative setting, lower bounds of 800tHM/yr for 1996-2025 are assumed[5].

Cost parameters are set as Table 3.1.2-3. All values are presented in real term of 1985 currency, and assumed constant during the planning horizon. Construction cost of LWR is assumed at 3000,000JPY/KWe, and parametric studies are made for the construction cost of FBR ranging from 0.9 to 1.1 times that of LWR. O&M cost is assumed at 5%/yr of construction cost for both LWR and FBR. Concerning the fuel cycle costs, the cost for LWR spent nuclear fuel storage is considered only for AFR storage, based on OECD/NEA (1985), and parametric studies are made for the lump-sum fuel cycle cost of the FBRs ranging from 0.2 to 1.5 times that of the from end part of the LWR fuel cycle,

3.1.3. Case Study (1): LWR Pu Recycling in Optimal Strategy.

Based on the settings described above, some case studies are made to show the fundamental characteristics of the model. First, the conditions are investigated under which Pu recycling in LWRs are introduced as part of the optimal strategy.

Table 3.1.2-3: The Assumed Costs and Prices.

Items	Value	Unit
Construction Cost (LWR)	300	10^9¥/GWe
O&M Cost (LWR/FBR)	15	10^9¥/GWe/y
LWR Fuel Cycle Costs		
Nartural Uranium Ore	35	$/lbU3O8
Uranium Enrichment Service	139	$/kgSWU
UO2 Fuel Fabrication	80	10^3¥/kgU
MOX Fuel Fabrication	130	10^3¥/kgHM
Spent Fuel Storage		
- AR	0	
- AFR	40+4/y	$/kgHM
Spent Fuel Reprocessing	170	k¥/kgHM
Discount Rate	5	%/y
¥/$ exchange rate	130	¥/$

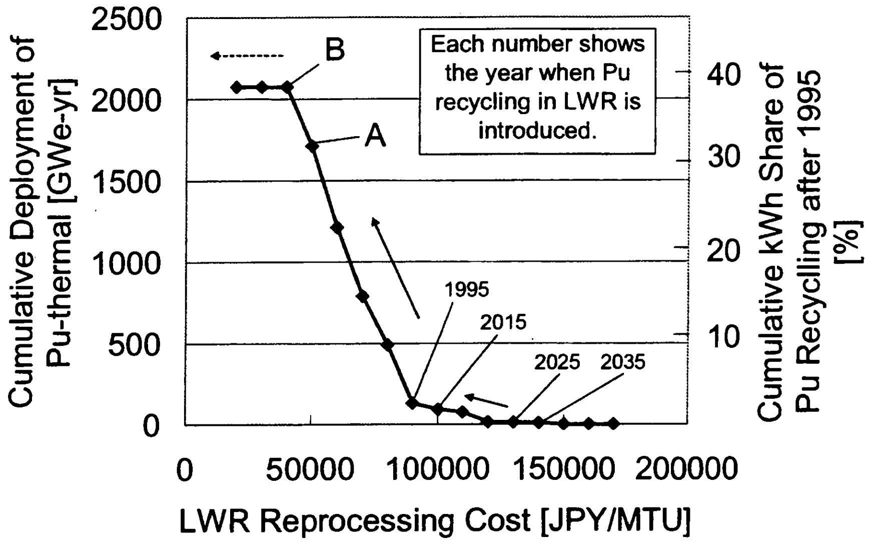


Figure 3.1.3-1: Case Study (1): The Optimal Condition for LWR Pu Recycling.

The result of parametric study for the LWR reprocessing cost is shown in Fig. 3.1.3-1. Pu recycling in LWRs is not economically justified under the reference setting of the reprocessing cost, 170,000 JPY/kgHM. With the reduced reprocessing cost value, Pu recycling in LWRs begins to appear in the optimal strategy. The less the reprocessing cost, the larger scale and the earlier utilization of Pu recycling is justified; and, the magnitude of Pu recycling reaches to the levels at which;

- the spent LWR fuels that should be stored in AFR storage are all reprocessed, which is shown with the mark of 'A' in Fig. 3.1.3-1, and further,
- all the spent LWR fuels are reprocessed, which is shown with the mark of 'B'.

In case that interim spent nuclear fuel storage is available, there arises a trade-off in the economics of LWR fuel cycle between the cost of storage and the present value of the reprocessing cost. The result implies that the fuel cycle is made flexible by the option of interim storage.

3.1.4. Case Study (2): FBR Introduction in Optimal Strategy.

As the second case study, the conditions are explored under which FBRs are introduced in the optimal strategy.

(1) Reference Analysis.

In the reference setting, no constraint is imposed on the reprocessing capacity of LWR spent nuclear fuels. The optimal reactor strategies calculated with various cost values can be categorized to three types, which are shown in Fig. 3.1.4-1 as areas (a), (b) and

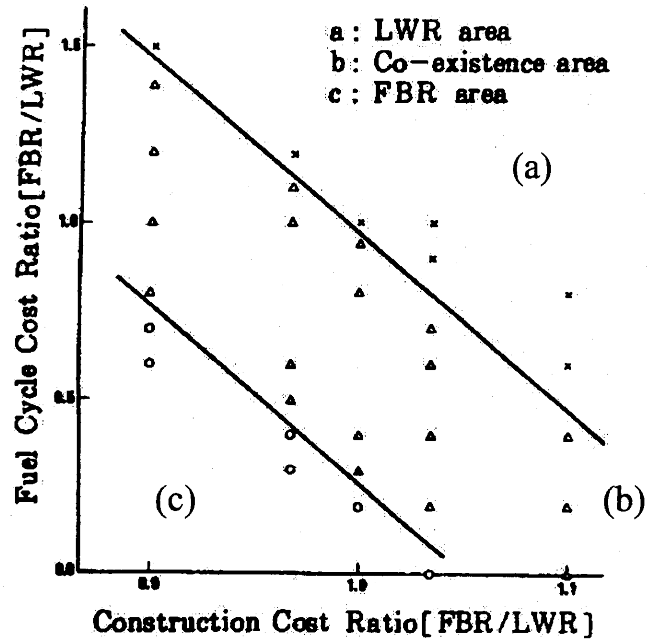


Figure 3.1.4-1: Case Study (2a): Optimal Condition for FBR Introduction.

(c), which are described as:

a. The LWR Area, where No FBR is introduced in the optimal strategy. Marked with crosses in Fig. 3.1.4-1.

b. The Co-existence Area, where FBRs are introduced but not at the maximum possible rate. Marked with triangles.

c. The FBR Area, where introduction of FBRs at the maximum rate and the earliest possible time is optimal. Marked with circles.

For the cases that the economic performances of FBRs is close to that of LWRs, the interim storage of LWR spent nuclear fuels provide the function of inter-temporal adjustment to the Pu supply/demand: thus, the area of co-existence of LWRs and FBRs is brought about.

(2) The Effect of the Reprocessing Program of Spent LWR Fuels.

A sensitivity case is investigated that the effect of lower bounds set for LWR reprocessing capacity at 800 tHM/y for 30 years after 1996[6].

The results of the parametric study under this commitment for LWR reprocessing are

[6] This boundary condition reflected the plan at the time when the analysis was done. By now, construction of the JNFL Rokkasho Reprocessing Plant has been delayed for a decade so that it is scheduled to commence in 2005.

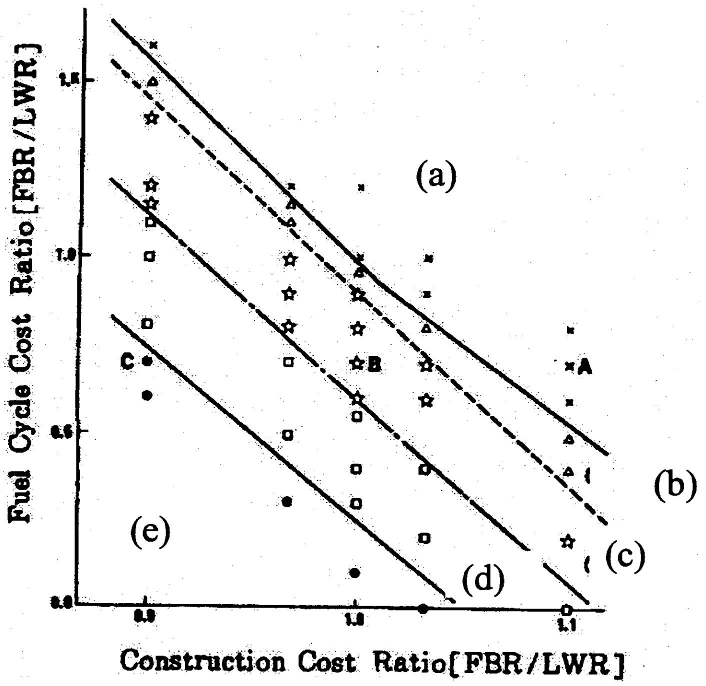


Figure 3.1.4-2: Case Study (2b): Optimal Condition for FBR Introduction under LWR Reprocessing Constraint.

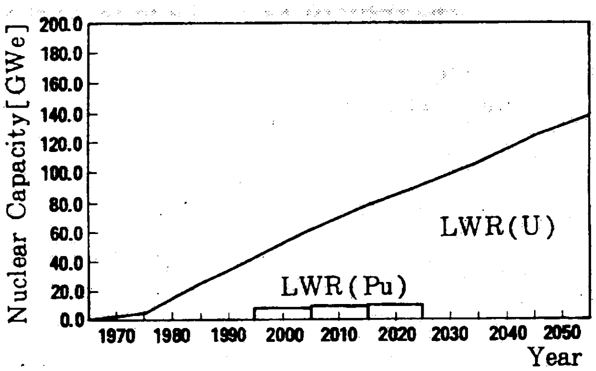
shown in Fig. 3.1.4-2. Comparison of this to Fig. 3.1.4-1 reveals that the area where the FBR introduction occurs in the optimal strategy is extended and that the patterns of optimal strategies are diversified. In Fig. 3.1.4-2, five different types of the optimal strategies are identified as follows:

a. The LWR Area, where no introduction of FBRs is optimal. All Pu recovered by the assumed reprocessing capacity is supplied to and consumed in LWRs. Marked with crosses in Fig. 3.1.4-2.
b. The Partial FBR Introduction Area, where FBRs are introduced partially along with the Pu recycling in LWRs within the assumed LWR reprocessing capacity. Marked with triangles.
c. The Constant FBR Introduction Area, where FBR introduction occurs as much as possible within the assumed LWR reprocessing capacity. Marked with stars.
d. The Accelerated FBR Introduction Area, where FBR introduction occurs with additional LWR reprocessing beyond the assumed capacity. Marked with squares.
e. The FBR Area, where introduction of FBRs at the maximum rate and the earliest possible time is optimal. Marked with double circles.

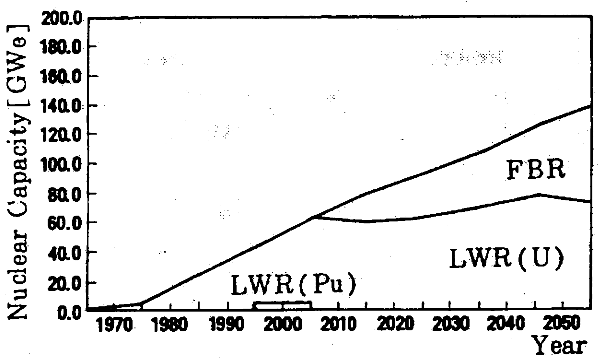
The co-existence area 'b' in Fig. 3.1.4-1 is divided into the three areas, 'b', 'c', and 'd' in Fig. 3.1.4-2. The result implies that the patterns of optimal strategy are diversified by the combination of storage and reprocessing LWR spent nuclear fuels.

3.1.5. Optimal Strategy of Nuclear Fuel Cycle.

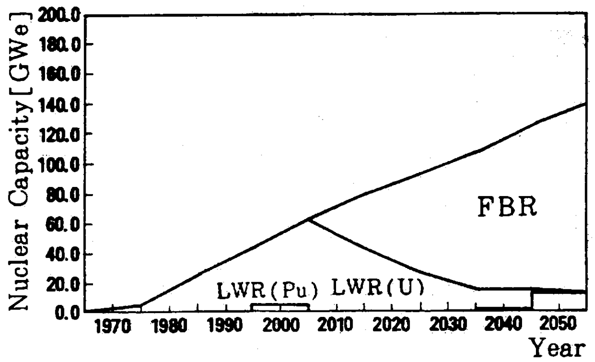
In the optimal strategy of the reference analysis where no constraint imposed on spent LWR fuel reprocessing, the reprocessing of spent LWR fuels is done just to meet Pu



(a) Point 'A' in Fig. 3,1,4-2.



(b) Point 'B' in Fig. 3.1.4-2.

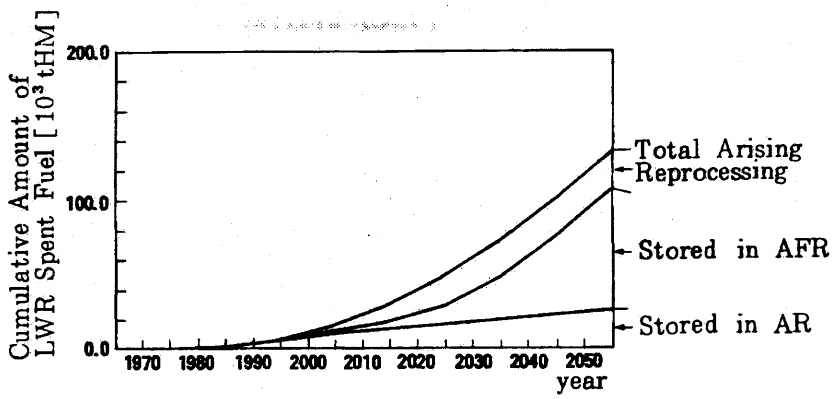


(c) Point 'C' in Fig. 3.1.4-2.

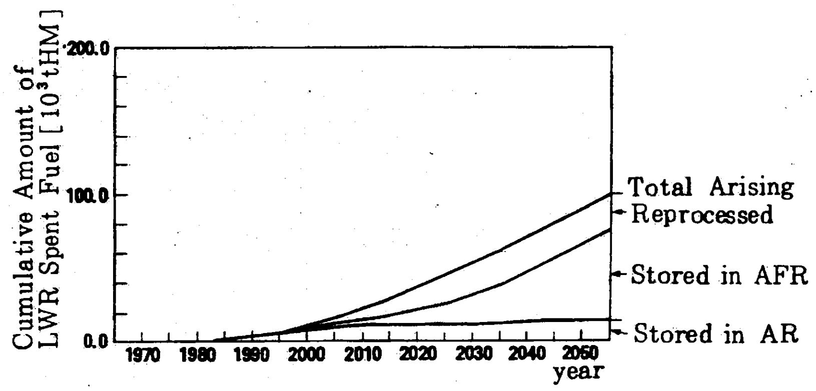
Figure 3.1.5-1: Illustration of Optimal Reactor Strategies.

demand occurring from the introduction and operation of the FBRs. The interim storage of spent LWR fuel is selected in the long-term optimal strategy to adjust the time-lag of Pu production and utilization.

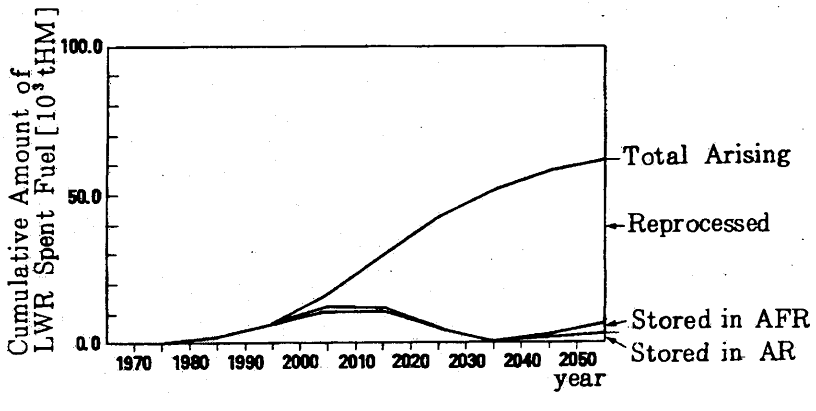
For illustrative purpose, here are described the optimal strategies for the three representative sets of cost parameters shown as 'A', 'B' and 'C' in Fig. 3.1.4-2. The



(a) Point 'A' in Fig. 3.1.4-2.



(b) Point 'B' in Fig. 3.1.4-2.



(c) Point 'C' in Fig. 3.1.4-2.

Figure 3.1.5-2: Illustration of Optimal Spent LWR Fuel Management.

optimal reactor compositions of these three cases are shown in Fig. 3.1.5-1 (a)-(c), while the corresponding optimal treatment of spent LWR fuels are presented in Fig. 3.1.5-2 (a)-(c), respectively.

Under the minimum constraint of LWR reprocessing capacity, there is also no requirement for Pu storage in the optimal strategy. When there is no Pu demand for FBRs, Pu which is recovered through the constrained reprocessing capacity is consumed by Pu recycling in LWRs. The spent LWR fuel storage plays the key role for enhancing the flexibility of the strategy by adjusting the time-lag of Pu balances.

3.2. World Energy Prospects and Nuclear Fuel Cycle.[7]

3.2.1. Foreword.

Nuclear energy is now at the crossroad worldwide. With series of accidents and mismanagement, including the criticality accident in the JCO Tokai Works in 1999, the global public tends to become increasingly critical about management of nuclear energy. Ironically, in global energy projection and simulation studies, whose particular example of the early-1990s attempts is found in Sinyak and Nagano (1994), it is difficult to draw consistent pictures for the world to satisfy both growing energy demands and stringent carbon emission control targets without substantive contribution of nuclear energy. If we avoid nuclear energy at all, besides strong enforcement of energy conservation and efficiency improvements, the only feasible pathways are either with vigorous introduction of renewable sources of energy, namely solar and wind, or with massive coal burning with carbon sequestration from the flue gas. In both of the cases, one must inevitably be prepared for certain adverse side effects.

This section does not address those social issues related to the future of nuclear energy. Instead, it tries to answer, provided those societal problems be solved or appropriately internalized in the analytic framework, to the questions such as:

- What cost range are desired or wanted for nuclear energy, namely FBRs?
- What sort of technological conditions affect the nuclear energy utilization, and by this, what type and level of technological innovation is desired or wanted?

Major parts of this report were presented in Nagano (2000). This part of the thesis is based on them, combined with revision and enrichments with some additional results.

[7] This section is based on Nagano (2002b).

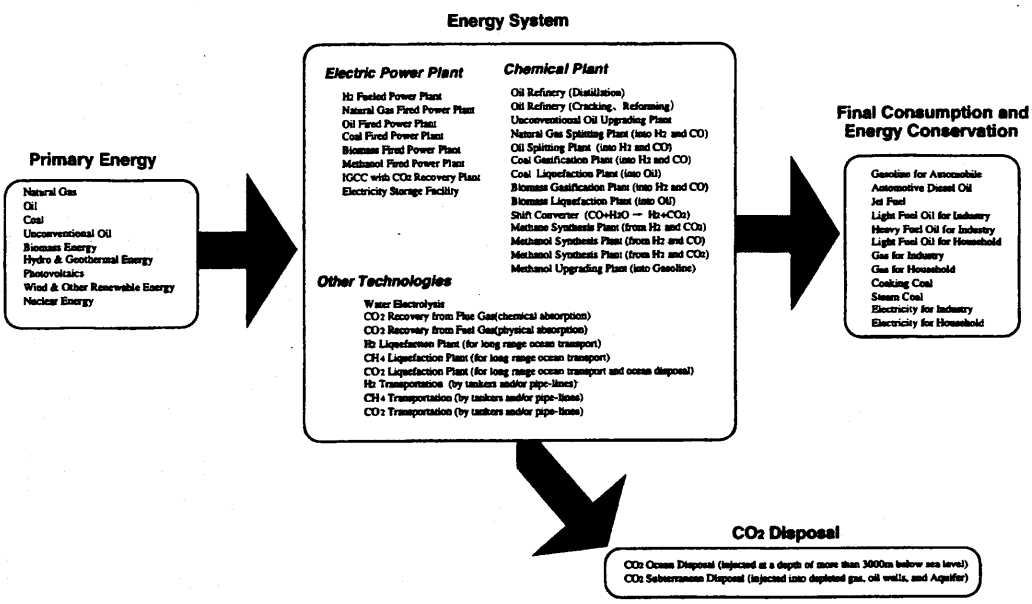


Figure 3.2.2-1: The Scope of the Original New Earth 21 Model.
(source: NE21 Working Group (1996).)

3.2.2. Methodology: the LDNE21 Model and Nuclear Sub-Model.

The simulation model developed in the study is based on the NE21 (New Earth 21) model. The original NE21 is a non-linear optimization model of global energy supply mix as well as carbon emission control measures, whose scope is shown in Figure

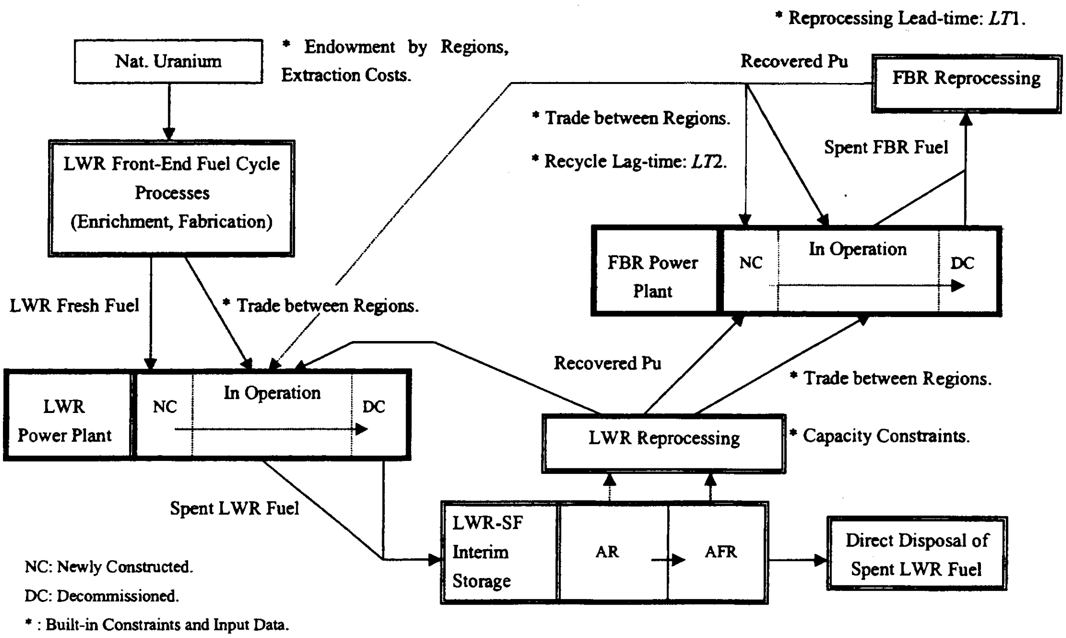


Figure 3.2.2-2: The Outline of FCOM, the Sub-Model Integrated with LDNE21.

3.2.2-1. For more details, see Fujii and Yamaji (1995) and NE21 Working Group (1996).

The original NE21 has been modified in numerous ways, to meet specific purposes of various studies. Among all, the LDNE21 (Linearlized Dynamic NE21) was applied in IPCC-SRES (Special Report on Emission Scenarios, see IPCC (2000)), to describe measures chosen to control atmospheric carbon concentration below 550ppm by 2100.

The author gave to the LDNE21 further integration with more detailed numerical representation of nuclear fuel cycle, namely Pu recycling based on conventional LWRs and more advanced FBRs. The original nuclear sub-model comes from FCOM, which was already introduced in the previous section while slight modification was made to ensure compatibility with LDNE21. The overview of FCOM as a LDNE21 sub model is shown in Figure 3.2.2-2. The initial integration of FCOM into LDNE21 was given by Fujino et al. (1997) and Yamaji et al. (1998). Nagano et al. (1999) is another step ahead in the course. This study is to further elaborate the model, whose refinements from those initial integrated model developments include;

- the nuclear reactor plant life is modified from 30 years to 40 years,
- Pu use in LWRs, as an alternative option to its use in FBRs, is built in,
- lead- and lag-times in the nuclear fuel cycle are more explicitly represented, and

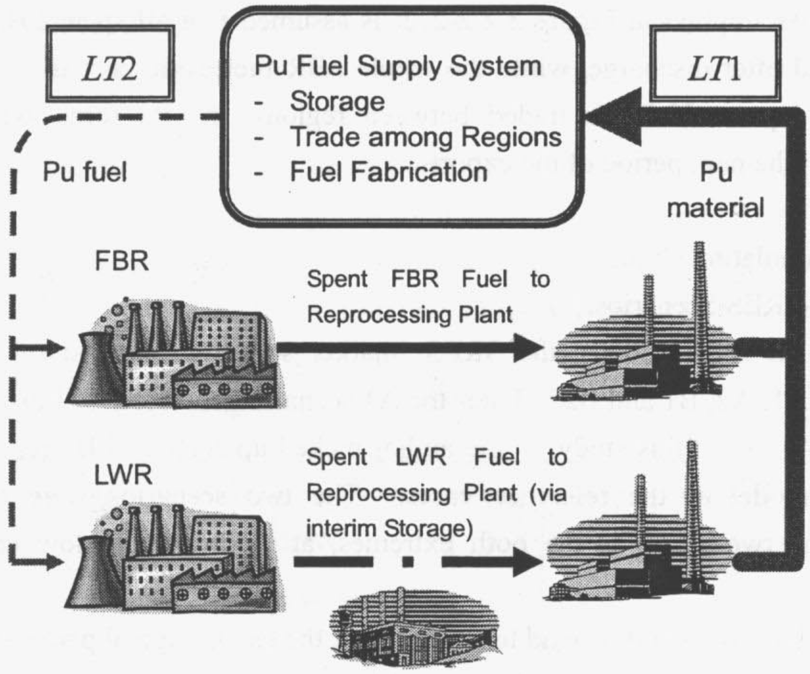


Figure 3.2.2-3: The Schematic Illustration of Modeling the Reprocessing Lead-time (*LT*1) and Pu Recycling Lag-time (*LT*2) .

- cost and technological data are updated.

Among other alterations, the change of nuclear reactor plant life from 30 to 40 years suggests both positive and negative implications. On the first hand, with increased power output, it may improve lifetime cost-performance of a reactor, if it is introduced. However, in the symbiotic system of LWR and FBR modeled here, lifetime extension of older plants would mean postponement of new reactor as its replacement, and thus delay or slow introduction of new technology, namely FBR.

For this third aspect, the following two parameters, *LT*1 and *LT*2, are introduced;

- lead-time for spent FBR fuel reprocessing (*LT*1), defined as the duration between discharge of spent nuclear fuel and when the recovered Pu comes out available, and
- storage of Pu in preparation for initial core and reload fresh fuel to FBR (*LT*2.)

The schematic illustration of *LT*1 and *LT*2 is given in Figure 3.2.2-3. It is assumed that *LT*1 and *LT*2 have their values between 0 and 10 years. As LDNE21 is a 10-year time step model, these parameters are approximated as follows. For *LT*1, Pu to be recovered from the spent FBR fuel discharged at a certain time period (t) becomes available at a ratio of $\{(10\text{-}LT1)/10\}$ in the same period t and the rest $LT1/10$ in the next period (t+1). For *LT*2, ($LT2/10$) of the Pu needed for new FBR installation in a specific period (t) should be set aside in the store in the previous period (t-1). Similar treatments are also applied to FBR equilibrium refueling, and for spent LWR fuel cycle as well. As implied in Figure 3.2.2-2, it is assumed that all spent FBR fuel is to be reprocessed after discharge, while the whole FBR fuel cycle cost is given as a single aggregate input. If Pu is traded between regions, the Pu turns available for the importer in the next period of the export.

3.2.3. Simulation Cases.

(1) IPCC-SRES Scenarios.

As shown in IPCC (2000), the SRES 'marker scenarios' consist of 4 independent scenarios; A1, A2, B1 and B2. Later the A1 scenario generated its 3 differentials; A1B, A1G and A1T. In this study, the author picked up A1B and B1 representations by LDNE21 model as the reference cases. The two scenarios were chosen simply because the two stand as the both extremes, at the high and low ends of energy demands.

Special attentions should be paid to the fact that the technological parameters of the foci of this paper are manipulated with no consideration on consistency with the 'story lines' of the original IPCC SRES marker scenarios. This is, as the author readily admits, an essential drawback of the paper and, as proposed for the next step, scenarios of the

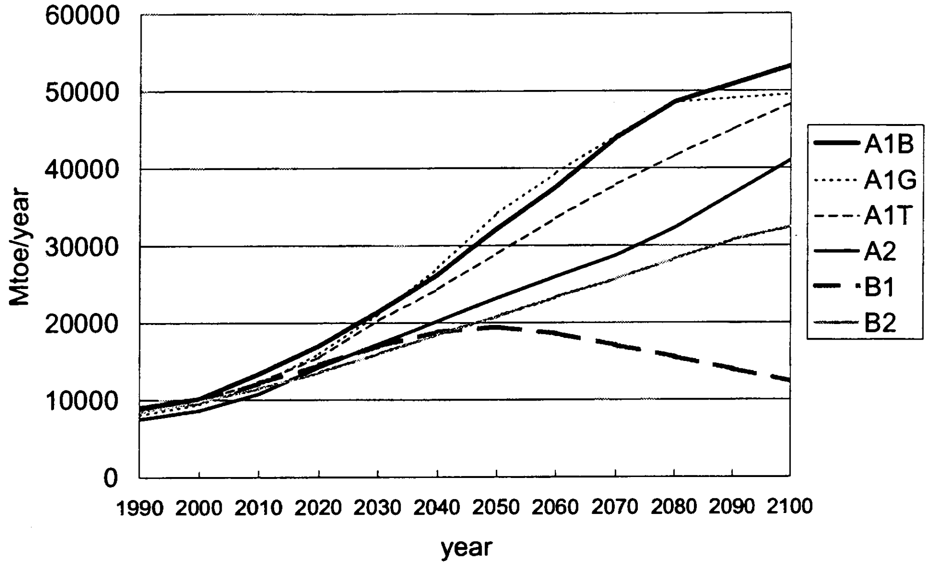


Figure 3.2.3-1: Primary Energy Consumption of the IPCC Marker Scenario Projections. (source: http://sres.ciesin.org/)

study's own should be developed in a fully consistent manner.

Figure 3.2.3-1 shows the original global energy demand levels of SRES marker scenarios. Note that, because of numerous differences of the methodology and specific assumptions embedded with each calculation, the base cases in this paper are not necessarily identical in quantities to the cases shown in Figure 3.2.3-1. The underlying ideas were transplanted from those marker scenarios to the base cases in this paper.

(2) Cost Assumptions for Nuclear Energy and Other Energy Technologies.

Table 3.2.3-1 shows the cost assumptions for nuclear reactors and fuel cycles in the case study. The reactor types assumed in the study are conventional LWRs and unspecified FBRs. Most of the data were taken from OECD/NEA(1994), while the Pu storage cost

Table 3.2.3-1: Cost Data Assumptions on Nuclear Energy Sector.

Cost Item	Unit	Value	Note
LWR Capital Cost	$/kW	3000	O&M Cost at 5%/year
FBR Capital Cost	$/kW	3000	O&M Cost at 5%/year
LWR Fuel Cycle			
Uranium Enrichment	$/kg-SWU	110	
UO2 Fuel Fabrication	$/kg-U	275	
MOx Fuel Fabrication	$/kg-HM	1000	
Spent Fuel Reprocessing	$/kg-HM	810	incl. HLW disposal.
Spent Fuel Storage	$/kg-HM	250	lump-sum for 40 years storage.
FBR Fuel Cycle Cost	c/kWh	1.522	
Plutonium Storage	$/g-Pu/period	10	lump-sum for 10-years.

Table 3.2.3-2: Fueling Characteristics of the Nuclear Reactors.

		unit	LWR (U Fuel)	LWR (Pu Fuel)	FBR
Generation Capacity		MWe	1000	1000	1000
Core Average Burnup		GWd/tHM	45000	45000	150000
Initial Core	Uranium	tU	76.1		69.7
	Enrichment	%	2.7		0.3
	fissile Pu	tHM	0		4
	Heavy Metal	tHM	76.1		75.3
Equilibrium Load	Uranium	tU/year	18.8	17.1	11
	Enrichment	%	4.2	0.3	0.3
	fissile Pu	tHM/year	0	1.134	0.76
	Heavy Metal	tHM/year	18.8	18.9	12.1
Equilibrium Discharge	Uranium	tU/year	17.7	16.5	10.1
	Enrichment	%	1	0.17	0.165
	fissile Pu	tHM/year	0.15	0.81	0.92
	Heavy Metal	tHM/year	18.8	18.9	12.1
Decommissioning Discharge	Uranium	tU	72.7		66.1
	Enrichment	%	1.83		0.269
	fissile Pu	tHM	0.506		4.8
	Heavy Metal	tHM	76.1		75.3

refers to OECD/NEA(1989). The overall FBR fuel cycle cost is set arbitrarily, as the cost level roughly equals to the LWR fuel cycle cost suggested from Table 3.2.3-1.

Table 3.2.3-2 shows the fueling characteristics of the reactors. The FBR shown in Table.3.2.3-2 is based on the MOX fuel technology and no further innovative designs are taken explicitly into consideration. If detailed data compatible to Table 3.2.3-2 become available, those advanced technologies may well be introduced in the simulation.

Concerning the natural uranium endowment assumed in the calculation shown in Table.3.2.3-3, the original data were the sum of 'Reasonably Assured Resources' and 'Estimated Additional Resources I' taken from OECD/NEA(1998), and then simply tripled to cover resources to be discovered. In the case study, ten times instead of three in the reference assumption is tested to see how the natural uranium endowment becomes a severe constraint for the future of nuclear energy.

The simulation cases in this paper are as follows: The 4 base cases are set for the two IPCC scenarios (A1B and B1) with no carbon constraints (Base) and with the constraint of global atmospheric carbon dioxide concentration 550ppm in 2100 (550ppm) at the reference cost and technological data. The sensitivity cases are tested for:

- Capital cost of nuclear power plants (LWR and FBR): 1,000-9,000 $/kW with the reference at 3,000,
- Natural uranium endowment: 10 times of currently known reserve with the reference at 3 times, and

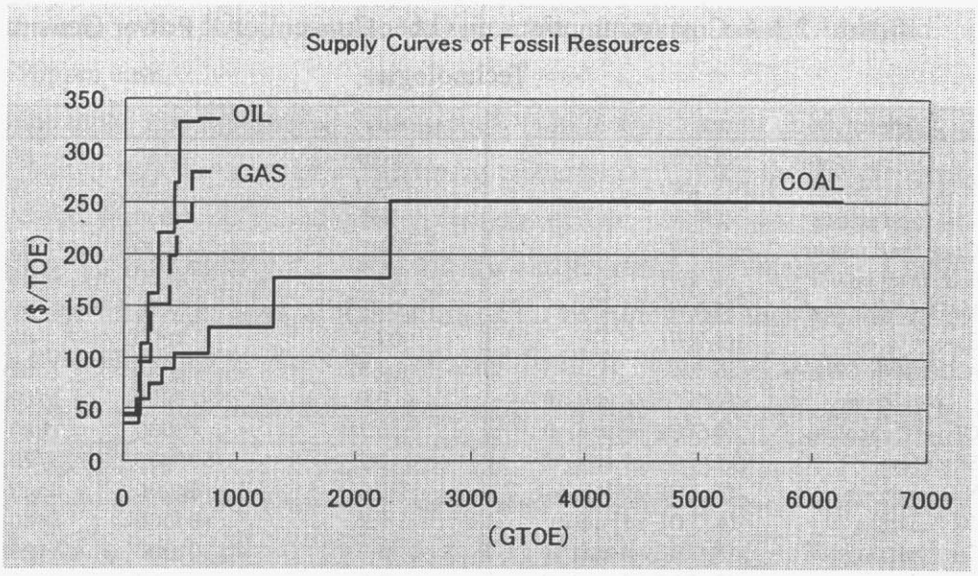


Figure 3.2.3-2: Global Fossil Energy Resource Endowment Assumed in the Study. (Source: Rogner (1998))

- Lead- and lag-times in Pu recycling, with reference of 4 years for *LT*1 and 2 years for *LT*2.

The assumptions for non-nuclear energy sectors are inherited from the original NE21 model in Fujii and Yamaji (1995). The fossil energy resources endowments, shown in Figure 3.2.3-2, are adopted from Rogner (1998), as other studies participated in IPCC SRES did. Assumptions on the other conventional power generation technologies are shown in Table 3.2.3-4.

Table 3.2.3-3: Natural Uranium Resource Endowment Assumed in the Study. [MTU]

	80[$/kgU]	105[$/kgU]
North America	1355790	1250280
Western Europe	674160	468360
Japan	0	0
Oceania	2340000	348000
Centrally Planned Asia	450000	300000
Other Asia	193500	451815
Middle East & North Africa	409920	117000
Sub-Sahara Africa	1475070	119400
Latin America	788700	9000
Former USSR and East. Europe	1176600	535500
World Total	8863740	3599355

Table 3.2.3-4: Cost Assumptions on Other Conventional Power Generation Technologies.

plant type	unit	Usage rate	construction cost	O&M cost	life time
H2 fueled power	($/kW)	0.85	2150	86	30
N.G. fired power	($/kW)	0.85	750	30	30
Oil fired power	($/kW)	0.85	850	34	30
Coal fired power	($/kW)	0.85	1300	52	30
Bio. fired power	($/kW)	0.85	1500	60	30
MeOH fired power	($/kW)	0.85	1450	58	30
Elec. storage	($/kW)	0.85	1000	40	30
IGCC with CO2 re.	($/kW)	0.85	2050	82	30
Oil refi. distil	($/TOE of cr.o/d)	0.7	29000	1160	30
Oil refi. gasoline	($/TOE of cr.o/d)	0.7	42000	1680	30
Shale oil U.G.	($/TOE of sh.o/d)	0.9	593000	23720	30
N.G. splitting	($/TOE of N.G./d)	0.9	164000	6560	30
Oil splitting	($/TOE of oil/d)	0.9	167000	6680	30
Coal gasification	($/TOE of coal/d)	0.9	203000	8120	30
Coal liquefaction	($/TOE of coal/d)	0.9	200000	8000	30
Bio. gasification	($/TOE of bio./d)	0.9	193000	7720	30
Bio. liquefaction	($/TOE of bio./d)	0.9	230000	9200	30
Methane synth.	($/TOE of CH4/d)	0.9	86000	3440	30
MeOH synth. (CO)	($/TOE of MeOH/d)	0.9	86000	3440	30
MeOH synth. (CO2)	($/TOE of MeOH/d)	0.9	96000	3840	30
Mobile method	($/TOE of MeOH/d)	0.7	46000	1840	30
Electrolysis	($/TOE of H2/d)	0.9	201000	8040	30
CO2 recovery (Ch)	($/C-ton/d)	0.9	56500	2260	30
CO2 recovery (Ph)	($/C-ton/d)	0.9	14500	580	30
H2 liquefaction	($/TOE of H2/d)	0.9	362000	14480	30
CH4 liquefaction	($/TOE of CH4/d)	0.9	87500	3500	30
CO2 liquefaction	($/C-ton/d)	0.9	28100	1124	30
Shift converter	($/TOE of H2/d)	-	-	560	-

3.2.4. Simulation Results.

(1) Role of Nuclear Energy in the Global Energy Supply.

Figure 3.2.4-1 shows the 4 base case results, in terms of the global primary energy consumption. Note that the simulation results presented and discussed in this section are solely those aggregated worldwide, although the model generates detailed results for each world regions.

Due to the conservative cost assumptions for nuclear energy as its capital cost at 3,000$/kWe, contribution of nuclear energy is not expected at all in the B1-Base where no carbon control is requested, while even in the A1B-Base where much more energy input is wanted, nuclear energy contribution remains marginal. With the 550ppm requirement, nuclear energy comes into the optimal strategy both for the A1B-550ppm and B1-550ppm cases. However, with smaller needs of energy in B1, natural gas receives more emphasis during the middle and 2nd half of 21st century. IGCC with carbon sequestration is the main competitor with nuclear energy for both A1B and B1 with the 550ppm constraint. In particular, additional power needs for carbon sequestration with IGCC almost doubles the primary energy demand. in the A1B-550ppm case.

In similar motel applications in Fujino et al. (1997) and Yamaji et al. (1998), nuclear energy output was far greater in the baseline scenario. Since the author is not fully familiar with the very details of those precedent studies, just a few remarks can be put in explaining this discrepancy. First of all, the earlier version of Integrated LDNE21 did not have the feature of lead- and lag-time of Pu recycling and thus presumed *LT*1 and *LT*2 as zero implicitly. Moreover, the modification of nuclear power plant lifetime from 30 to 40 years, described in Section 3.2.2., should give its implication pronounced with its negative side.

This former aspect confirms the importance and justification of modeling the technological details, typically the lead- and lag-time in this study. Further scrutiny, at any rate, is needed for reasoning these discrepancies.

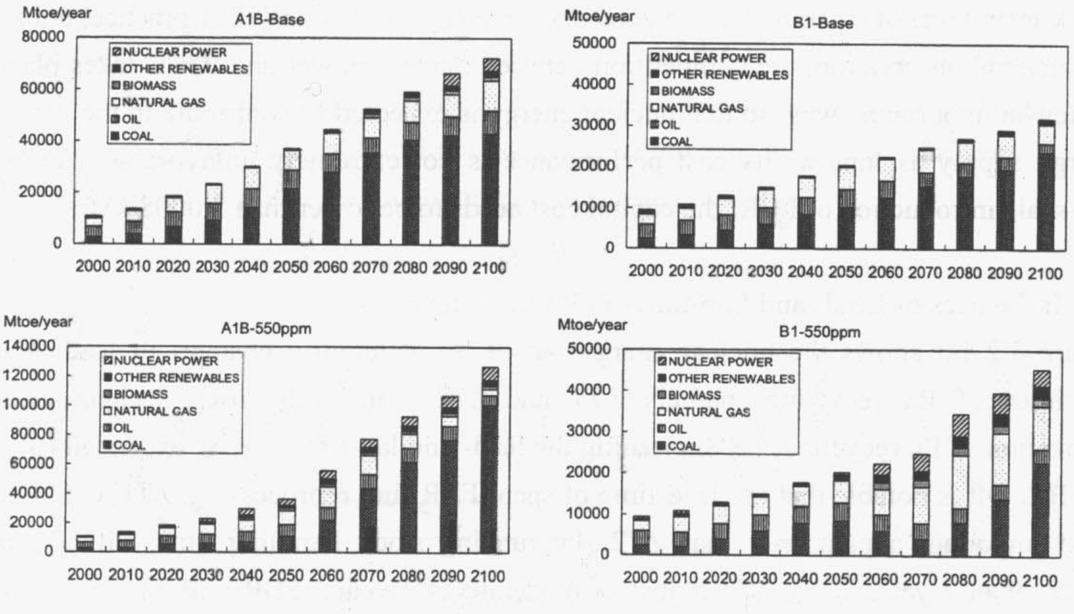


Figure 3.2.4-1: The 4 Base Cases for the Sensitivity Study.

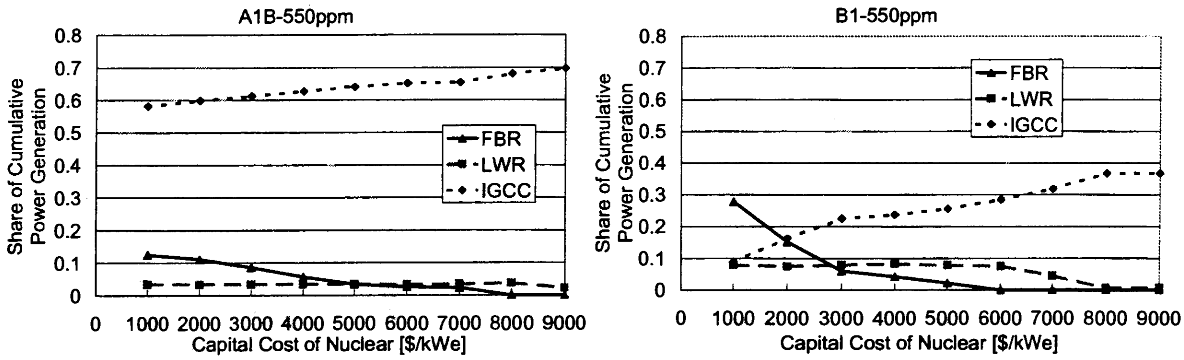


Figure 3.2.4-2: Competition between Nuclear Power and IGCC in the 550ppm constraint cases.

Figure 3.2.4-2 shows how nuclear energy and IGCC are competing each other, by parametric changes of capital cost of nuclear power plants ranging 1,000-9,000$/kWe. In Figure 3.2.4-2, the share of each technology in the global cumulative power supply for the entire period analyzed by the model, i.e. 1990-2100, is plotted against value of the capital cost of nuclear power. With A1B scenario where energy demand is very high, the role of nuclear energy is limited under the moderate conditions of cost performances of nuclear energy. With B1 in turn, nuclear energy is expected to grow to contribute the largest share of power in the 21^{st} century. It is notable that FBR will be introduced even if its capital cost is higher than 5,000$/kWe, though at a marginal scale. It is usually the case with a linear programming model to obtain so-called 'bang-bang' solutions, in which patterns of optimal solution change at a certain break-even level of a parameter in a zero-one manner. In this LDNE21 practice, unlike this general observation, the competition between nuclear power and IGCC takes place somewhat in a robust way, so that nuclear energy is expected to contribute to the global energy supply as long as its cost performance is not extremely unfavorable. For a full-scale introduction of FBR, the capital cost needs to be lower than 3,000$/kWe.

(2) Influences of Lead- and Lag-times in Pu Recycling.

Figure 3.2.4-3 shows the nuclear energy output by parametric changes of lead- and lag-times of Pu recycling, namely *LT*1 and *LT*2. In both cases, technological innovation of Pu recycling, i.e. shortening the lead- and lag-times, leads expanded roles of FBR. It is notable that the lead-time of spent FBR fuel reprocessing, *LT*1, could be more important a parameter than *LT*2, Pu running stock handling time. If *LT*1 is shorter than 2 years while *LT*2 is just as moderate as 2 years, FBR will be introduced and expanded at its maximum possible rate so that it provides as much energy as possible.

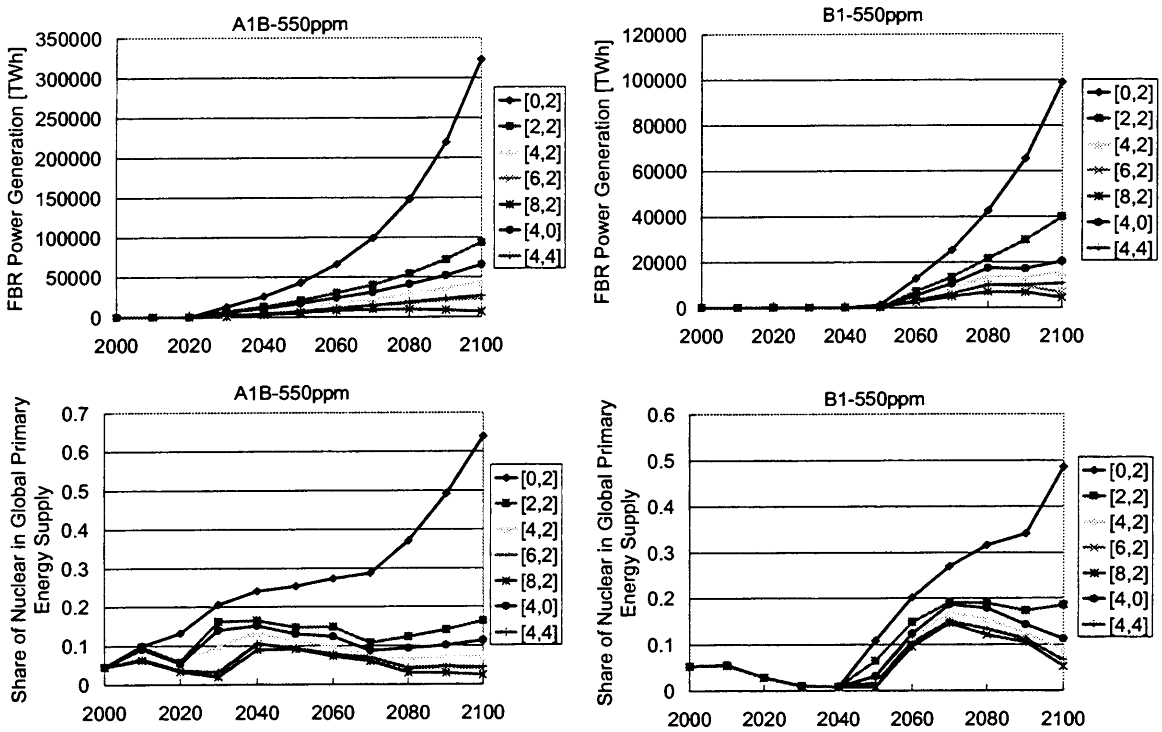


Figure 3.2.4-3: Sensitivity Analysis on Lead- and Lag Times of Pu Recycling System. (note: parameter set shown as [$LT1$, $LT2$].)

(3) Importance of the Natural Uranium Resource Constraints.

Figure 3.2.4-4 is the changes of nuclear energy output by increasing the natural uranium resource endowment from the reference 3 times of the currently known resources to 10 times, in the same format of Figure 3.2.4-2. Even with this large natural uranium resource endowment, 42 million ton (tU) compared with 12.5 million tU in the reference assumption, natural uranium is exhausted by 2100.

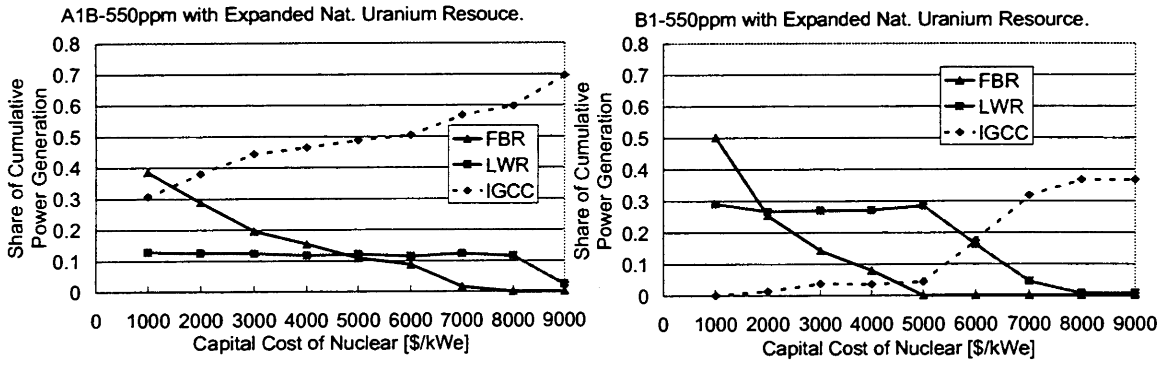


Figure 3.2.4-4: Sensitivity Cases with Expanded Natural Uranium Resource Endowment.

While a larger amount of uranium resource allows nuclear energy to play a larger role, interestingly enough, it does not necessarily mean introducing FBR. At around the high end of its capital cost, uranium resource addition pushes up the use of LWRs, and the introduction of FBR is not justified at 7,000$/kWe in the A1B-550ppm and at 5,000 $/kWe in the B1-550ppm cases, although both of the levels were justified with a smaller uranium endowment in Figure 3.2.4-2. Without introducing FBR, the natural uranium resource is utilized to get the maximum energy value with LWRs, and a certain amount of Pu is recycled in LWRs correspondingly to the overall cost conditions.

In summary, the uranium resource endowment may come up as an acute constraint in the course of 21^{st} century if we expect the maximum energy output of nuclear energy.

(4) Value of Nuclear Energy.

Figure 3.2.4-5 shows the value of nuclear energy utilization, which is expressed in terms of the reduction of the objective function, total net present value of global energy system cost, with reference to the 'no-nuclear' case with extremely high capital costs of nuclear energy. Figure 3.2.4-5 also shows the global cumulative electricity production from LWR and FBR combined.

The lower the capital costs of nuclear energy, the more energy production and thus the greater the total economic benefits nuclear energy provides. The value of nuclear energy, suggested in Figure 3.2.4-5, might as well be understood as the total investment justifiable for nuclear technology R&D.

Here, the results present a set of recursive questions; if the mankind expects good performance of future nuclear technology through enhancing R&D, they would be able to decide to invest more for R&D, and thereby secure the expected level of performance. If expected performance of nuclear technology would be somewhat poor, then any significant R&D investment would be justified and thus performance would eventually be never good enough.

This presents a tough challenge to the humankind; we must always repeat to ask ourselves to what extent nuclear technologies can become developed and what level of performance of technology can be obtained, and only based on the answer to that question we can decide an appropriate-as-we-think level of R&D investment coupled with magnitude of contribution from nuclear energy. If those prospect would fail in an unfortunate side, where nuclear technology will turn out poorer than expected even after R&D, we must obey the fact that certain amount of benefit we expected from nuclear energy will be lost. With this unhappy side of uncertainty, actual investment might be underestimated than optimal.

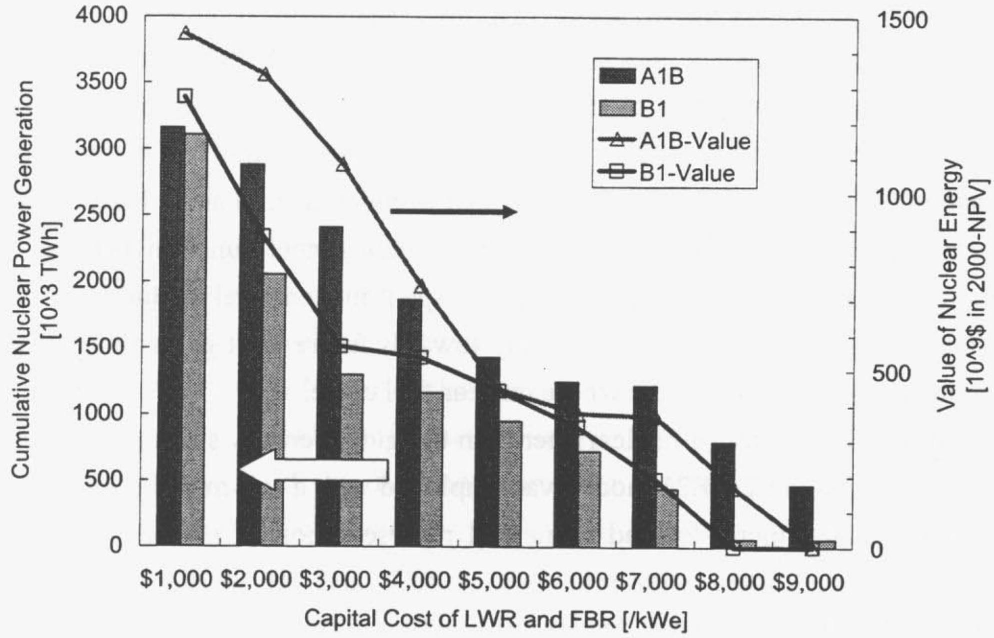


Figure 3.2.4-5: Value of Nuclear Energy Utilization.

The author admits that the results shown in Figure 3.2.4-5 are by far short to make a precise valuation of optimal investment for nuclear technology R&D worldwide. One conclusion can be manifested, however, that by the nature of this recursive question, the global community must keep looking at prospects of nuclear energy, regardless of the level of actual utilization then, at any time. If they find an optimal level of energy utilization and R&D investment, a reasonable decision should be made so that such an optimal path should not be missed but pursued in a timely manner.

3.3. Concluding Remark.

Chapter 3 presented the energy and nuclear fuel cycle modeling frameworks, with which the author attempted to describe optimal patterns of nuclear fuel cycle management in harmony with nuclear energy utilization pathways. Chapter 3 started with the development of Fuel Cycle Optimization Model (FCOM), and further extended to its integration with the LDNE21 global energy model, in order to analyze spent nuclear fuel management in an overall framework of nuclear fuel cycle and the global energy system. FCOM solves a long range (90 years) cost minimization problem of the LWR (light water reactor) – FBR (fast breeder reactor) symbiotic system based on linear programming. The optimal solution provides a desirable evolutionary pattern of plutonium (Pu) economy with Pu supply from reprocessing of spent LWR fuel as its key parameter. FCOM's superb feature is, despite a compact model, to obtain an optimal solution of management of spent LWR fuel integrated with reactor mix patterns. Through numerical experiments, it is concluded that spent LWR fuel storage is chosen to adjust future uncertainty as it gives flexibility to the whole nuclear fuel cycle to allow spent LWR fuel reprocessing according to Pu demand. The illustrative simulation runs showed that, while reprocessing of spent LWR fuel is undertaken in accordance with Pu demands, storage of spent LWR fuel provides the adjustment function between Pu supply and demand. This means that storage of spent nuclear fuel should be chosen actively as a measure to cope with uncertainty towards future as it gives flexibility to the management and operation of the whole nuclear fuel cycle.

In the analysis of future roles of nuclear energy in the global energy strategies up to the year 2100, the integrated LDNE21 model was employed with a sub-model derived from FCOM, which enabled more detailed numerical representation of nuclear fuel cycle. The base cases were chosen with reference of A1B and B1 marker scenarios of IPCC-SRES. In the base cases where no carbon dioxide emission control is considered, nuclear energy is utilized in a marginal scale or even none. In the cases with constraints of the atmospheric carbon concentration at 550ppm in the year 2100, nuclear energy will be employed as one of the main sources of electricity in the 2nd half of 21st century. The magnitude of nuclear energy utilization depends largely on its cost characteristics in the competition with IGCC with carbon sequestration. The simulation results suggest that under favorable cost conditions for nuclear energy, the constraints of natural uranium resources will come out as more acute, so that the global energy system will consume all available uranium resources to obtain maximum energy values. This does not necessarily mean, however, a large-scale introduction of FBRs. In particular, with hindrance of lag-time in plutonium recycling, introduction of FBRs would be deterred and, in the worst end, plutonium burning in LWRs is justified. With this respect, technology developments and innovations are needed not only cost characteristics but also technological performance of plutonium recycling systems with fast breeder reactors as its main actor.

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CHAPTER 4

Theory of Storage
- Optimal Storage Duration and Influence of Technological Progresses -

4. Theory of Storage: Optimal Storage Duration and Influence of Technological Progresses.

This chapter summarizes the optimality conditions and their key aspects for spent nuclear fuel management strategies from the engineering-economic point of view. After presenting a theory of optimal duration of storage, a review of underlying factors such as the economy of scale, the economy of scope, the learning-by-doing effect, and benefits of R&D are reviewed theoretically and empirically. This chapter is based on Nagano (1998a) and Nagano (2002).

4.1. Introduction: The Role of Spent Nuclear Fuel Storage.

One might eventually regard spent nuclear fuel storage with negative perception as postponement of decision or transfer of responsibility to future generations. The author wishes to emphasize, however, the positive aspects of spent nuclear fuel storage, which should be recognized more clearly and explicitly in order to develop desired future strategies.

There are three roles of importance in storage. Firstly, it has a function of emergency management. If an excess amount of spent nuclear fuel is generated beyond the capacity of storage pool co-located with power reactors, some additional storage devices are required to secure continuation of operation of the power reactors under such risks. Secondly, storage is necessary to manage spent nuclear fuel as running stock and feed to reprocessing facilities. This not only secures smooth operation of the reprocessing plant but also helps in flexibly balancing supply and demand of plutonium, which is the function specified clearly in Japan's current fuel cycle policy as 'energy resource stockpile' stated in Atomic Energy Commission of Japan (1994).

Finally, and even more importantly, the author puts an emphasis on the third role. While storing spent nuclear fuels and wastes properly, one could take time for technology R&D of treatments and processing after the storage, or further refinement of future strategy to incorporate more advanced technologies. The cost incurred for the storage would well be paid off by the revenue and benefit to be obtained from those technology improvements in the subsequent processes. This means, after all, that storage would be an opportunity to yield profit in the overall strategy, and also helps better to maintain flexibility and compatibility with socio-economic circumstances surrounding nuclear development.

Spent nuclear fuel storage is not a process that can not be helped in order to avoid temporal overflow of spent nuclear fuel stockpile, but rather should be recognized as an appropriate way to choose in conjunction with promotion of research and development.

4.2. The Theory of Storage.

4.2.1. The Optimality Conditions.

As stated above, storage has an important role to secure time for research and development. The following is an attempt of mathematical formulation to capture cost-benefit relations of storage and R&D in the strategic analysis of spent nuclear fuel management in Nagano (1997), Nagano (1998a) and Nagano (2002).

Figure 4.2.1-1 shows the scope of problem. Suppose that a unit, i.e. 1 tHM, of spent nuclear fuel is discharged from a reactor plant, which is to be stored until it will be reprocessed or disposed. From the reprocessing, corresponding amount of Pu will be recovered, which will then be fabricated as mixed oxide (MOX) fuel and reloaded to the reactor or another. The problem to be addressed here is to optimize the duration of storage to maximize total utility function, i.e.

$$\begin{aligned} TU = & - f_1(x) \\ & - e^{-rx} \cdot f_r \cdot (1 - i_r)^x \\ & - e^{-rx} \cdot f_2(y) \cdot (1 - i_2)^x \\ & - e^{-r(x+y)} \cdot f_m \cdot (1 - i_m)^{(x+y)} \\ & - e^{-r(x+y)} \cdot f_3(z) \cdot (1 - i_3)^{(x+y)} \\ & + e^{-rT} \cdot U \rightarrow \max . \end{aligned} \tag{1}$$

$$s.t.\ T = x + y + z \tag{2}$$

where,

- TU : Total utility at net present value at the year of the spent nuclear fuel discharge,
- $f_1(x)$: Cost of spent nuclear fuel storage for x years,
- f_r : Cost of reprocessing,
- i_r : Rate of reprocessing cost reduction due to 1 year addition of R&D,
- $f_2(y)$: Cost of storage of the corresponding amount of Pu for y years,
- i_2 : Rate of Pu storage cost reduction due to 1 year addition of R&D,
- f_m : Cost of MOX fuel fabrication with the corresponding amount of Pu,
- i_m : Rate of MOX fabrication cost reduction due to 1 year addition of R&D,
- $f_3(z)$: Cost of storage of the corresponding amount of MOX fuel for z years,
- i_3 : Rate of MOX fuel storage cost reduction due to 1 year addition of R&D,
- U : Utility obtained from the MOX fuel burning at T years from the discharge of the original spent nuclear fuel,

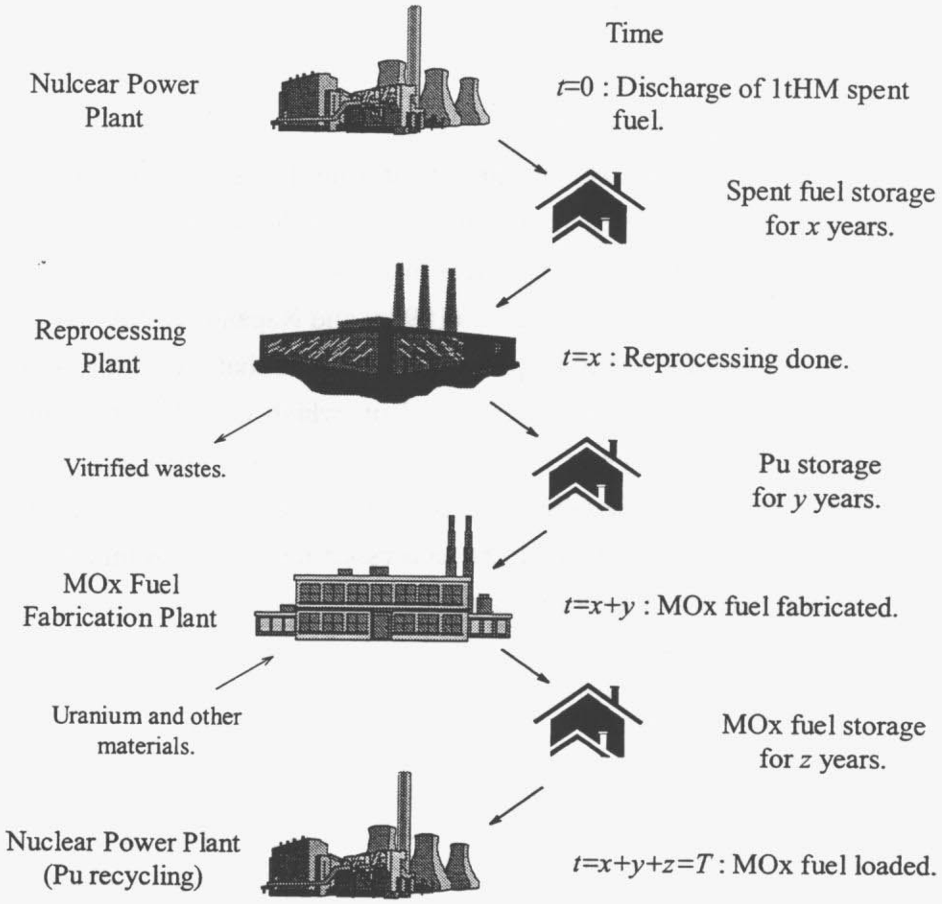

Figure 4.2.1-1: The Problem Definition.

r : Discount rate.

At this moment, the utility of Pu burning (either by FBR or light water reactor (LWR)) is quite uncertain, as implied by major countries' withdrawal from FBR development. If U is assumed as zero for simplification, then the original utility maximization problem turns to the total cost minimization. For another simplification, let various improvement rates i_x equal to i uniformly. Then, the formula (1) turns to the following formula.

$$TU = - f_1(x) - e^{-(r+i)x} \cdot f_r - e^{-(r+i)x} \cdot f_2(y) - e^{-(r+i)(x+y)} \cdot f_m - e^{-(r+i)(x+y)} \cdot f_3(z) + e^{-rT} \cdot U \rightarrow \max. \qquad (3)$$

The assumption of uniform rate of technology improvement is translated as increase of discount rate from r to $(r+i)$ superficially. However, the nature of technology improvement is not merely a function of time spent for R&D but indeed also influenced by the experiences accumulated throughout research, development and commercialization. This is one of the largest issue, among all in this report, that needs further refinement. Now to solve to problem, the *laglange* coefficient λ is introduced.

$$I = TU - \lambda(T - x - y - z) \qquad (4)$$

Then, the following 4 necessary conditions for optimality are derived:

$$\frac{\partial I}{\partial x} = -f_1'(x) + (r+i)e^{-(r+i)x} \cdot f_r + (r+i)e^{-(r+i)x} \cdot f_2(y) + (r+i)e^{-(r+i)(x+y)} \cdot f_m + (r+i)e^{-(r+i)(x+y)} \cdot f_3(z) + \lambda = 0 \qquad (5)$$

$$\frac{\partial I}{\partial y} = -e^{-(r+i)x} \cdot f_2'(y) + (r+i)e^{-(r+i)(x+y)} \cdot f_m + (r+i)e^{-(r+i)(x+y)} \cdot f_3(z) + \lambda = 0 \qquad (6)$$

$$\frac{\partial I}{\partial z} = -e^{-(r+i)(x+y)} \cdot f_3'(z) + \lambda = 0 \qquad (7)$$

$$\frac{\partial I}{\partial T} = -r \cdot e^{-rT} \cdot U - \lambda = 0 \qquad (8)$$

Here, another assumption for simplification, $f_3(z)=f_3'(z)=0$, is introduced. This seems reasonable as storage of fresh MOX fuel, though shielding and safeguards requirements will be imposed, may not be too costly in comparison among the other cost items Another justification is that fresh MOX fuel, if once fabricated, should be used instantly, which suggests z=0. Then, from equation (7);

$$\lambda = 0 \qquad (9)$$

Thus, the first implication is derived from equations (8) and (9). If the utility function of Pu uses U is positive, then I is a uniformly declining function of T and thus T=0, which means that storage of spent nuclear fuel is not used and spent nuclear fuel should be reprocessed immediately. In turn, if U is negative, I is a uniformly augmenting function of T, which means that storage of spent nuclear fuel should be utilized as long as appropriate.

$$f_1'(x) = e^{-(r+i)x} \cdot f_2'(y) + (r+i)e^{-(r+i)x} \cdot (f_r + f_2(y)) \qquad (10)$$

If one can assume that Pu storage is always too costly, then;

$$f_1'(x) = (r+i)e^{-(r+i)x} \cdot f_r \qquad (11)$$

The equations (10) or (11) is the fundamental form of the optimality condition to determine the optimal duration of each of the storage options, which makes the following two equal;

- the increase of cost of storage due to 1 year prolongation of storage duration, and
- the decrease of the net present value of total cost of all processes after the storage due to a 1-year delay caused by prolonged storage.

The latter factor consists of a change of net present value due to 1-year discounting and improvement resulted from R&D efforts taken during the storage duration. Note that the improvement in this notation should be defined in a broad sense, so that reductions of institutional and transaction costs, such as improved public awareness and acceptance, more efficient and appropriate planning into the future, should be recognized as parts of those technology improvement. Also note that the above formulation does apply also for the case of direct disposal, simply replacing suffix r for reprocessing with d for disposal.

4.2.2. Numerical Examples.

(1) Optimal Storage Duration.

Based on the published cost data (OECD/NEA (1991) and OECD/NEA (1994)), the author tried to solve the original problem numerically. The result is shown in Figure 4.2.2-1. If discount rate r (added with the uniform rate of technology improvement i) equals to zero, there is no reason to postpone, and the optimal strategy is to skip storage and go immediately to the next step, either reprocessing or disposal. In the cases of positive discount rate and technology improvement, an optimal storage duration could be obtained which minimizes the total system cost. It should be noted that this characteristic is highly dependent to the functional form how storage duration influences to the storage cost.

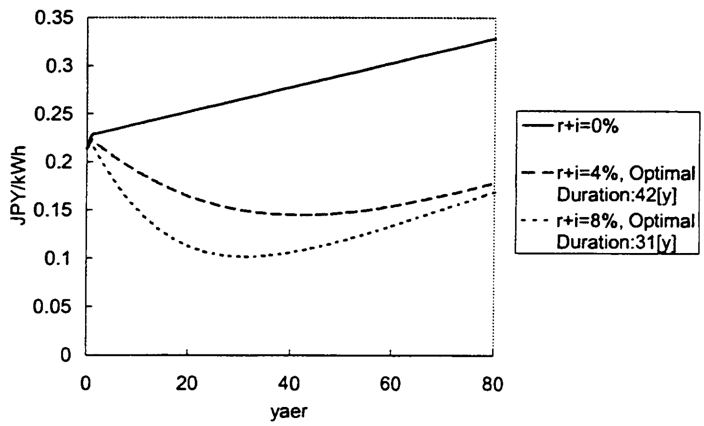

Figure 4.2.2-1: The optimal storage duration based on the cost data from OECD/NEA (1991) and OECD/NEA (1994).

(2) Effect of Uncertainties.

The problem has been dealt with as maximization of the expected value of utility function, or minimization of the expected value of total cost. In reality of today, however, it is apparently not enough to explore strategies to obtain desirable score in average, but indeed it is the efforts to minimize future uncertainties that are wanted, regardless of small fluctuation of utility or costs.

Based on this observation, here the author attempts an extension to uncertainty consideration. Among items to constitute the objective function, it would be rather difficult to foresee sudden spike of costs for each process in the assumed nuclear fuel cycle in the near future while technological improvements are expected. In this regard, uncertainties could well be incorporated in the problem by putting conservative assumptions on technological improvement parameters. Reprocessing of spent nuclear fuel must be recognized as the exception of this, since its technological maturity is yet insufficient at present and a certain degree of fluctuation of its cost should be kept in mind as likely, varying from cost decrease due to technological improvements to cost increase caused by unexpected troubles and incidents. These uncertainties can be controlled and lowered over time by continued efforts to accumulate operational experiences.

On the other hand, the largest uncertainty factor should be those related to the value of Pu uses. While the author made an attempt to explore energy values of nuclear power and its competition among other energy sources in chapter 1, he must admit he has not yet found any decisive enough basis to judge whether or not Pu uses should be promoted for various aspects, such as inter-energy competition, CO_2 emission control strategies or concerns and/or oppositions from public. Whichever the final judgment would be, this uncertainty must be lowered and removed from now on through discussions and debates in the society.

After all, the author modifies the original problem (formula (1)) to derive the following portfolio optimization problem taking uncertainties into consideration.

$$\begin{aligned} TU^{*}-\alpha*\sigma(TU) = \; & -f_1(x) \quad -e^{-rx}\cdot f_r\cdot(1-i_r)^x \\ & -e^{-rx}\cdot f_2(y)\cdot(1-i_2)^x \\ & -e^{-r(x+y)}\cdot f_m\cdot(1-i_m)^{(x+y)} \\ & -e^{-r(x+y)}\cdot f_3(z)\cdot(1-i_3)^{(x+y)} \\ & +e^{-rT}\cdot U \\ & -\alpha_1*\sigma_r\left[e^{-rx}\cdot f_r\cdot(1-i_r)^x\right] \\ & -\alpha_2*\sigma_U\left[e^{-rT}\cdot U\right]\rightarrow \max. \end{aligned} \qquad (10)$$

where,

α : factor of risk averseness,

$\sigma(TU)$: a penalty coefficient caused by uncertainties, such as the standard deviation of expected value of the total utility function. In the right-hand side of the formula (10), this factor is represented by the following two items; the one related to reprocessing cost (σ_r), and the other related to the utility of Pu uses (σ_U).

In order to solve this problem, one needs to know probabilistic distributions (or standard deviations, at least) of those factors under uncertainties, namely reprocessing costs and utility values from Pu uses. Under the present circumstances, it should be extremely difficult (if not impossible) to get assumptions on those uncertainties in a reasonable and objective manner, while one might attempt to apply his or her own subjective views.

Here, the author maintains within some qualitative observations. Under standard sets of cost assumptions, such as those used in the calculation in Figure 4.2.2-1, the optimal strategy suggested by the original problem of formula (1) will be the one where spent nuclear fuel storage for the duration x^* is employed followed by immediate reprocessing and Pu uses, when a value of x^* is found to equalize the following two factors (a) and (b), namely;

(a) the sum of the following three:

a-1) the cost increase due to 1-year prolongation of spent nuclear fuel storage,

a-2) the change of net present value of the costs of processes after reprocessing due to 1-year delay, and

a-3) the cost reduction due to 1-year addition of R&D efforts before reprocessing is done.

(b) the loss of utility due to 1-year delay of recycle uses of materials recovered from reprocessing.

In formula (10), penalty factors resulted from uncertainties of reprocessing costs and utility of Pu uses are added to the original problem in formula (1). These uncertainties, in the simplest case, are expected to be removed over time. Therefore, the optimal solution for formula (10) will be such that according to the degree of uncertainties a longer storage duration x^{**} than the optimal solution x^* for formula (1), i.e. $x^{**}>x^*$. The larger the risk averseness parameters α_1, α_2, the longer the optimal duration of storage.

Looking back the original problem of formula (1), the objective function should be in most cases predominated by the utility function of Pu uses among other factors, which occupy quite small portions of nuclear power generation costs. If this stands true, optimality conditions are determined by the present value of utility of Pu uses. If it is positive, the earliest possible recycling of Pu as the other technical conditions allow will be optimal, i.e. $T \rightarrow 0$, while if negative the latest possible recycling will be optimal, and if other conditions do not limit T, ultimately no recycling as $T \rightarrow \infty$. Here, a portfolio problem similar to formula (10) is applied, and then we obtain the optimal timing of Pu recycling T^{**} determined by degree of risk averseness, which replaces T in formula (2). With this new boundary condition and an alternate objective function removing U from formula (10), we obtain a modified optimization problem, which generates an alternate optimal storage duration of spent nuclear fuel according to uncertainties of reprocessing costs as well as risk averseness against them.

This relationship is illustrated in Figure 4.2.2-2. In this case, the utility value of Pu recycling is assumed as positive, which results in an anomaly solution of immediate recycling, i.e. $T^{*}=0$. If we neglect this special case, the optimal duration of spent nuclear fuel storage will vary depending on degree of risk averseness against reprocessing costs.

Through considerations above, the author concludes that storage of spent nuclear fuel will be chosen as optimal solutions as it is beneficial to obtain time to explore clear picture toward future under uncertainties. We implement spent nuclear fuel storage, not because of postponement of decision making or putting off the burden to future generations, but indeed as the optimal measure to tackle future uncertainties.

The author admits the above reasoning remains within qualitative observations without strictly solving the problem, either analytic or numerical. Extensive works are necessary to obtain quantitative implications by clearly defining uncertainties in nuclear energy strategy planning.

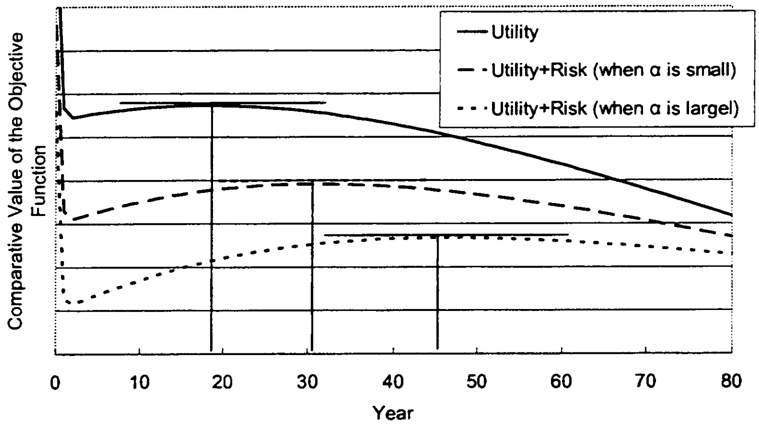

Figure 4.2.2-2: An Illustration of Uncertainty Considerations.

4.3. The Economics of Storage: The Economies of Scale and Scope, The Learning Effect and R&D Benefits.

Theoretically, there are four factors that predetermine optimal conditions on how, where, when and for how long time storage devices are to be installed. In the following sections, the author tries to review each of the factors, according to Nagano (1998b) and Nagano (2002).

4.3.1. The Economy of Scale

This widely-known phenomenon is defined as the larger the capacity of a certain process, the lower the unit cost of production, as in the following formulas:

$$\frac{TC(p)}{TC_0} = \left(\frac{p}{p_0}\right)^{\gamma} \qquad (11)$$

$$\frac{UC(p)}{UC_0} = \frac{\frac{TC(p)}{p}}{\frac{TC_0}{p_0}} = \left(\frac{p}{p_0}\right)^{\gamma-1} \qquad (12)$$

where,

$TC(p)$: Total cost of production at the capacity p,

TC_0 : Total cost of production at the reference capacity p_0,

γ : Scale exponent (0□γ□1),

$UC(p)$: Unit cost of production at the capacity p,

UC_0 : Unit cost of production at the reference capacity p_0.

The smaller the value of γ, the more evident the scale merit and the smaller the unit cost of production. If the capacity is proportional to the volume (i.e. *l* to the third, where *l* is a representative length) and the total cost is proportional to the area (i.e. *l* to the second), then the scale exponent γ equals to 2/3=0.67. This is particularly true where a scale-up can be done simply by expanding the size and capacity of machinery equipment.

In the field of nuclear power generation, the scale exponent experienced in the power plants constructed in the United States is evaluated as 0.7 according to Mooz (1978) or not identifiable in Mooz (1979). Another example is found in the small and medium reactor study conducted by IAEA (1984). It concluded that the scale exponent is in the range of 0.4-0.5 with the lower number applied to the smaller capacity, i.e. in the range of 200-400 MWe. These imply that although statistical credibility is low, we could, to some extent at least, believe in this phenomenon in the case of nuclear power plants.

In the case of spent nuclear fuel storage, an IAEA study generated through a worldwide survey a diagram that shows how the unit storage cost declines as capacity expands for various storage technology options in IAEA (1990). Although it is difficult to figure out specific number of γ, superiority of water pool and vault storage for AFR (away from reactor) storage at large capacity (i.e. 3,000 MTHM (metric ton of heavy metal) and after) can be seen clearly. Dry cask storage shows no significant scale merit when capacity becomes 1,000 MTHM and larger. Another example of diagram reported for the United States in Anderson (1995) shows us a large potential of scale economy for vault storage in the capacity range of 200-1,000 MTHM, as γ even smaller than the '2/3 power theorem'.

In the Japanese situation, a sensitivity analysis shows about the storage cost of water pool storage, dry cask storage and vault storage along with the storage capacity from 1,000 to 5,000 MTHM, as γ values at 0.802 for water pool, 0.874 for dry cask and 0.823 for vault according to Yamaji et al. (1987). In another assessment, in the range of 3,000-10,000 MTHM, one can see at around 0.7 for water pool, 0.8-0.9 for dry cask and vault in Nagano et al. (1990). Although these individual examples are not explanatory enough to prove any rule, it is implied that scale economy is expected in the case of water pool storage to a larger extent than for dry cask storage. Furthermore, the scale economy of spent nuclear fuel storage is more evident in a smaller range of storage capacity, e.g. 500-1,000 MTHM.

4.3.2. The Economy of Scope

This is considered as efficiency improvement and cost reduction through enhanced coordination and collaboration among different production processes. Such benefit is obtained from, for example, shared use of common resources and equipment.

In the field of spent nuclear fuel management, the economy of scope has its importance in strategic planning of whether individual storage devices are installed to each power plants or collective storage facilities in rather small number of places. In this case, the above mentioned scale economy should also be paid attentions to. Moreover, it should not be overlooked that the burden of transportation of spent nuclear fuel would differ substantially between these cases.

An example of the economy of scope in the other sense can be found in Gorleben, Germany, where a pilot plant of spent nuclear fuel conditioning is now under construction. This facility will be used not only for testing and demonstration of the spent nuclear fuel conditioning technique, i.e. rod consolidation, but also a repair facility for a deficient dry casks received in the adjacent cask storage facility, which does not have a hot cell of its own. Another example worth mentioning here is in Würenlingen, Switzerland, where ZWILAG, an extensive waste storage facility, is under construction. As this facility will store all kinds of radioactive wastes generated in all over Switzerland, some of the facilities and resources would be possibly used commonly for various purposes and types of wastes.

The economy of scope would be even more pronounced in considering regional or international collaboration, not only actual operation of nuclear fuel cycle but also research and development of technology options, with respect to appropriate sharing of burdens, skills and resources, and fruits of such activities.

4.3.3. The Learning Effect

This famous phenomenon is expressed in the following formulas:

$$C(n) = C_0 \cdot \delta \cdot \left(\frac{n}{2}\right)^{-\beta} = C_0 \cdot n^{-\beta} \qquad (13)$$

$$\delta = 2^{-\beta} \qquad (14)$$

where,

$C(n)$: Production cost of the n-th unit of product,

C_0 : Initial production cost,

β : Learning coefficient ($0<=\beta$),

δ : Learning factor ($0<\delta<=1$).

The learning factor δ is the rate of cost improvement at each time when the cumulative number of production doubles. The learning effect was found in many industrial production processes such as automobile manufacture. One can easily imagine that this effect is more evident in such production process where a large number of standardized products or operations are repeated. In the field of nuclear energy, the learning coefficient in the United States was evaluated as -80.92 US$(1978)/kWe in Mooz (1978), which is understood that each time when the cumulative number of reactor unit becomes 2.72 times, the unit cost of construction becomes 80.92 US$(1978)/kWe lower. In the subsequent round of evaluation, the number was even larger as -96.23 in Mooz (1979).

For spent nuclear fuel storage, it seems little data available for now to what extent we could expect from this learning-by-doing effect. It could be mentioned that we have observed a significant decline of price of storage casks. In Yamaji et al.(1987), the price for a cask was reported as more than 300 million JPY(1987), but experts say that we have captured technology improvement during these years and now the price could be well 30-50% lower than this. Note that this would be resulted from either technological progress of cask manufacture or simply enlarged competition in the real market. These are both considered, after all, as fruits of learning-by-doing effect in a broad sense. Moreover, as there are yet few commercial spent nuclear fuel storage facilities in Asia, further improvement forged by more competition will be very likely as the market grows.

This learning effect is also an important factor to determine whether standardized unit storage devices are installed sequentially according as demand increases or a large capacity is installed at the beginning at one time. In this case, a trade-off with the economy of scale becomes an issue that needs to be carefully examined.

4.3.4. Benefit from Research and Development

Storage of materials has its value to obtain time to promote R&D, and thereby reducing costs of subsequent processes. A theoretical framework to see how long they are kept in store has been presented in 4.2.

In reality, benefit from R&D will realize in one or multiple of the above mentioned factors. Learning effect should be enhanced by R&D, while R&D may enable scale-up of facilities. Actual strategy planning of spent nuclear fuel management should therefore take combinatory effects of the above all into full consideration.

4.4. Concluding Remark.

This chapter summarized the author's attempt to develop a methodological framework of optimal strategy planning of spent nuclear fuel management. The key component of it is the dynamic trade-off relations among the economy of scale, the economy of scope, the learning by doing effect and R&D benefits. In other words, optimization of how large, where, when and how long spent nuclear fuel storage should be implemented and utilized is the heart of the issue. The author should readily admit that both data collection and development of analytic tools are now at preliminary stages only, and further efforts should be undertaken. Along with the methodology development and numerical simulations, actual and realistic ways of consensus building and negotiation for strategies of national and regional scales should also be focused and explored, as the author plans to address in the future.

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