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A Study on Multilateral Management Options for Spent Nuclear Fuels in Northeast Asia Using Multi-criteria Evaluation

다기준 평가를 활용한 동북아 사용후핵연료

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에너지시스템공학부

노 현 엽

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노현엽의 박사 학위논문을 인준함

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Abstract

A Study on Multilateral Management Options for Spent Nuclear Fuels in Northeast Asia Using Multi-criteria Evaluation

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Civilian nuclear energy is still considered as a reasonable alternative to cope with the depletions of fossil fuels and the increase in greenhouse gas emissions. Many Asian countries have national plans to maintain or to increase their dependence on nuclear power despite the growing safety concern from Fukushima accident. Operations of nuclear power plant inevitably lead to the discharge of spent nuclear fuels (SNFs) which present serious challenges in safe disposal. So far only two different strategies are industrially used for managing spent fuels around world. Either the SNF is reprocessed to recover usable materials with some reduction of waste volume or it is directly disposed in a deep geological repository. Considering the risks of nuclear safety, security or nonproliferation relating to SNFs, SNF management is considered as national challenge in Northeast Asia where population densities are very high. Especially in the cases of Taiwan, Japan and ROK, it is difficult to employ two industrial strategies. The direct disposal option is not suitable for regions with high population density and/or with unstable geological conditions.

Commercial reprocessing is restricted from both economy and safeguards aspects. With significant delay in finding solutions, The Republic of China (Taiwan) is forced to shut down nuclear power plants with the saturation of on-site storage. In the case of ROK, it is also headed towards similar course with the SNF saturation in 2024, and Japan has faced the same difficulty in managing SNFs. In this context, there has been several exploration for multilateral cooperation to the spent nuclear fuel management since the early time of peaceful use of nuclear energy. Now, multilateral approach suggested in 2000s has proven to be practical in case of the front end of fuel cycle as demonstrated by International Fuel Bank or International Uranium Enrichment Center while such effort for the backend cycle is yet to be developed.

In past studies on SNF management options, some have examined unilateral and bilateral solutions to cope with the saturation problem with domestic perspective, whereas the other studies in broader perspectives have considered various solutions including multilateral options. In their evaluation, a set of criteria employed in earlier studies covered various factors as a whole, but without considering multilateral features in criteria. Therefore this thesis is designed to complement past studies with broadened criteria to evaluate to multilateral options for SNF management. The primary goal of this study is to set at examining and recommending feasible multilateral options for spent fuel applicable to the Northeast Asian region where high population density and low trust in Governments have created intense public concern. To achieve the goal of this study, the following research questions were determined:

1) What are the possible multilateral options for SNF management in Northeast Asia, and then how can these be evaluated?
2) Which multilateral option is preferred, and what criteria should be considered as significant?
3) What are the strategic plans for introducing multilateral options to Northeast

Asia and the ROK?

Available options are examined by the process of elimination in order to reduce to a few choices suitable for Northeast Asian countries for multinational approach. To evaluate relative merits, a set of qualitative and quantitative criteria related to spent nuclear fuel management and its multilateralization have been derived., Finally the analytic hierarchy process (AHP) method has been employed as the best one for the multi-criteria decision making approach after reviewing available methods. The AHP method was applied using various evaluation criterion the SNF management or the innovative nuclear fuel cycle system. Moreover, it includes the multilateral characteristics based on the definition and basic principles of Multilateralism. Resultant seven top-tier criteria are selected to include the area of technology, nuclear safety, security and nonproliferation, environmental impact, economics, domestic acceptance, and multilateral acceptance. For more detailed assessment, a total of twenty second-tier criteria are defined as the in-depth evaluation basis. For acceptable options for SNF management in Northeast Asia, three multilateral options are selected as follows.

First, a "regional SNF repository" established for disposing of SNFs in a joint repository facility which satisfies both geological conditions on the long-term safety and security requirements against human intrusion. This option is regarded as one of the most practical solutions since it does not modify original forms of SNF. It also can be featured as that candidate host countries can be not limited to nuclear power countries. Countries in the region regardless of own operating nuclear power plants can host the facility only if there are suitable sites.

The second option is the concept of "regional reprocessing and storage", which operates commercial reprocessing capacities and safeguards all sensitive nuclear materials within a joint facility. This approach utilizes the multilateral

framework for a stable supply of commercial reprocessing services without spreading the sensitive technologies. Furthermore, enhanced security measures and safeguards can be expected by the joint control of sensitive materials produced by reprocessing. High Level Wastes generated at the facility will be bound to the country of origin or to a regional repository.

The last, a "multilateral partitioning and transmutation (P&T)", is an approach based on future scaling-up of lab-proven innovative technologies that can reduce the final disposal burdens of SNF through P&T of high level wastes into intermediate and low level wastes. However, it needs significant amounts of time and money to promote from current stage of research and development (R&D) to commercialization thus a multilateral cooperation can be effective in its progress. Intermediate level waste/low level wastes will be bound to the country of origin considering that many countries already operate such repositories.

Based on the selected criteria and possible multilateral options, this thesis establishes a comparative assessment model on suitable option(s) for multilateral SNF management. According to the results of expert survey for assessing practical and professional options of "regional SNF repository" preferred for SNF management in Northeast Asia.

A "regional SNF repository option" receives the highest preference in most criteria. It is worthwhile to note that this option is similar with the ongoing proposal by Australian state government. The "multilateral P&T" is the next favorably evaluated option particularly on public acceptance, political support, ethical consideration and multilateral identity.

The "regional reprocessing and storage" has relatively high acceptance only in the technology criteria. The main difference between these two recycling options is originated from the fact that the former, "multilateral P&T", can eliminate the waste disposal burdens fundamentally. In addition it can also allow cooperation without discriminations in technical aspects because this

option is based on innovative technologies requiring further R&D efforts.

The most notable point is that the factors considered as important by the expert group are different from general perceptions. Feasibilities in technology and economics would be considered as important factors for deciding a national policy, R&D investment, or long-term plan but this study identifies the importance of other factors such as nuclear safety, security and nonproliferation, public acceptance and intention of hosting in the case of multilateral SNF management. Considering required time and features of multilateral SNF management, it indicates that public acceptance and siting as the requirement for long-term policy should be considered more important than technology and economics in current.

If the multilateral management options for SNFs are to be introduced in Northeast Asian region, to manage SNFs, member countries must take proactive measures to enhance the level of regional nuclear safety, security and nonproliferation. In return, the multilateral cooperation on this matter can serve both as a confidence building measure easing the tensions in Northeast Asian region, and as a foundation for continuous collaborations among the regional countries. In case of ROK, if multilateral options are promoted in parallel with the domestic strategy for SNF management, the improvement of public acceptance can be achieved by providing alternatives to current national strategy to widen choices for national SNF management plan. Finally, it is emphasized that the multi-criteria evaluation model established in this thesis should be further verified to actively respond to the changes of policy environments on SNF management.

Keywords: Backend nuclear fuel cycle, Spent nuclear fuel management, Northeast Asian region, Multi-criteria evaluation, Analytic hierarchy process, Multilateral management options
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Chapter 1 Introduction

1.1 Background

Management of spent nuclear fuel (SNF) is an inescapable problem that must be solved properly and timely for the safety and security of public. In most countries using civilian nuclear power, SNFs are discharged from nuclear reactors, and accumulated to wait for various management steps until final wastes are disposed of in a repository. Considering the already accumulated and additional expected arising SNFs from normal operations, all the necessary management options should be prepared for future generations regardless of what worldwide nuclear industry outlook would be. It means that it requires both a reactive measure for existing SNFs & resultant wastes and proactive measures for predicted ones considering all cases of national scenarios.

To this date, the global nuclear power capacity has been steadily grown with time even though several disastrous events including the Three Mile Island, Chernobyl and Fukushima accidents have caused disruptive changes. According to the IAEA's Nuclear Technology Review 2015, nuclear power capacity would grow from 372 GWe to 401 GWe in the low projection and to 699 GWe in the high projection by 2030 [1]. This trend of growing capacity is expected to continue with newcomer countries considering, planning and/or starting new nuclear power programs. [2] The trend is based on the belief that that nuclear power is the only massive and inexpensive alternative of fossil fuels while reducing green-house gas emission. As of Power Reactor

Information System of the IAEA, there are 444 operating commercial nuclear power plants and 64 additional plants under construction around the world [3]. This status of commercial nuclear power plants will bring high demands on the nuclear fuel cycle services including both in the frontend and in the backend. As for the frontend nuclear fuel cycle, supplying capacities from uranium mining to fuel fabrication are sufficient to meet international demands but the situation in the backend cycle is not [4]. Increased commercial nuclear activities, in turn, will raise the urgency for preparing solutions for SNF management.

The amount of discharged SNFs depends on how much activities are exerted in nuclear power plants. In this regard, Northeast Asian region should be considered as the most important area. In this region, the electrical capacity depending on nuclear power production is predicted to continue increasing even other regions maintain their status quo or reduce those capacity. Of the world's operational reactors and reactors under construction, 24.1% and 45.3%, respectively, are within this region [5]. Furthermore, there are national plans to add nuclear power plants in each of the Asian countries. Figure 1.1 shows the distribution of nuclear power plants presently in operation and under construction, and it is obvious that the density of nuclear power plants in this region is extremely high in the world.

In Asian region, there are four traditional nuclear power countries; China, Republic of Korea (ROK), Japan and Taiwan. They have mainly driven the civilian nuclear market growth in Asia, and this driving-force will be strengthened by newcomers in the long-term perspective [6]. Thus, it is expected that the net stockpiles of spent nuclear fuels in this region would be

firmly increased by about 1.63 times as shown in Figure 1.2 [7].

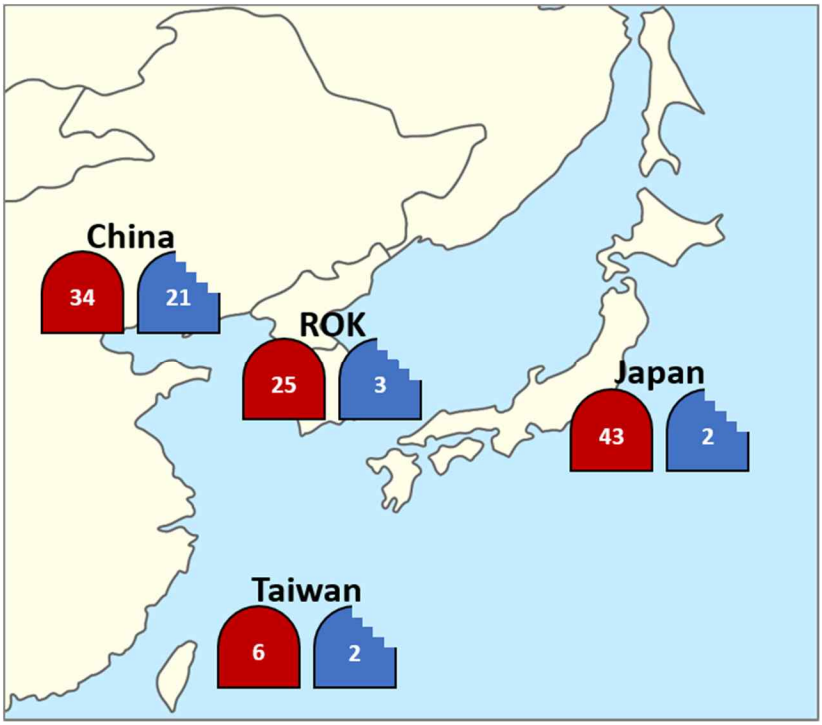

Figure 1.1 Nuclear power plants in Northeast Asian region

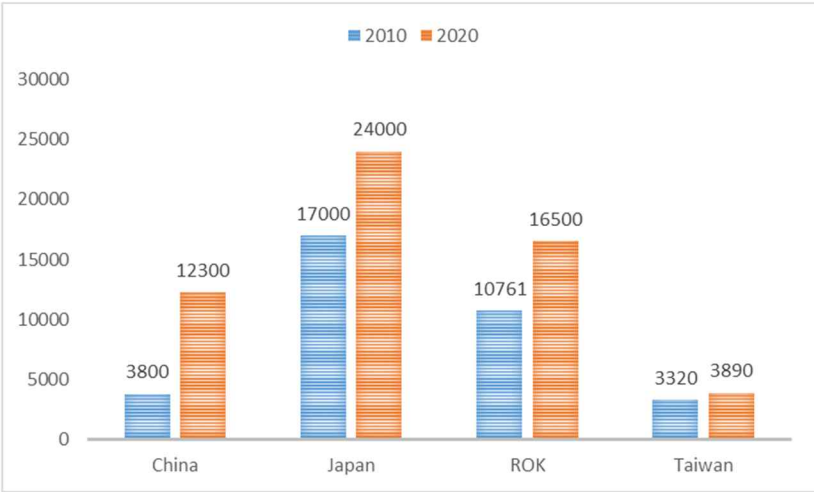

Figure 1.2 Spent nuclear fuel stockpiles in Northeast Asian (in tons)

The rise in Chinese nuclear power capacity is the most notable across the world. Nuclear electricity production share in China was 2.11% in 2013 but is expected to increase given that there are 24 new nuclear power plants under construction, with these comprising 36.2% of total reactors being constructed [8]. As a declared nuclear weapon state, China has a capability for commercial reprocessing of SNFs and has plans to become self-sufficient in most stages of nuclear fuel cycle. Now the Chinese government is preparing a geological repository for high-level wastes (HLW), and acceptance of HLW is anticipated from 2050 [9].

ROK considers nuclear power as an important energy source because one third of its domestic electricity production depends on this source. The nuclear energy program in ROK was initiated for energy security, to minimize dependence on imported fossil fuels [10]. As one of non-nuclear weapon states, ROK adopts the once-through fuel cycle and has no enrichment and reprocessing capabilities. However, there is no obvious solution for SNF management despite an anticipated SNF saturation in 2024 [11].

Nuclear energy has an important role in Japan, notwithstanding the Fukushima accident, so there are 43 operable reactors and two units under construction. The Japanese nuclear program was also initiated with the intention of minimizing dependence on energy imports and maximizing its utility. In this reason, the Japanese government has adopted the closed fuel cycle as part of its national strategy, thus Japan also has reprocessing capability, making it the only exception amongst states in current nonproliferation regime. Japan has a full fuel cycle set-up, including enrichment and reprocessing of

SNF, and now has a plan for searching the site of HLW disposal [12].

Taiwan, importing 97.5% of its energy, operates six units of nuclear power plant that provide one quarter of base-load power because nuclear power is considerably cheaper than other alternatives [13]. However, the Democratic Progressive Party elected in January 2016 has a non-nuclear stance and intends to phase out nuclear power by 2025 thus the Taiwanese nuclear capacity would be expected to gradually decline. The biggest problem emerged in recent is the SNF saturation; the on-site SNF pools in Jinshan and Guosheng will be full in 2016, and introduction of geological repository for HLW is too far to solve the urgent matter [14].

If any proper measures are not introduced in timely, the operation of nuclear power plants should be stopped and it cannot avoid that the SNF managements are placed in jeopardies on safety, security and proliferation. Considering high density of nuclear power plants in this region, it can foresee that any kinds of nuclear accidents based on lax management of SNFs will extensively influence on neighbor countries. Moreover, the SNF management in Northeast Asian countries is important not only to each four countries but also to other Asian newcomers since they want to introduce nuclear power plants with a guarantee on service supplies in the whole fuel cycle. Considering difficulties and risks on SNF management in a newcomer country, it is necessary to establish a good precedent on the matter of SNF management in Northeast Asia prior to the beginning of newcomers' expansions. That is why this study mainly focuses on Northeast Asia as a target region for SNF management.

1.2 Management of spent nuclear fuel

After cooling periods in on-site pool and interim storage, nowadays two different strategies are used for managing spent fuel from power reactor. Either the SNF is stored and then reprocessed to recover usable materials (uranium and plutonium) or it is directly disposed in a deep geological repository. However, the former is strictly controlled as a sensitive technology in the global nuclear non-proliferation regime thus only several countries, which are recognized as nuclear states in the NPT (China, France, India, The Russian Federation and the United Kingdom), are allowed to have commercial reprocessing capacity. Global reprocessing capacities, 5,370t HM per year in current, are not enough to deal with all SNFs yearly produced 10,000t HM by worldwide nuclear power plants [15]. In contrast, the latter option is not restricted by international regimes but highly dependent on the domestic conditions of host country. Stable and sound geological conditions are necessary to host a disposal facility since it should keep spent nuclear fuels in safe and secure for a few hundred thousand years. Moreover, direct disposal option is generally heavy going with low public supports in local or domestic areas. All of these limitations make the problem of SNF management difficult to solve in each nuclear power countries in the world. Only three countries (Finland, Sweden and France) are in progress of siting and licensing stages. In addition to these two options, the innovative technologies are being developed for reducing the radiotoxicity and volume of SNFs but all of these efforts still remain in the early phase of research and development (R&D). Figure 1.3

shows a series of processes up to the final disposal of SNFs.

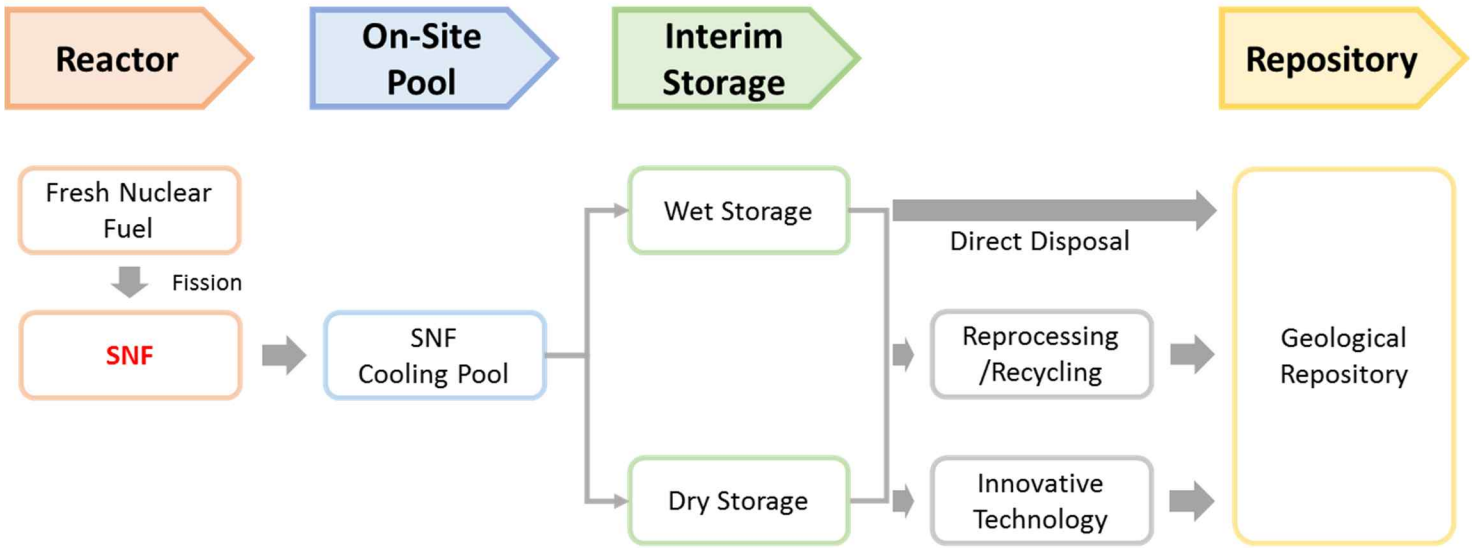

Figure 1.3 Management options for spent nuclear fuel

As mentioned above, it is not easy to manage SNFs in each countries because of realistic limitations in domestic approaches or commercial markets. The concept of multilateral approach to the nuclear fuel cycle is raised to promote nuclear fuel cycles beyond a national control. It has been suggested to provide an institutional mechanism not only for reducing global concerns on nuclear proliferation risks but also for satisfying needs on assurance of fuel cycle services. Theoretical concept is founded on the multilateralism in International Relations, which is defined as a collaborating measure for achieving shared goal among members. In 2003, Mohamed ElBaradei, the former Director General of IAEA, had suggested to consider multilateral approaches for managing spent fuels and radioactive wastes [16]. Since then several multilateral proposals has been raised and discussed by key actors in nuclear industry; national governments, non-governmental and international organizations. Thus it is necessary to examine multinational measures for managing SNFs in considering those options or policy decisions.

The other issue is the general perception on the SNF management. When it comes to this issue, it is generally considered as an industrial policy for peaceful use of nuclear energy, and it is also related to R&D activities in the scientific and technical aspects. Prior to policy decision for SNF management, its feasibility is required to promote national R&D project or program. In preliminary feasibility study, the following criteria would be used for justification; technical feasibility, economics, risk assessment and policy analysis [17-19]. All possible options for SNF management are prone to depend on technologies used in managing processes because levels of safety, security

and proliferation risk are different according to each selected options. In this way, some studies performed by experts in arms control or nonproliferation mainly evaluate technical options with the nuclear proliferation perspective [20-22]. Other studies focus on economic feasibility for allocating finite resources in promoting R&D project or policy. The economics on SNF management options had been performed in several studies but the results were different by research organizations [23-25]. The other factors would be also required but they are regarded as less important than those above. Therefore the technical and economic feasibilities have been considered as key factors for evaluation of SNF management policy. Furthermore it is also believed that technical development or economic compensation can enhance public acceptance and political support. However, is this kind of perception effective to establish a national plan for SNF management? Here it needs to examine in detail whether the existing recognitions of technology and economics on this issue are reasonable.

1.3 Objective and scope

In the previous sections, it clarifies the facts that the issue of SNF management in Northeast Asian region is pointed out as an important issue, and that multilateral cooperation should be considered as a measure to overcome realistic and potential limitations on the current backend cycles. In this regard, the purpose of this study is to evaluate the multilateral management options for SNFs with consideration on various criteria, and to suggest the strategies for

SNF management which are applicable to Northeast Asia and ROK. The goal of SNF management is to solve the problem properly and timely in safe, secure and proliferation-resistant manners so a sustainable use of civilian nuclear energy would be achieved. Many countries facing difficulties on promoting a national SNF management policy are to consider unilateral or bilateral approaches. As such, this study is supposed to consider multilateral approaches to solve SNF management problem not only in Northeast Asian region but also in ROK. The main focus here is on how an evaluation model specified in multilateral SNF management can be established, and which multilateral option and criteria can gain high weightings, then what the practical implications for Northeast Asia and ROK are.

Northeast Asia is the main target in this study but it does not restrict potential members only within this region so actors from other region or international organizations can be also consider as key participants. As such, the term of "multilateral" means that it is neither unilateral nor bilateral so number of member states are over three. This term is originated from the theory of International Relations, multilateralism. In addition, this study only considers the ultimate solutions for SNF management. In the case of interim storage, it could be regarded as a temporary measure to prolong the saturation of SNFs for earning time to prepare ultimate measures thus interim storage option is not included in further discussion. Lastly, the managing objects are limited to SNFs discharged from the LWRs. Those SNFs are handled as common problems among Northeast Asian countries while CANDU fuels, which are mainly concerned by ROK, are too specified to generalize.

Chapter 2 Literature Review

This chapter emphasizes three arguments as research rationale for this study through reviewing literatures; (1) the limitations of existing multilateral approaches, (2) the necessity of this study, and (3) the adequacy of research methodology used in this dissertation. Since the beginning of operating nuclear power plants, many engineers, scientists, and policy makers might have considered how to manage SNFs because it would not be avoidable in the uses of commercial nuclear power. On this matter, it is generally recognized that the responsibility on SNF management is primarily belonged to the origin state which uses fresh fuels to produce electricity [26]. Moreover, it is also accepted that necessary services for predisposal of SNFs can be provided by some countries which have relating capacities in compliance with the global norms. Those are relating to the reason why domestic direct disposal and commercial reprocessing of SNFs have been performed, and why multilateral cooperation is needed to consider as a possible measure.

The following review discusses two arguments according to perspectives in national and in global/regional on the issue of SNF management. Although both consider several options for SNF management, and evaluates them with suggested key criteria, there might be a missing point to develop in detail. The literatures reviewed in this section can be regarded as incomplete since there are numerous publications on this matter. However findings based on the selected studies may be enough to support the rationale of this study.

2.1 Multilateral approaches for nuclear fuel cycle

As for nuclear fuel cycles, there have been a number of discussions and efforts on multilateral nuclear cooperation since the end of Second World War. The history of civilian nuclear power, from the late 1940s to now, can be divided into three phases; (1) Atoms for peace, (2) Plutonium economy and (3) Nuclear renaissance with enhanced nuclear nonproliferation and security.

In the first period, nuclear power was recommended for civilian purpose but there were concerns on nuclear proliferation risks because of the dual-nature of nuclear energy. Thus the early proposal for multilateralization of nuclear fuel cycles aimed to transfer national capacities on nuclear fuel cycles to multilateral control (Baruch Plan 1946). After that, various multilateral approaches had been examined in 1970s and 1980s; the IAEA study on Regional Nuclear Fuel Cycle Centres (1977), the International Nuclear Fuel Cycle Evaluation exercise (1977-1980), the Expert Group on International Plutonium Storage (1978-1982) and the IAEA Committee on Assurance of Supply (1980-1987). In this era, suggested studies are featured as technically feasible and economically attractive proposal, and mainly being focused on the back-end fuel cycle including spent fuel reprocessing and plutonium containment [27-30]. During the period of 1990s to early 2000s which was a so-called Nuclear Renaissance, nuclear power industry had grown rapidly so stable supplying of fuel cycle services had been required, and problems in the backend fuel cycle had been gradually presented around the world. According to this trend, multilateral approaches focused on SNF management but no progressed; International

monitored retrievable storage system (1993) and International interim storage scheme (1997). Eventually this issue has been reignited in the early 2000s. In the Economist, October 2003, an unequivocal statement with strong justification for multinational nuclear cooperation was made by Mohamed ElBaradei. Thereafter a number of proposals were suggested by several states, business corporations, and international organizations [31,32]. There were twelve proposals relating to multilateral assurance of fuel cycle services in 2000s but now only four are endorsed by IAEA; International uranium enrichment center, Russian Low Enriched Uranium (LEU) fuel reserve, IAEA fuel bank and Enrichment bonds [33]. It can be understood that all the ongoing cases are targeting the frontend side despite the high demands on the backend side. (See Figure 2.1)

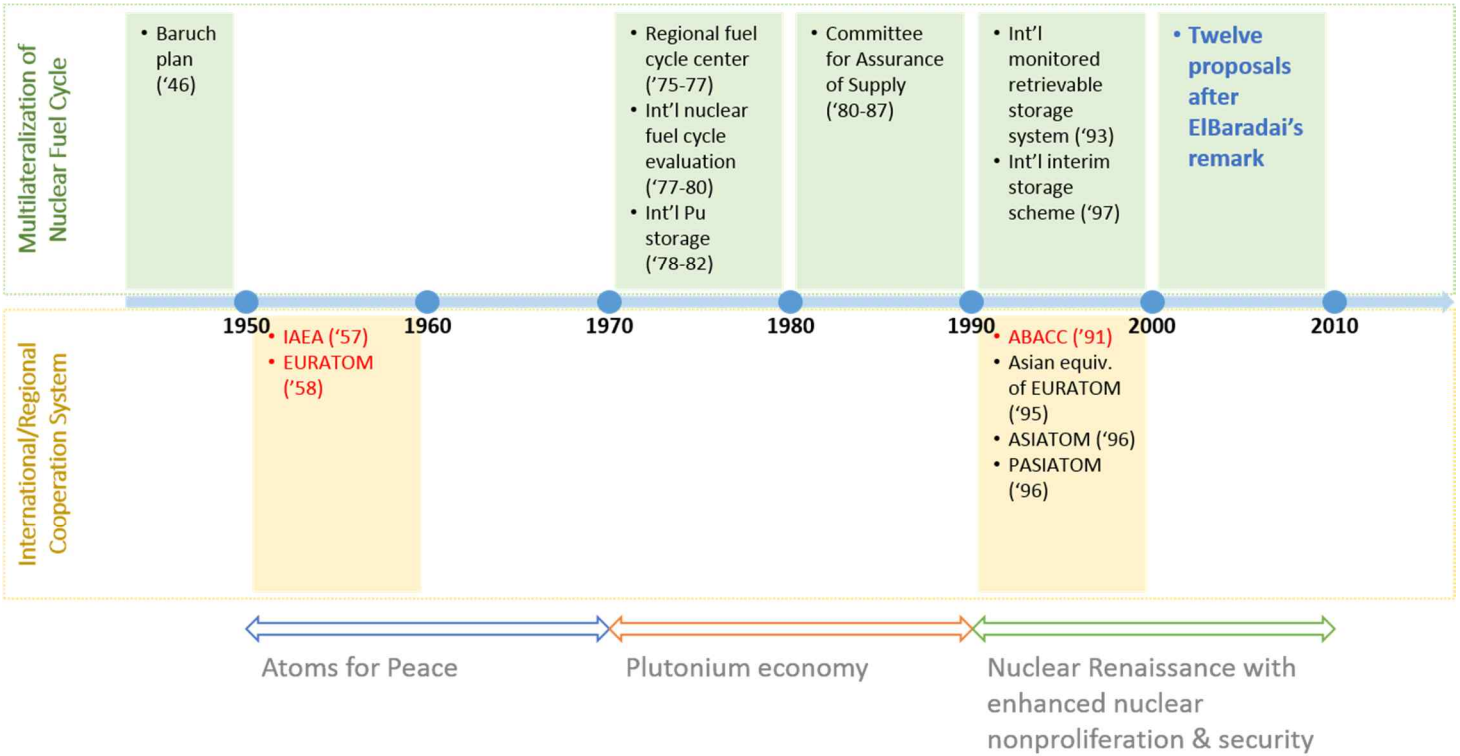

Figure 2.1 Previous suggestions on multilateral nuclear cooperation

2.2 Evaluations of spent nuclear fuel management option

There have been two kinds of studies on searching options of SNF management; one is to select options for SNF management in national perspective, and the other is with more broad perspectives, global, regional or generalized consideration. They are different in research motivation and scope on SNF management options. Considering the purpose of this study, which is to suggesting the multilateral strategy applicable to Northeast Asia and ROK, it mainly considers the studies performed with the ROK, Asian, and generalized perspectives. Dividing scopes in detain for further discussion, all literatures can be classified according to two standards; How much expanded to find a solution for SNF management, and How many criteria are considered for its evaluation. The former varies in scope from unilateral option to multilateral approaches, while the latter ranges from single evaluation criterion to multiple criteria.

As a simple approach, unilateral or just single option would be evaluated by a sole standard. In this field, each criterion such as economics, radiological impact or proliferation risk is used for its evaluation of target options [20-25,34]. In spite of its simplicity, however, this approach is not generally used since there are substantial constraints on a policy evaluation. Instead, it can be considered as a supplementary measure for supporting decision processes.

In the case of national perspective, the research motivation is mostly oriented from the urgency on preparing a policy or strategy in response to the domestic SNF saturation. The selected studies in this category examine possible

options to utilize own assets in domestic, or to contact other actors in a commercial nuclear power market. As for their evaluation procedures, various factors are considered as key evaluation criteria to select the best option. In the ROK, several policy researches have been performed since the mid-1990s. Song and Shin (1995) structured a hierarchy model to evaluate national policy on the backend fuel cycle. They considered three domestic options according to five criteria, and confirmed the effectiveness of analytic hierarchy process on this issue [35]. Kim et al. (1998) variated the evaluation procedure with separation of criteria into tangible and intangible, and included DUPIC option, the newest one at that time [36]. Studies for finding preference on technical options for SNF management had been performed with considering technology and economics as key evaluation criteria [37-39]. As the SNF management issue become increasingly serious in 2000s, Kim (2009) suggested a long-term national plan for SNF management from interim storage to final disposal, which includes mostly unilateral options except one oversea reprocessing [40]. Lee and Kim (2015) narrowed the research scope down so it only considered unilateral solutions [41]. In the same vein, similar studies have been performed by other researchers in the USA, South Africa and European Commission [42-44]. They were also to examine their own assets to manage SNFs, and to evaluate on potential unilateral options with multiple criterions. Common features among previous studies in this category can be summarized that technical and economic aspects are important factors for evaluation, and they only cope with unilateral or bilateral options. Moreover, many of them understood this matter as a decision making problem, and confirmed the

effectiveness of this perception.

On the contrary, the studies in generalized perspective are initiated by the necessity of SNF management solution with reducing risks on proliferation and security, and they open the possible options including multilateral cooperation. There were various publications consisted with suggestion of evaluation criteria and/or possible options. In the INPRO study, which was aimed to suggest basic principles for innovative nuclear system, SNF management should be evaluated with seven criteria [45]. Similarly Kim at el (2014) suggested the key evaluation criteria derived from survey; safety and technology, environmental impact, economic feasibility, social factors, and institutional factors [46]. IAEA (2013) suggested the SNF management options especially for newcomers or small-scale nuclear countries. It used seven criteria to assess six combinations of storage, recycling and disposal steps [47]. The study targeting Asian region discussed on instruction of a multilateral fuel cycle system, and it suggested the most specific scenario and requirements for cooperating among Asian countries [48]. The other study for Asian region examined possible four options, and analyzed benefits, challenges, impacts and feasibilities of multilateral SNF management [49]. In these researches, the multilateral options are suggested as effective and possible solutions for SNF management. The differences in criteria would be also affected by multilateral characteristics. (See Table 2.1)

In recent, there have been discussed on two kinds of idea for managing SNFs; one idea is the fuel leasing and take-back service, and the other is the geological repository for international SNFs and intermediate radioactive wastes. The former strongly supported by Russian Federation aims to lease

fresh nuclear fuels to customer countries then take back used fuels to Russian facility for reprocessing [50]. This structure has existed in the commercial contract between Russia and Iran. Russian domestic law allows to import of Russian-origin SNFs used in foreign countries for reprocessing and to return the wastes remained. Furthermore, the Russian government is also considering additional measures to reduce the burden of radioactive wastes returning to the origin country [51,52]. The other idea is strongly suggested by the South Australian state government, which is a concept of geological repository for international SNFs. The royal commission has conducted a comprehensive investigation for years, and recently published the final report in May 2016. The state government considers the disposal of international SNFs and intermediate wastes not only to earn economic benefits but to strengthen its leverage on nuclear power industry. In addition to the international disposal concept, the fuel leasing options is also considered to create a synergy effect with the backend service [53]. Both ideas can be possible options to overcome obstacles on SNF management in each countries, especially in some countries with poor geological condition, small-industrial scale, deadlock in siting.

Table 2.1 Evaluation criteria and options for SNF management in the literatures

	Evaluation criteria	Options for SNF management
Song and Shin, 1995	Energy security / Economics / Technical feasibility / Domestic issues / International relations	Once-through cycle / Closed cycle / Wait-and-see
Kim et al, 1998	Fuel requirement / Discounted cost / Cost sensitiveness / Environmental impact / Energy security / Economics / Technical feasibility / Domestic issues / International relations	Once-through cycle / Off-shore reprocessing / DUPIC / MOX in PWR and Rep-U in PHWR / Pu-U mixture in PHWR
Kim and Park, 2007	Sustainability / Environmental-friendliness / Proliferation-resistance/ Economics	Direct disposal / DUPIC / PUREX-MOX / Pyroprocessing-SFR
Kwon and Ko, 2007	Sustainability,/ Environmental-friendliness / Proliferation-resistance /Economics / Technical feasibility	Direct disposal / DUPIC / PUREX-MOX / Pyroprocessing-SFR

Table 2.1 Evaluation criteria and options for SNF management in the literatures (continued)

	Evaluation criteria	Options for SNF management
Kim et al, 2007	Technical feasibility / Economics / Domestic acceptance / International relations	Direct-disposal / Off-shore reprocessing / Domestic reprocessing
Lee and Kim, 2015	Safety / Technical feasibility / Economic feasibility / Fairness / Political feasibility / Security	Direct disposal / Wait-and-see (long-term storage) / Recycling (with Pyroprocessing)
IAEA, 2014	Economics / Infrastructure / Waste management / Proliferation resistance / Physical protection / Environmental impact / Safety	N/A
IAEA, 2013	Safety / Security / Nonproliferation / Economics / Political, legal and societal factors	National storage and disposal / Reprocessing abroad, recycling nationally or abroad, and national disposal / Reprocessing, recycling and disposal abroad / National storage, then disposal in a shared facility / Fuel leasing / Wait-and-see

Table 2.1 Evaluation criteria and options for SNF management in the literatures (continued)

	Evaluation criteria	Options for SNF management
Kim et al, 2014	Safety / Technology / Environmental impact / Economic feasibility / Social factors / Institutional factors	N/A
Tazaki and Kuno, 2014	Nuclear nonproliferation / Assurance of supply / Nuclear safety / Nuclear cooperation agreements / Third-party liability / Siting / Multilateral involvement / Access to technology / Economics / Transportation / Geopolitics / Political acceptance	JPN-ROK cooperation for ENR / KAZ-RUS-VIE-JPN-ROK for fuel leasing & take-back
Sandia Nat'l Lab., 2015	N/A	Direct disposal / Take-back programs / Third party option / Multilateral approach (in add-on, cooperation, and supranational)

2.3 Research rationale from a gap in the literature

Several studies reviewed in the above have suggested various evaluation criteria, and assessed options for SNF management. It is commonly accepted that the procedure of choosing policy on SNF management is considered as a decision making problem with multiple criteria. The suggested criteria cover many aspects on the matter of SNF management, and the potential options are also applicable to target countries. The domestic studies have covered options in unilateral and bilateral approaches, while those of regional or global have included, or even emphasized, multilateral options as important alternatives. However, the worldwide progresses on SNF management have been not much, and multilateral options cannot work in current.

There are still missing gaps in the literature. The gaps are required to be filled by further studies on evaluation of multilateral approaches for SNF management. First, considering the fact that most progresses in multilateral approaches to the nuclear fuel cycles have been in the frontend side, it needs to examine feasible multilateral options in the backend side, which aims to deal with accumulated SNFs. However, multilateral options have been only considered in the generalized perspective. The majority of domestic studies are used to review prospective technical options in the backend side but those options are not easy to promote by a state-level. Even though using commercial market as a bilateral approach, the capacities are too limited to solve whole SNF problems around world. In the most extensive view, the internationalized option planning to use all available abilities would be also an unrealistic approach.

Instead, the cooperation within target region and some neighboring countries would be more effective to deal with problems of SNF management in the region. This kind of collaboration is required to consider in detail, and the applicable options are needed to discuss on the selected region. In this study, it aims on the matter of SNF management in Northeast Asia and ROK so this region would be considered as the target area

Second, the evaluation criteria used in previous studies are various but no one covers all of those criteria. In addition, some sets of suggested criteria are not enough to consider multilateral options. The issue of SNF management is related to technology, safety, security, proliferation risk, environmental impact, economics and other sociopolitical aspects. If it combines with multilateralization, more features originated from multilateralism should be included. As for the fact that SNF management policy and its multilateralization are very complex, it requires a holistic and systematic evaluation, which fills the missing criteria in the literature.

Third, future studies require practical implications for the target region because a number of suggestions had been made but no one is applied in a real case. It will allow this study to analyze conditions both in surrounding and internal of Northeast Asian region. Previous studies have usually discussed or suggested ideas in generalized or conceptual manners thus they were regarded as less meaningful in practicality. Otherwise, the urgency of SNF management in some countries was not reflected in the generalized studies so it would be insufficient in practicality.

Chapter 3 Research Design

This study attempts to suggest the multilateral options for SNF management applicable to Northeast Asian region. The goals are managing SNFs in safe, secure and proliferation-resistant, and fortifying the sustainability of nuclear power industry in this region. It is also expected that the multilateral cooperation would contribute to build a mutual-trust among Northeast Asian countries. To achieve this research purpose, it will answer the research questions to develop a holistic evaluation model for multilateral SNF management, and to assess possible options with multiple criteria through the expert survey. At last, practical implications would be introduced based on the answers mentioned above. This dissertation suggests a multi-criteria evaluation model specified in multilateral SNF management, and analyzes the experts' opinion on possible multilateral options in this region and criteria utilized in the evaluation model. This allows researchers considering other multilateral options or targeting other region to evaluate in a systematic approach that covers various factors in complete consideration. Furthermore, the results could help decide the policy directions of Northeast Asia and ROK. The following sections describe research questions and approaches used to justify further discussions in this study.

3.1 Research questions and approaches

As for the multilateral SNF management, it should be connected to various

factors because this matter is combined SNF management and its multilateralization. In addition to this complexity in evaluation criteria, there are a number of options being considered. If the evaluation is finished, it is required to affect to policy recommendations in practical meanings. That is why this kind of researches has been performed. In Northeast Asian region, the SNFs are accumulated in each countries but not easy to manage them in normal approaches. It is impossible to keep using the nuclear power without managing SNFs in time. The shutdowns of nuclear power plants, which are anticipated in Taiwan, can be occurred in other countries. The measures in unilateral and bilateral have shown limitations on preparation of SNF management thus multilateral options should be considered as a key approach to resolve the current impasses in Northeast Asian region. It is expected that the answers to following questions would help to achieve the goal of this study, suggestion of multilateral options for SNF management in Northeast Asia. To discover multilateral strategies that would help to manage cumulative SNFs in this region, the first research question is:

What are the possible multilateral options for SNF management in Northeast Asia, and then how can these be evaluated?

In order to select the multilateral options, it requires a systematic measure for evaluating possible options. Previous studies have figured out the fact that selecting policy on SNF management can be understood as a decision making process. Moreover, they used various evaluation criteria which are differently

defined in each cases. This dissertation strives to select applicable options among the possible multilateral combinations, and to construct an evaluation model based on the decision making assumption. The suggested model requires to be specified in multilateral SNF management so various aspects are considered to define its evaluation criteria. The established model will be utilized in this study, and it can be also applicable to evaluate other sets of multilateral options. Maximizing its utility, it aims to be constructed as holistic, systematic and objective. Therefore it will allow to discuss on multilateral options and its evaluation criteria in detail, then the second question is:

Which multilateral option is preferred, and what criteria should be considered as significant?

To evaluate multilateral options for SNF management, this study collects the opinion of experts group as an important input on the established evaluation model. Experts are selected by considering their expertise and experience on the matter of the backend nuclear fuel cycle. In policy decision making on a complex issue, it would be a reasonable approach depending on professional insights and experiences of experts. The result from expert survey is supposed to analyze into the preferences on multilateral options and the weightings of evaluation criteria. Furthermore, this process will also help verify the evaluation model suggested by this study. Through analyzing the survey result and causes, practical implications would be deducted thus the last question is:

What are the strategic plans for introducing multilateral options to Northeast Asia and the ROK?

As a systematic study on SNF management policy, it is required to provide practical lessons applicable to the target region. Based on the analysis of internal and external conditions in Northeast Asia, this study suggests the policy recommendations for multilateral SNF management. Furthermore this study reviews the ROK's status on SNF management, and then suggests strategic actions for integrating multilateral options into domestic policy. All steps answering research question can be drawn into Figure 3.1.

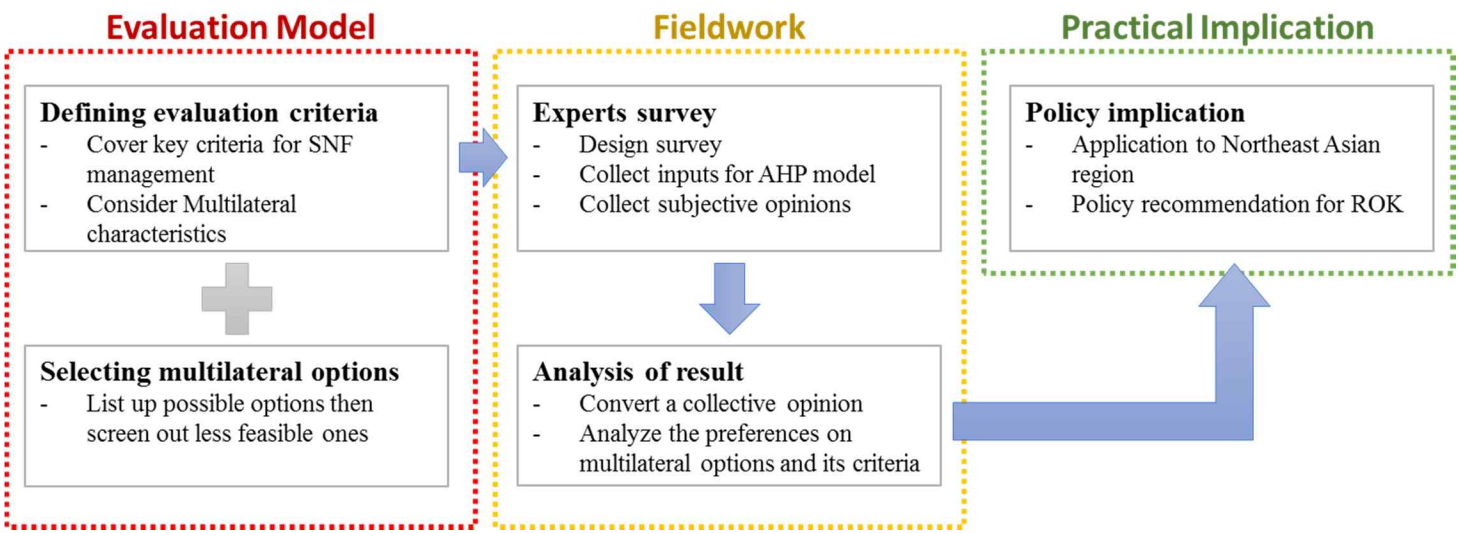

Figure 3.1 Research process flowchart

3.2 Multi-criteria evaluation model

In real world, it is common to make a specific decision or to select one options among other alternatives according to multiple standards for judgement. Considering the decision process with multiple criteria, it can be regarded as a multi-decision making (MCDM) problem. The purpose of MCDM is to support some decision makers solving such problems involving many evaluation criteria, and it usually considers the problems into a systemized structure to allow batter understanding and decision [54]. Thus MCDM techniques can be applied to identify a one most preferred option, to prioritize several options, or just to distinguish acceptable from unacceptable options [55]. The main topic of this study, multilateral management options for SNFs, can be considered as a MCDM problem since it involves many issues and selects feasible option among alternatives. That means the multilateral options is related to not only quantitative factors but also qualitative ones. In addition, this issue covers broad factors in technical, engineering, social, political and international relations. Thus it would be valid to consider the multilateral SNF management as a MCDM problem. In this regard, it needs to review possible MCDM methods for further discussion.

Since the early 1970s the MCDM problems had been actively dealt with in academic area, and it had been theoretically developed with various MCDM techniques [56,57]. Types of MCDM can be divided into two group; one type is Multiple Objective Decision Making (MODM) and the other is Multiple Attribute Decision Making (MADM). The former aims is to find an optimized

option which is the most suitable to achieve an objective among infinitive alternatives implicitly defined by its own restrictions. In contrast, the latter is an approach to select a most preferred option within a set of alternatives in a finite number. In the case of decision making on public or national policy, number of potential options is limited in number. Moreover, the general goal of decision making is to choose an option reflecting well its priority or preference among policy candidates. With this perception, it can conclude that the methods for MADM are more suitable for this kind of decision process than those of MODM. Therefore, it explores the pros and cons of typical MADM methods; Scoring Method, Goal Achievement Method, Multi-Attribute Utility Theory (MAUT), Outranking Method, and Analytic Hierarchy Process (AHP) [58,59].

First, the scoring method allows decision makers to give the relative weights on evaluation factors, and to rate each options with considering the weighted factors [60]. This model is consisted of three steps; giving weights on evaluation factors, rating options according to the factors, and then deducting total grades of each options by compositing prior results. This approach is regarded as simple but too subjective in decision process because it has weak a theoretical basis. There is no theoretical guide for weights on criteria and for consistency check on responses of decision makers.

Second, the goal achievement method was developed by Morris Hill (1967) to overcome the limitations of cost-benefit analysis [61]. This method is to clarify goals and to estimate achievement score on each goals, then it synthesizes them to evaluate as a whole. The term of "goal" used in here can be translated as the final state attained by proper measures for a given task,

which has similar meaning with an evaluation factor in other approaches. It has advantages on combining qualitative and quantitative information and on systemizing decision process for policy goals, and besides it is easy for understanding and application. However, it has problems not only in subjective weighting process but in integrating information in different scales.

Third, the theoretical basis of MAUT is the concepts of utilities and utility functions. The term of "utility" is defined as a kind of values given in key factors of decision making, and it can be expressed as utility functions [62]. In this approach, the weights on evaluation factors can reflect relative importance of the factors only if the scores are in dimensionless scale. Utility functions can be applied to transform from the raw performance values of alternatives against diverse factors both factual and judgmental to a dimensionless scale, and they are used to obtain a higher utility values. There are merits in covering various factors and in using utility functions in assessing decision makers' attitudes on a task. Nevertheless it is hard to derive the utility functions, and impossible to check its consistency.

Fourth, the outranking method is to perform assessments on items with the binary relations among them. It assumes data availability similar to that required in the MAUT approach. In other words, it requires evaluation criteria and alternatives to be specified, and uses a given data set at the beginning. The ELECTRE or PROMETHEE methods are the two most popular examples of outranking methods. It is useful to consider factors both in qualitative and quantitative, and to examine the relations among each alternatives through concordance and discordance indexes. But it has disadvantages on the

theoretical basis and integration of weightings given by several decision makers.

Lastly, the AHP is a structured method for supporting and analyzing complex decision makings, which is based on mathematics and psychology. This method was developed by T. Saaty in the 1970s [63], and since then it has been elaborated and refined by the studies of other scholars. The AHP considers decision making problems as a hierarchy structure consisted of goal, criteria and alternatives. It is useful to evaluate the preferences of each alternatives through consecutive pair-wise comparisons [64,65]. With characteristics of matrix in the linear algebra, weights calculation and consistency check are possible. Moreover, it expands its application areas for a single decision makers to group decision making cases. However, there is no objective standards in constructing a hierarchy model which is a key element of the AHP method. (See Table 3.1)

Table 3.1 Comparison of typical MCDM mothods

	Advantage	Disadvantage
Scoring Method	• Simple	• Not established weighting method • Difficulty in consistency check • Subjective scoring
Goal Achievement Method	• Easy to understand • Considering alternative's effect on each of groups	• Subjective weighting • Scale inconsistency in integration
Multi Attribute Utility Theory (MAUT)	• Quantifying qualitative evaluation items	• Difficult to derive utility function • Difficulty in consistency check
Outranking Method	• Quantifying qualitative factors • Unified scale	• Subjective weighting • Arbitrariness on handling of alternatives and criteria • No group decision making method
Analytic Hierarchy Process (AHP)	• Easy to understand/apply • Theoretical basis on weight calculation • Providing secondary processing data for consistency check	• Lack of theoretical basis for structuring hierarchy

This study aims to consider the issue of SNF management as one of multi-criteria decision making problems, and to find multilateral options applicable to Northeast Asian region. In this regard, it needs an evaluation model to evaluate multilateral SNF management options for further discussion. To construct an evaluation model specified in multilateral SNF management, it requires following conditions for maximizing its availability; considerations on both qualitative and quantitative factors, objectiveness in decision-making process, simplicity in application and verification, reflection of structure in decision-making, and permission on collective opinion. As mentioned above, decision making is usually related with various factors that should be considered as a whole. The process of decision making requires not to be subjective in weighting or ranking steps because the resultants will be used for public purposes with an objective validity. In the aspect of methodology's effectiveness, it needs to avoid complex procedures on data gathering and analysis since decision making process would be performed within limited time and manpower resource. At last, the decision making intends to evaluate potential options by key criteria for achieving a final goal. All of these elements in the process can be structured as a hierarchy, which is usually accepted as a structure of decision making. In addition, a policy decision would not depend on a single person but collect opinions from many experts. These characteristics of decision making should be considered to select a research methodology for this study. Satisfying all of these requirement, the AHP method is chosen as the key research methodology in this study.

The AHP method is to derive ratio scales from pair-wise comparisons.

The inputs can be obtained from quantitative values such as cost, dose rate and other quantifies in measuring scale, or from qualitative opinions based on experience and knowledge. One of useful features of the AHP is its availability to convert the measurement of intangible criteria to tangible ones through ratio scales. That means ratio scale can also allow to quantify subjective opinions obtained by survey questionnaires. Moreover, by the processes of breaking decision problem down into its constituent elements and constructing them in a logical approach from the upper to the lower levels, the simple pair-wise comparisons can be combined for overall decision making [66]. It is based on the construction of hierarchy model. The AHP method is widely used in the areas from simple personal judgements to complex and public decision making problems including establishment of governmental policy, feasibility study and mediation of conflict.

Professor Saaty explained the procedure to apply AHP method is as follows; decomposing a decision making problem into a hierarchy model, making pair-wise comparisons and establishing priorities among the elements in the hierarchy structure, synthesizing judgements to generate a set of overall weights and evaluating and checking the consistency of judgements [67].

Construction of hierarchy structure

In the AHP, it subdivides down the properties of decision making problem into a final goal, related attributes and alternatives, and all of these elements constitutes each levels of a hierarchy structure. Figure 3.2 shows a general hierarchy structure composed of three level. Top level represents the ultimate

goal of the problem, and the second level is made of evaluation criteria and their sub-criteria importantly considered in choosing one of alternatives. Finally all possible alternatives under consideration are at the lowest level.

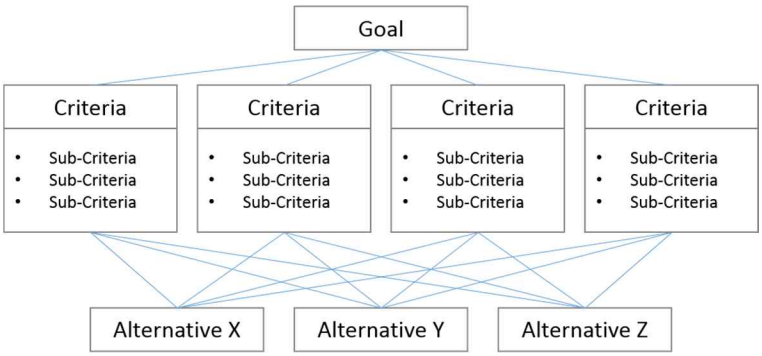

Figure 3.2 General hierarchy structure used in AHP

Pair-wise comparisons

The next step in the AHP procedure is to perform pair-wise comparisons among the elements. Comparing one element to another according to an upper factor, it allows to deduce relative measures between them (See Figure 3.3). Thus relative priorities or weights can be drawn in sequential comparisons in this step. Saaty and Vargas suggested a 9-point scale approaches for pair comparisons [68], and the definition of scale is described in Table 3.2.

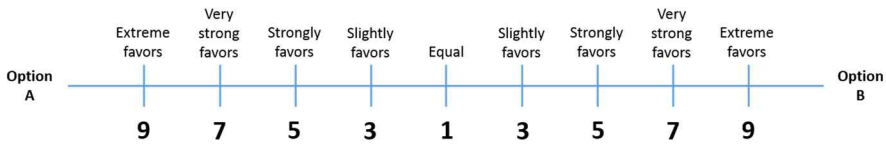

Figure 3.3 Scale bar for pair-wise comparison

Table 3.2. Scale for pair-wise comparison

Scale	Definition	Description
1	Equally important	Two activities contribute equally to the objective
3	Slightly important	Experience and judgement slightly favor one activity over another
5	Strongly important	Experience and judgement strongly favor one activity over another
7	Very important	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extremely important	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	

Results of the comparisons for each elements can be expressed in term of integer values from one to nine. Higher number means the biased element is considered more important than the other being compared with. In addition, this evaluated value satisfies the reciprocal condition: If A is evaluated as x times more important than B, then B is $1/x$ times more important than A. All comparisons are sequentially performed from the lowest level to the top level. The number of comparisons depends on the number of elements (n) thus it needs to select proper elements not to perform too much comparisons. In practice, it is recommended that n is not over 8 to 10 for the reliable and consistent judgements without confusing.

$$(number\ \ of\ \ comparisons\ \ ) = \frac{n(n-1)}{2} \tag{3.1}$$

After finishing all comparisons, it is possible to make the comparison matrixes for each elements in equivalent level. The size of comparison matrix is dependent on the number of elements (n) that produces n by n matrix. For example, in a comparison matrix A, an element of a_{ij} can be regarded as an estimated value of w_i/w_j which means a relative weight of element i for j. Matrix A satisfies the reciprocal condition $a_{ji} = 1/a_{ij}$ for all elements so the values of main diagonal elements are all one. That is so-called a reciprocal matrix.

$$A=[a_{ij}] = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & & w_2/w_n \\ \vdots & & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \tag{3.2}$$

To obtain weighing vector $w_T = (w_1, w_1, \ldots, w_n)$, Saaty suggested the eigenvector method, which considers the eigenvector of matrix as the weight vector w_T, and uses eigenvalue (λ) for consistency check. That is to deduce w and λ corresponding the relation of $Aw = \lambda w$ or $(A - \lambda I)w = 0$. In addition to the Saaty's method which is regarded as a precise approach, there are other approaches to calculate weights and consistencies approximately such as simplified calculation method, geometric mean method, power method [69]. However, these methods are not much different in precisions of calculated results, thus approximation methods are evaluated as applicable to the AHP analysis [70]. There are several commercial software packages that are able to

support a person to make a reasonable decision [71], for example, Expert Choice and MakeitRational are widely used as a software package for the AHP analysis. However, as an individual research, this study will use Microsoft Excel to calculate and analyze results instead of using commercial programs. The reason why Excel worksheet is chosen is that is useful to manipulate enormous data and its internal function allows to calculate approximated eigenvectors and eigenvalues for the AHP analysis [72].

Overall weights and consistency check

If the weight vectors among the alternatives and criteria are calculated respectively, it can be possible to deduce relative overall weightings of each alternatives for achieving the final goal. As the last step, consistency analysis is performed to assess whether the responses on comparisons are consistent or not. If all the answers are consistent, the maximum eigenvalue λ_{max} will be equal to n, the number of comparing elements, and in the case of inconsistency, the λ_{max} will be greater than n. Based on these properties, consistency index (CI) and consistency ratio (CR) are defined for judging the consistency of responses.

$$(Consistency\ Index\ ,CI) = \frac{\lambda_{max} - n}{n-1} \tag{3.3}$$

$$(Consistency\ Ratio\ ,CR) = \frac{(Consistency\ Index\ ,CI)}{(Random\ Consistency\ Index\ ,RI)} \tag{3.4}$$

Table 3.3 Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The CI reflects the consistency of decision maker's judgement with average deviation from consistent case. In practice, a CI of 0.1 or below is regarded as acceptable. If any higher value at any level indicates that the judgement is not consistent so it needs to re-examine or exclude. As higher *n*, it would be more difficult to meet the acceptance criteria, CI < 0.1 so the concept of CR is used as a typical cut-off standard. This is the ratio of given CI value to average CI obtained from randomly generated reciprocal matrixes with one to nine integers (See Table 3.3). As Saaty suggested, the answers satisfying CR < 0.1 are accepted as "reasonable consistent" but other researches use CR < 0.2 as a screening criterion which can evaluate as "tolerable consistent" in practical AHP applications.

This study is going to utilize the AHP method for multi-criteria analysis on multilateral SNF management. To establish a specific evaluation model, it needs to select evaluation criteria and possible options then the multi-criteria evaluation model specified in multilateral SNF management can be structured. In a practical evaluation, it requires to introduce decision makers with enough experiences and understandings on this matter. Thus the professional personnel, not the public, are considered as target respondents.

3.3 Expert survey

In the case of decision making procedure especially in the public or national policies, the final decisions are made by key decision makers in high levels of an organization. Considering the complexity of matters, the decision makers would generally depend on various professional advices from experts in the fields. Not to be biased, an advisory expert group is required to support decision makers' judgements. That is, the professional experiences and understandings on the issue considered can serve as a basis for decision making process.

This study aims to consider the issue of SNF management and its multilateralization, which is one of the most complex and professional matters. Thus the experts' opinions can have a significant impact on deciding the domestic strategy for SNF management that are determined and promoted by the high level governmental officers. In this reason, expert survey has been considered as a key measure for evaluating the main topic of this research, multilateral SNF management in Northeast Asia. Prior to the following discussions, it is necessary to clarify how to select experts as proper respondents for this study among a large number of experts.

There are numerous experts relating to the each matters such as nuclear fuel cycle, spent fuel management, or nuclear cooperation, but it is not sure all of them can cope with those matters in a holistic view. As mentioned above, the issue of multilateral SNF management are relating with multiple factors so it would be practically impossible that a single expert can evaluate this matter as a whole. Instead, multiple experts should be involved to conduct the multi-

criteria evaluation. Therefore, selection of experts is regarded as an important task in this study, so it considers following features to constitute an expert group.

First, the experts are required to cover not only in technical but in sociopolitical aspects of the multilateral SNF management because of its complexity. For this reason, it tries to consider the experts with various academic backgrounds, expertise, and affiliations. Second, even though this study is to focus on Northeast Asia in a regional aspect, it does not limit experts within this region. It aims to manage SNFs in this region but the multilateral solutions can be introduced by broaden cooperation, so nationalities of experts are diverse. Most of all, deep understandings on this matter are necessarily required thus it prefers an expert with recognized expertise and experience for a reliable response.

Based on these conditions, this study had contacted fourteen experts to invite as a survey respondents, and twelve of them had approved this research. The number of expert targeting in this study might be regarded as small in size, but it would not insufficient with considering practical limitations. There are a less number of experts on multilateral SNF management than you think, and it is also reduced sample size since limited time and efforts to meet the professionals. To overcome this problem, competence and compatibility of experts are considered as key selection criteria. It will be described more detail in the section of design of expert survey.

Chapter 4 Multi-criteria Evaluation Model Specified in Multilateral Spent Nuclear Fuel Management

To construct a multi-criteria evaluation model specified for this study, it is required to consider various aspects of multilateral SNF management. The criteria are required to balance each criterions; technical and engineering versus social and political. Those also cover both features in quantitative and qualitative so all of them are required to utilize in the evaluation model as a whole. To avoid answering too many pair-wise comparison in the AHP survey, it is necessary to limit the number of evaluation criteria as a reasonable level, which is usually recommended not to exceed over ten in each level of AHP structure. As mentioned in the previous chapter, seven criteria have been derived, and these can be categorized according to their features as shown in Figure 4.1. These seven criteria can be regarded as top-tier criteria, and each of them will be defined or explained in detail by second-tier criteria in following section. In the evaluation model suggested in this study, it assumes that all of criteria are mutually independent.

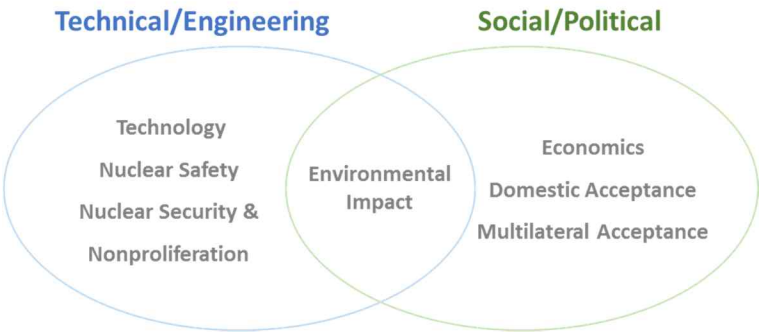

Figure 4.1 Categorized criteria for multilateral SNF management

4.1 Evaluation criteria

There are two kinds of process to select key criteria utilized in an evaluation model. One is an expert consent-based approach, which deducts criteria on target issue through the professional judgements. This approach has positive in justification on selecting criteria, while it takes not only much time and efforts but a possibility not to correspond to the researchers' original intention. The other approach is that all evaluation criteria are suggested by researchers. In contrast to the former, it can structure an evaluation model not to deviate from the original purpose but it requires a certain reasoning on selecting and organizing criteria to secure validity on the model. Understanding pros and cons in both approaches, this study is following the latter. It aims to discuss a new multi-criteria evaluation model specified in multilateral management options on SNFs, and it is planned to consider extensive factors not only in SNF management but its multilateral features definitely. Therefore this study would suggest evaluation criteria as following (See Table 4.1), and all of top criteria

and its sub-criteria will be introduced in the evaluation model.

Technology

As for the technical aspects which relate to SNF management, it includes following two factors; 1) Rationality of SNF management, and 2) Elements considering the applicability of key technology. In the aspect of SNF management, key technology must be appropriate for the purpose of SNF management, which are to manage SNF properly and timely for sustainable use of nuclear power (Suitability). In application of the technology, it should be fully developed or verified for its utilization (Availability), and it requires less difficulties in access to the technology (Accessibility).

Nuclear Safety

According to the classification of nuclear accident causes [73], the causes can be divided into three types; 1) Humanities and social, 2) Physical and technical, and 3) Natural and environmental. Accidents originated by the first two causes would be raised in operation of nuclear systems, while the last relates to a system robustness to external events, which is necessary to consider as important after the Fukushima accident (System resilience). In a multilateral framework, nuclear safety issues in system operation can be divided into two parts; static system operation (Accident tolerance in operation) and material transportation (Accident tolerance in transportation)

Nuclear security and nonproliferation

SNF management relates to the issues of sensitive materials and technologies so it should consider followings; 1) Physical Protection, and 2) Nuclear Proliferation Resistance. These two elements are clear to define (Physical protection and nuclear proliferation resistance). In current, there is no norm to regulate the multilateral framework on SNF management thus existing international regime or norm can be applied as a minimum standard on this matter (Compliance to international regime/norm).

Environmental impact

It is inevitable that radioactive wastes are produced in the process of SNF management thus any radiological effects to environment should be considered definitely. National legislations [74,75] also require to consider various influences on environment in pursuing business projects or policies (Non-radiological Impact).

Economics

The Costs used in nuclear industry consist of internal cost and external cost [76]. Internal cost means any expenditures directly used including construction, operation and maintenance (Internal cost), while external costs covers additional outcomes for accidental risk, policy and post processing. In this study, external costs are divided into costs for multilateral system hosting/promotion (Cost of social conflicts), and for risk of the target system (Environmental cost). The former is regarded as an important on bribes or social investments for

enhancing local supports, and the latter is used for maintain target systems in sound status.

Domestic acceptance

For multilateral SNF management, it is necessary to receive widespread supports from local public at the proposed site for hosting (Public Acceptance), and from key actors who have authorities to make decisions on the national policy (Political Support). In addition, it is regarded as a controversial issue which relates to transferring responsibilities on the burdens of SNF management. The SNF management should be proceeded in fair and ethical ways not only in the same generation but to the future generation (Ethical considerations).

Multilateral acceptance

For managing SNFs in multilateral framework, it is necessary to introduce a multilateral system, and to operate it well to achieve the goals of multilateral SNF management. In this view, it suggests following two requirements; 1) Establishment of the multilateral cooperation, and 2) Maintenance of the multilateral cooperation. Existing of the host state (Intention of Hosting) and sustainable structured system (Possibility of Institutionalization) would be important requisites for establishing multilateral SNF management. The multilateral system would continue only if the basic principles defined in the Multilateralism [77] should be kept well (Multilateral Identity); generalized principles of conduct, indivisibility, and diffuse reciprocity.

Table 4.1 Definition of evaluation criteria

Top-tier criteria	Second-tier criteria	Definition
Technology	**Availability**	The key technology applied to selected scenario should be fully developed or verified to utilize for SNF management (geological repository, reprocessing, long-term storage, participation and transmutation).
	Suitability	The key technology must be suitable/appropriate for the purpose of SNF management. In addition, its technological features in operation and management should be well connected/combined with existing systems in the long term.
	Accessibility	A key technology is accessible when it has less difficulties/obstacles in export for implementation and application
Nuclear safety	**System resilience**	The nuclear system for SNF management should maintain its safety in case of external events or natural disasters occur (considering geological, hydrological characteristics and etc.).
	Accident tolerance in operation	The target nuclear system can be assessed as safe when the system minimize/avoid the accidental damage (or its risk) occurred in operation.
	Accident tolerance in transportation	The target nuclear system can be assessed as safe when the system minimize/avoid the accidental damage (or its risk) occurred in domestic/transnational transportation.

Table 4.1 Definition of evaluation criteria (continued)

Top-tier criteria	Second-tier criteria	Definition
Nuclear security & nonproliferation	**Physical Protection**	The nuclear security level can be enhanced with appropriate measures against theft of nuclear materials or sabotage to nuclear facilities for SNF management.
	Nuclear proliferation resistance	Proper means/measures which prevent misuse/diversion of sensitive material and technology can strengthen the nuclear proliferation resistance.
	Compliance to International Regime/Norm	It could observe/comply existing international regime/norms, and cooperate with international organization to achieve the goal of nuclear security and nonproliferation in the anticipated SNF management system.
Environmental impact	**Radiological impact**	The operation of SNF management system must minimize various radiological impacts on the environment. It includes ionizing radiation, heat, or nuclide leakage from the target facilities.
	Non-radiological impact	The construction/operation of SNF management system must reduce various non-radiological impacts on the environment.

Table 4.1 Definition of evaluation criteria (continued)

Top-tier criteria	Second-tier criteria	Definition
Economics	**Internal cost**	This internal cost is all tangible expenses for construction, operation, maintenance and transportation in the SNF management system. These cover management of accident risk, establishment of safety regulation.
	Cost of social conflicts	It is spent for the resolution of local conflict over siting issue. This is a part of external cost for the SNF management system.
	Environmental cost	This cost corresponds to the values required/consumed for managing SNF; costs for long-term management, disadvantages to territorial use and natural/energy resource utilization.
Domestic acceptance	**Public acceptance**	The success or failure for participating the regional/multilateral cooperation for SNF management rests on public acceptability in each member states. Especially in case of siting issue, the local acceptance in proposed area would be the most important factor.
	Political support	It would be advantageous for promoting the regional/multilateral cooperation when strong political will/support from governments can be obtained. The driving force of cooperation is highly based on the political decisions.

Table 4.1 Definition of evaluation criteria (continued)

Top-tier criteria	Second-tier criteria	Definition
Domestic acceptance	**Ethical consideration**	The process for achieving the goal of SNF management and the resultants should be fair/ethical among member states, and between generations.
Multilateral acceptance	**Multilateral Identity**	When the target cooperation scenario has the unity (not a dichotomous/differential approach) in role, position and benefit, then it can be evaluated as an ideal regional/multilateral cooperation.
	Intention for hosting	A scenario can be feasible/practical in proportion to the strong intention to host regional/multilateral facility for SNF management. The easier selecting/finding candidate to host the facility, the more advantageous policy implementation can be.
	Possibility of institutionalization	The systemized and sustainable cooperation would be maintained with the low possibility on betrayal and breakaway of member states, then it can be evaluated as institutionalized cooperative system.

4.2 Multilateral management options for spent nuclear fuels in Northeast Asia

It is necessary to review the possible options for SNF management before discussing its multilateralization. The SNFs from light water reactors (LWR) is cooled in on-site pool for several years then they will be sent to interim storage (wet or dry) for decades. Next step can be chosen generally among three options; direct disposal to repository; disposal of vitrified HLW after reprocessing; Burning transuranic elements using partitioning and transmutation (P&T) an innovative approach. They are different in various aspects in application, capability, or requirement.

This research only regards these technical branches for SNF management as basic forms of cooperation, and constructs the possible multilateral options for the multi-criteria evaluation model. The multilateralization of SNF interim storage is also an important issue. Actually, many countries have trouble in preparing an interim storage before saturating SNF inventory. If a multilateral/regional interim storage is established, it can function as a 'SNF Bank' that SNFs can be stored in and withdraw from the multilateral facility according to management plans of each member states. However, as mentioned earlier, this study is to discuss on the ultimate solutions for SNFs not focusing on temporary measures.

There can be many possible combinations of SNF management steps whether each steps exists in domestic or in multilateral area. In the case of direct disposal, its multilateralization is quite simple only when the problem of siting

is resolved. That is concluded as a multilateral repository. In contrast, the other options are complexed according to places of each steps. The cases based on reprocessing, it is required to consider both long-term storage and geological repository. Commercial reprocessing is restricted to access thus this step should be controlled under multilateral framework, or at least by a black-box measure, which guarantees only services without permission on access to sensitive technology. Final disposal can be happened in domestic or multilateral sites. In this approach, separated plutonium and uranium are produced as resultants thus concerns on these fissionable materials would be raised only if proper measures are not applied. Therefore it requires a shared facility for long-term storage for these sensitive materials to reduce risks mainly on nuclear security and proliferation. At last, as innovative measures for reducing burdens of SNF, the P&T can be also considered as one of feasible options. This aims to separately eliminate high-level, long-lived nuclides within transmutation process so it does not need a long-term SNF storage. Combinations of partitioning, transmutation processes and final disposal of residues in intermediate and low level are possible. Partitioning process is to separate TRUs as a mixture with minor actinides, which is more proliferation-resistant procedure, but this step is required to operate in multilateral framework for its transparency. The other steps including transmutation and repository can be selectively positioned. All of these combinations are shown in Figure 4.2.

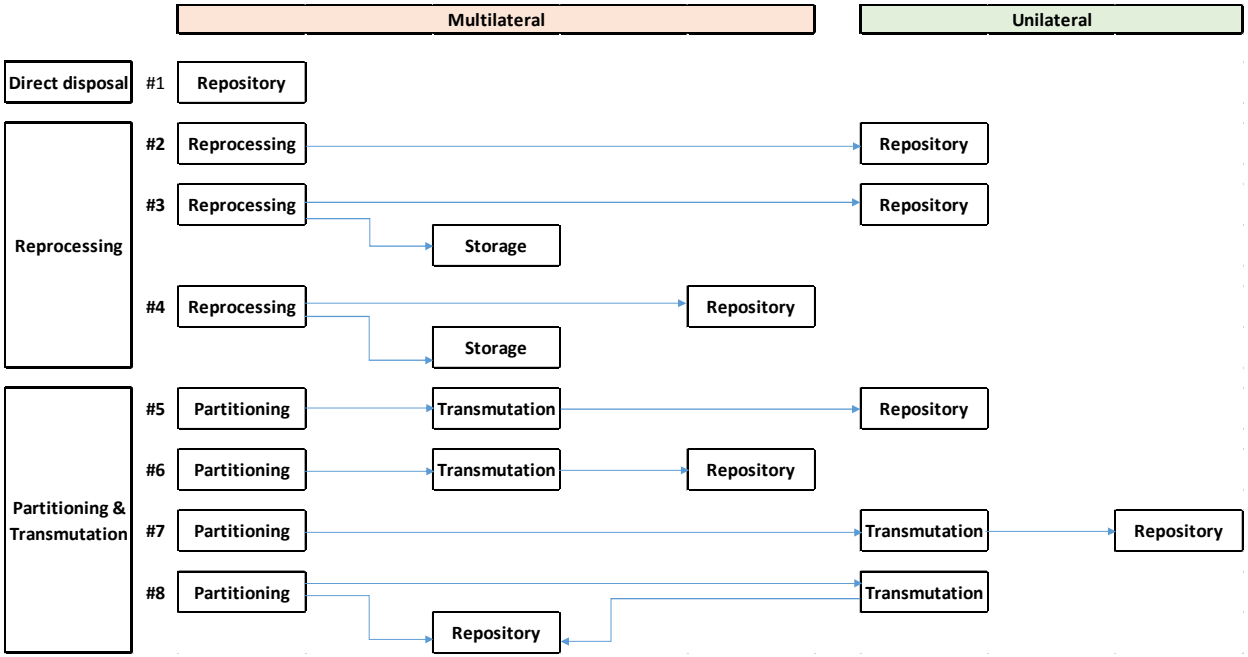

Figure 4.2 Combinations of multilateral management options for SNF

Among the eight combinations, this study selects some of multilateral options for further discussion. In the selection procedure, it consider at least one of options in different technical basements as an evaluation object since this condition allows compare some factors based on different technologies. In addition, this study excludes options which are in similar structure of existing bilateral options or which is a kind of variation of the other multilateral option. The second option (reprocessing in multilateral and repository in unilateral) is not much different to an oversea reprocessing in commercial nuclear market. Moreover, the fourth, sixth and eighth options are accepted as or connected to variations of multilateral repository option thus these can be excluded. Considering an effectiveness of SNF management process, the separation of partitioning and transmutation steps, which is described in the seventh, is not recommended because it circulates target materials in the combined system to reduce its radiotoxicity and volume. As results, this study consider three options for multilateral SNF management; Regional SNF repository, Regional reprocessing and storage, Multilateral P&T. The term of regional means to use management capacities in the target region, while that of multilateral used in the P&T option means that it is unnecessary to be restricted in physical region for R&D of an innovative measure. The further discussions are based on the following five assumptions for multilateral SNF management:

(1) "Multilateral" means that member states (or non-governmental actors) are over three so the multilateral cooperation can allow members from other region to join in.

(2) It considers only spent fuels from LWR as research objects

(3) Transportation and Storage cask are developed to meet basic engineering requirements.

(4) All members are responsible for managements and costs of construction, operation and maintenance, and the host states can gain profit from providing services.

(5) It is mandatory for all multilateral scenarios to apply proper system of accounting for and control of nuclear material.

In here, the term of "multilateral" is based on the concept used in International Relations; Practice of coordinating national policies in groups of three or more states [78], or coordinating relations among three or more states in accordance with certain principles [79], phenomenon that occurs between states but not only states [80]. In this context, this research aims to discuss on management of regionally accumulated SNFs through a cooperation among countries, not internationally. The target range is clearly shown in Figure 4.3.

Figure 4.3 Target range of multilateral SNF management

As already mentioned in the section of research scope, CANDU fuels are excluded in the following evaluation model and further discussion. Despite the ROK's interest on managing the CANDU fuels, this study focuses on the LWR fuels to collect common interests according to a multilateral perspective. The

LWR fuels are more familiar to most experts since this type of reactors are widely operated worldwide. In addition, considering differences in features of both fuels, it cannot be easily resolved in a single generalized evaluation form. That is the reason why this study consider only LWR fuels. The other assumptions relate to requisites for constructing and maintaining the potential multilateral options for SNF management.

Regional SNF repository

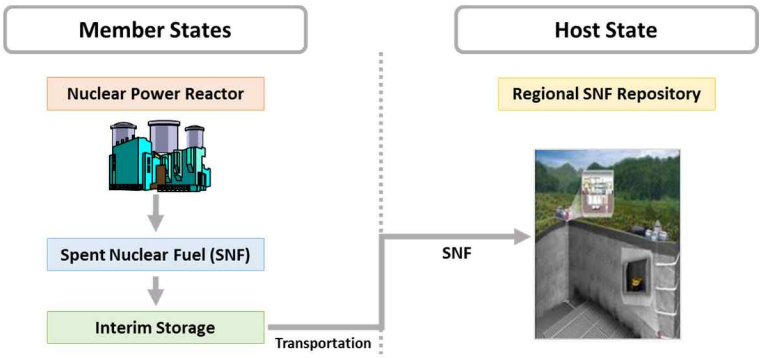

Figure 4.4 Regional SNF repository

This option suggests the simplest solution for final SNF disposal so each members would sent their SNF after cooling period. It will not modify configurations of SNF. The most important requirement for host country is the geological stability for a long-term (over historical time scale) so an area near volcanic zone should be avoided. In addition, it is not required that the host should be industrialized in nuclear power thus any volunteer suitable to site condition will be possible. This approach needs the one-way transportation of SNF from members to the host, and less complex than other options.

The form of cooperation can be understood as a construction of new multilateral facility within the territory of host country. As potential members, Taiwan, Japan and ROK would participate in this option, and Australia who has experiences on internationalized repository. As a key player, USA should be considered as a member or at least observer in the multilateral cooperation. Enhancing a transparency in activities on SNF management, participation of IAEA would be helpful to establish and operate the multilateral facility.

Regional reprocessing and storage

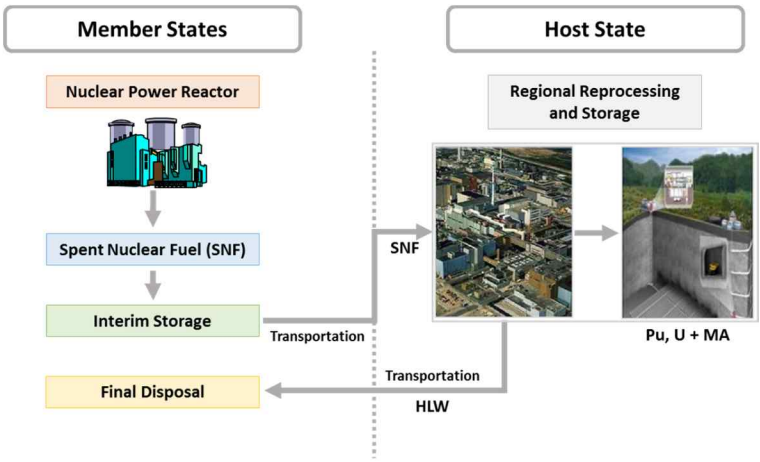

Figure 4.5 Regional reprocessing and storage

This option uses capabilities of commercial reprocessing in Northeast Asia, which are only allowed to Japan and China. In addition, separated fissile materials are stored in the regional facility under multilateral framework with enhanced safeguards measure and security. This approach can be characterized as a guarantee of reprocessing service without access to sensitive technology.

Separated plutonium and uranium are able to fabricate fresh fuels later thus it has a value on maximizing utility of energy resources. Multilateral facilities can be sited separately in multiple host states; Reprocessing in one state and Stored in the other state. The nuclear or radioactive materials will be transported back and forth, therefore the origin state of SNF should have a responsibility to dispose of HLW.

In this approach, the form of cooperation is regarded as a combination of guarantee of service supply and new multilateral facility within the territory of host country. First of all, this option is based on the assumption that technical holders (Japan and China) will contribute their capacity for solving regional problems of SNF management. As potential members, Taiwan, Japan and ROK would require to participate in this option, and Russia who has a commercial capacity can be a cooperation partner. USA and IAEA are also considered like in the first option for establishment and operation of the multilateral facility.

Multilateral partitioning and transmutation (P&T)

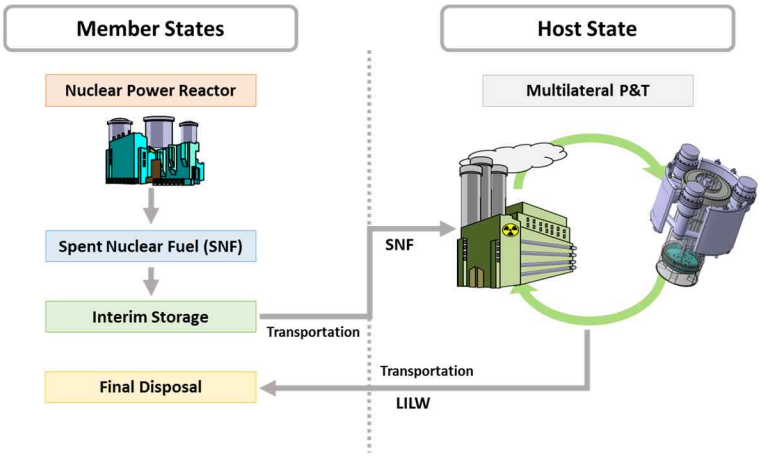

Figure 4.6 Multilateral partitioning and transmutation

This is based on the innovative technology reducing radioactivity, heat and waste volume so it would be plausible to reduce the burden of final disposal in each member. However, it is a relatively novel technology with less experiences, and ongoing in the worldwide. Considering time and cost required, it is reasonable to collaborate among some countries interested either/both in developing advanced recycling process and in the generation four reactors (as a burner). The nuclear or radioactive materials will be also moved back and forth, but the origin countries would have less responsible for the final disposal than the former option since it is much lowered in radioactive level.

This option aims to form a new multilateral facility based on innovative measures for minimizing long-term burdens in disposal of SNFs. It is not clear which country would have an intention for hosting the P&T facilities, while countries not only who are suffered from SNF management but who strives to

exploit new technologies, can be potential members; Taiwan, Japan, China and ROK. USA and IAEA are also considered like in the first option for establishment and operation of the multilateral facility.

Table 4.2 Selected multilateral options for SNF management

Option	Description	Key Technology	Potential Partner
#1 Regional SNF repository	- Simplest solution for SNF disposal - Requirement for geological stability - Non-nuclear state can be a host	Geological disposal or deep repository, transportation	ROK, Taiwan, Japan, Australia and USA (+ IAEA)
#2 Regional reprocessing and storage	- Utilizing regional reprocessing cap. - Assurance of service supply - Joint control of separated Pu/U/MA	Reprocessing (e.g. PUREX), storage of TRUs elements, transportation	ROK, Taiwan, Japan, China, USA and Russia (+ IAEA)
#3 Multilateral partitioning and transmutation	- Based on innovative technologies Reducing burden of high-level waste disposal - Need to cooperate from R&D step	Partitioning (metallurgical process) and transmutation (fast reactor or ADS), transportation	ROK, Taiwan, Japan, China and USA (+ IAEA)

4.3 Evaluation model

The multilateral SNF management is a complex issue related with various factors so this study has regard it as a MCDM problem. Moreover the AHP method has been chosen for analysis of multi-criteria evaluation in this study. For constructing a multi-criteria evaluation model specified in multilateral SNF management, it needs to combine evaluation criteria with possible options as a hierarchy structure.

As for a multi-criteria evaluation system, it is consist of several levels including goal, evaluation criteria and its sub criteria, and alternative. This hierarchy structure is useful to aware a problem in systematic manner, and to achieve the evaluation goal in the top-level. The purpose of this study, evaluation criteria and possible multilateral options have been clarified in the earlier sections thus all can be combined as shown in Figure 4.7. Based on this structured model, the AHP surveys are conducted by experts in the field of the backend fuel cycle.

The suggested evaluation model can be understood as an unprecedented one covering multiple criteria especially including multilateral features because previous studies had not considered. If new multilateral options become feasible for SNF management, this model would be still available to evaluate because of its organized structure. It needs a modification only if there is a change in the evaluation criteria. This study has firmly established the multi-criteria evaluation model for multilateral SNF management, and the AHP survey, analysis and discussions would be conducted according to this model.

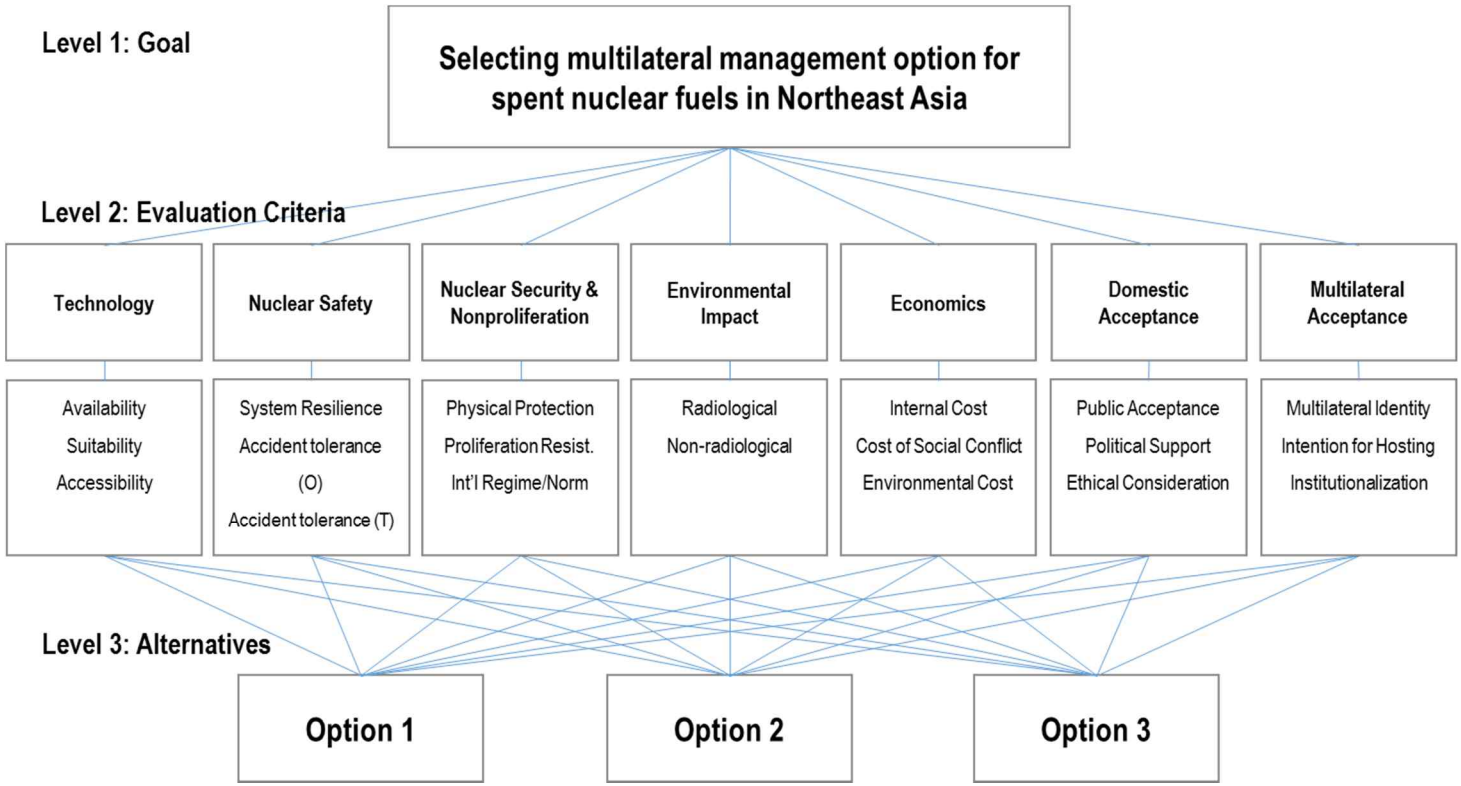

Figure 4.7 Multi-criteria evaluation model specified in multialteral SNF management

Chapter 5 Expert Survey: Collective Opinion from Nuclear Expert Group

5.1 Design of expert survey

The fieldwork, which is to collect input data for the evaluation model suggested in this study, has been mostly conducted by interviews of the selected experts. The questionnaire is constructed corresponding to the generalized AHP method, pair-wise comparisons with nine-point scale. The AHP method was originally developed to help a single decision maker to select an option among the others [81]. However, it has since been extended to apply to a group decision making procedure where some single decision makers is consisting a group.

To use a number of responses from experts as a collective opinion, there are several methods for collective decision making in the AHP according to the facts whether it classifies survey respondents, or uses interval-values instead of individual raw data (See in Figure 5.1) [82]. In this study, the geometric mean method is utilized to collect individual judgements, and it assumes that all experts are regarded in equal, thus each responses received from different experts are rated as equivalent. In contrast to the other methods, this one does not require additional selective processes according to subjective standards. The twelve experts are different in many features thus this study judges that it would be more reasonable to consider all of them in equivalent values of expertise, knowledge and experience.

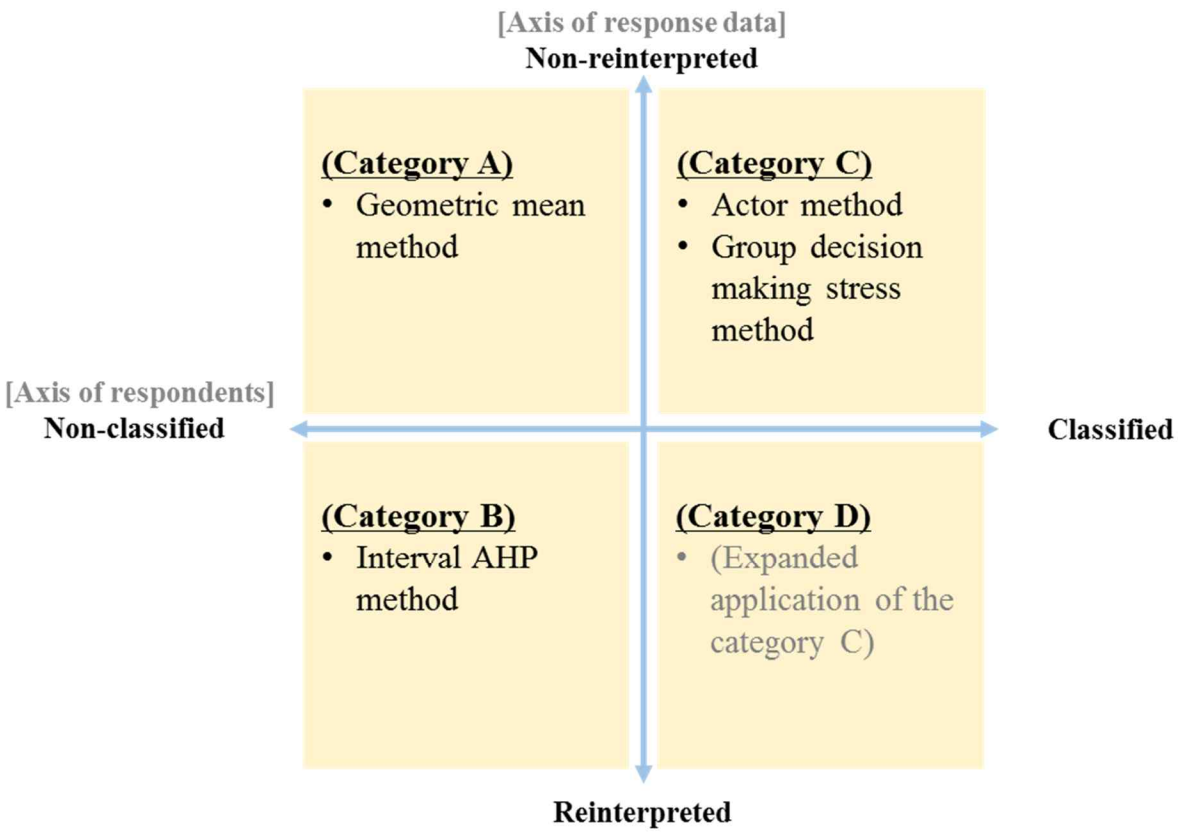

Figure 5.1 Selection of methodology for a group decision making in AHP

In the position to design this survey, the constitution of expert group is the most important task. To gather inputs for the multi-criteria evaluation mode, the expert group has been supposed to include individuals specialized not only in technical but in sociopolitical. In addition, it has planned to consider experts both from Northeast Asian region and from the others.

With this regards, the expert group has been constructed but it has been limited in number. The followings describe the difficulties considered in this survey. First, the procedure of finding proper experts is more difficult than one may think. It is generally expected that there are many experts on this matter but only some of them are understanding on multilateral SNF management. Second, it is limited by the methodology itself, interview approach. It is necessary to explain the background information and guideline for the survey process whenever the interview is performed. This approach is based on an interactive form thus it is unavoidable to take much time and effort. Third, not all responses from experts are available since some of responses could not meet the consistency ratio requirement, which is required not to exceed 0.2. In this study, the group opinion holds an effectiveness for further discussion despite individual responses cannot be used for analysis. It means that the number of experts considered in this study is good enough to analyze since the competence of experts are sufficiently guaranteed [83].

The experts answering the survey questionnaire are different in nationality, academic background and working area but they have enough experiences in this field. It was originally designed to conduct surveys on fourteen experts, and there has been twelve returns except one Canadian

researcher and one Chinese scholar. The summarized information of anonymized twelve experts is listed in Table 5.1 and distribution of experts' academic backgrounds and nationalities are shown in Figure 5.2 and Figure 5.3.

Table 5.1 Information of survey respondents

Expert	Nationality	Working experience	Type of organization	Area of Expertise	Remarks
A	UK	45 years	Consultancy	Nuclear safety, security and waste management	Experience in national waste management agency
B	Belgium	32 years	National R&D	Nuclear safety, nonproliferation, fuel cycle and international relation	Deputy director of national research institute, additional expertise in cost estimation and ADS system
C	Austria	52 years	Consultancy	Nuclear security, nonproliferation, fuel cycle, disarmament and international relation	Experience as a government officer
D	USA	25 years	NGO	Political science, economics, nuclear security, nonproliferation, fuel cycle, disarmament and international relation	Senior fellow

Table 5.1 Information of survey respondents (continued)

Expert	Nationality	Working experience	Type of organization	Area of Expertise	Remarks
E	Taiwan	30 years	University	Nuclear safety and system reliability	Distinguished professor
F	Malaysia	46 years	University	Nuclear safety, security and international relation	Professor Emeritus, former deputy director general and head of department of IAEA, and head of national research center
G	Japan	40 years	University	Nuclear security, nonproliferation, fuel cycle, disarmament and public participation	Former vice chairman of JAEC of the Cabinet office, vice president of research institute
H	ROK	27 year	NGO	Nuclear nonproliferation, waste management and fuel cycle	Former research in national research institute

Table 5.1 Information of survey respondents (continued)

Expert	Nationality	Working experience	Type of organization	Area of Expertise	Remarks
I	ROK	25 years	National policy research institute	Nuclear security, nonproliferation, international relation and political science	Former policy advisor to the minister
J	ROK	27 years	National waste management agency	Nuclear fuel cycle and waste management	
K	ROK	8 years	University	Nuclear security, nonproliferation and fuel cycle	Former research in national research institute
L	ROK	23 years	University	Nuclear security, nonproliferation, disarmament and international relation	Former policy advisor to the minister

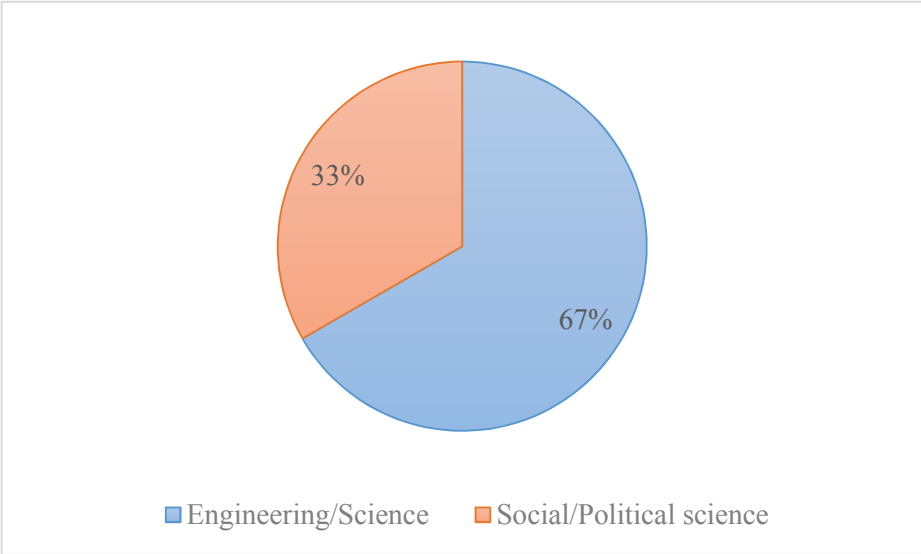

Figure 5.2 Academic background of respondents

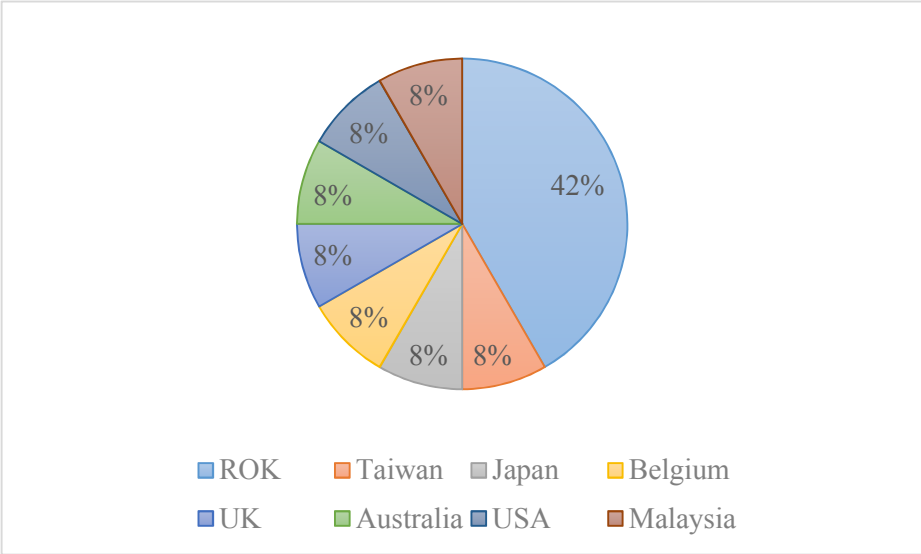

Figure 5.3 Nationality of respondents

5.2 Result and discussion

This section aims to analyze the results on expert survey. Each of twelve individual sets could not be an effective answer because some of them is over the consistency ratio standard, empirically under 0.2. Therefore the results will be assessed as collective opinions; (1) in the whole expert group, and (2) in two sub-groups according to academic background.

Collective opinion of expert group

The order of preference on feasible multilateral options are following; regional SNF repository, multilateral P&T and regional reprocessing & storage. It is clear that the expert group more prefers regional repository option than the others because this option earns high ratings in the criteria of nuclear security & nonproliferation, and nuclear safety. Comparing multilateral P&T and regional reprocessing & storage options, the former is slightly preferred than the latter. One of noticeable thing is that the multilateral P&T option overwhelms the others in the aspects of domestic and multilateral acceptances. (See Figure 5.4 and Figure 5.5)

In the comparison regional SNF repository and multilateral P&T, the repository option has been preferred mostly in fourteen sub-criterions except in acceptances. The key reason can be inferred as that the repository option as a simplest way does not include any process of manipulation on SNFs despite long-term burdens of their management. In contrast, multilateral P&T is rated the highest in following six sub-criterions; cost of social conflict, public

acceptance, political support, ethical consideration, multilateral identity, and intention for hosting. This option has been highly evaluated in the above factors because efforts for eliminating the burdens of SNFs can be an important motivation to consider multilateral cooperation for SNF management. If CANDU fuels are considered to manage in multilateral options, the preferences order or degree could be different in the perspective on ROK. However, this issue cannot be generalized as a regional issue for attaining consents from other countries. Thus it has been excluded in the early stage of research design.

There is not a big difference in preference between multilateral P&T and regional reprocessing and storage. Regional reprocessing & storage wins rather on technical availability and suitability, while multilateral P&T receives higher rates on nuclear security & nonproliferation, domestic acceptance and multilateral acceptance. According to the features of these options, multilateral P&T is based on innovative technologies with certain merits for SNF management which are reductions in volume, radiotoxicity and managing period. Furthermore, a challenging task from R&D step also provides an equivalent opportunities to cooperate with others. Otherwise, regional reprocessing & storage is based on commercial reprocessing technology but it is restricted under the global nonproliferation regime. Thus it is better than the P&T option in the evaluation of technical aspect but competitive in others.

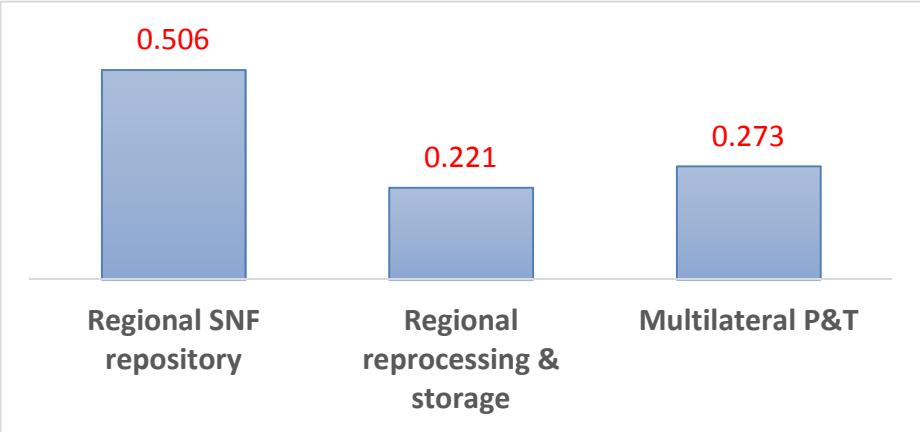

Figure 5.4 Preferences on multilateral options

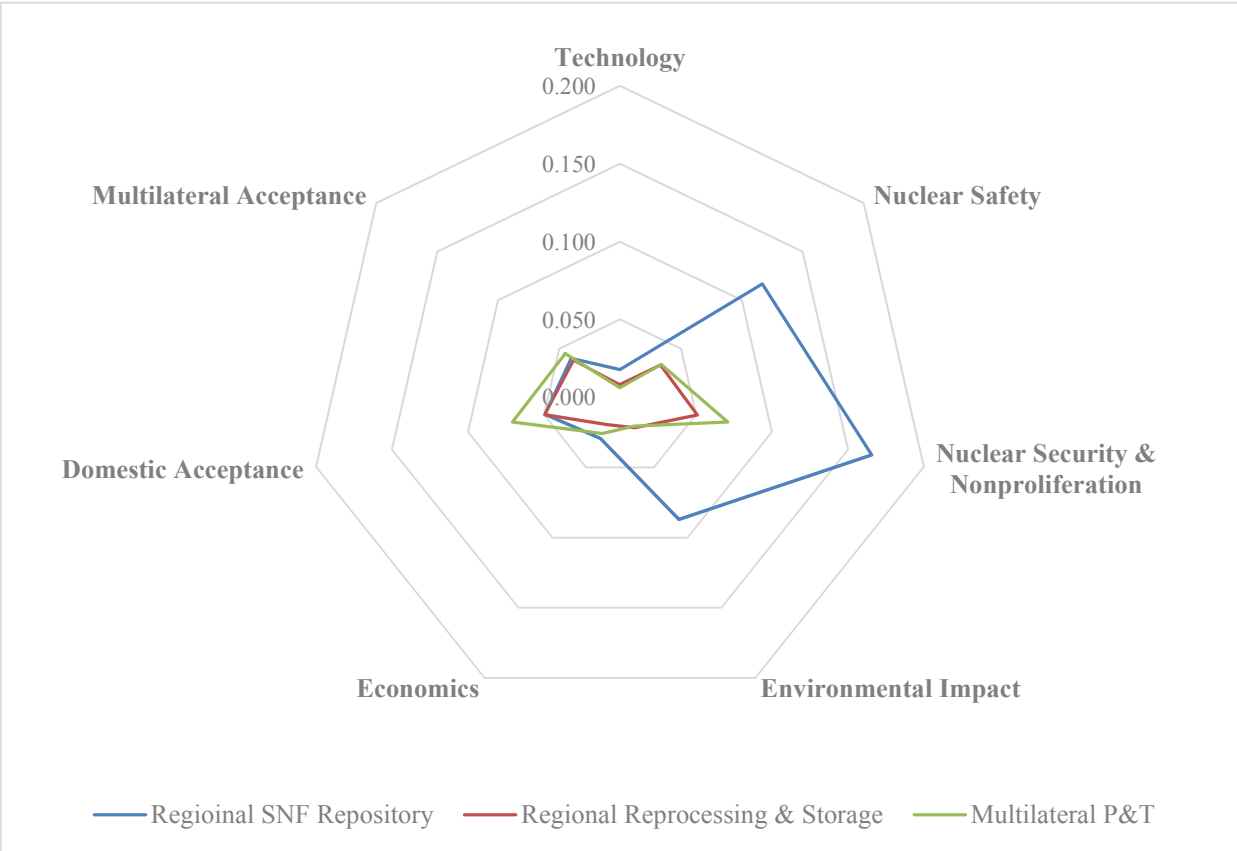

Figure 5.5 Preferences on criteria in each options

When considering all evaluation criteria in detail, all of the weightings on twenty sub-criteria can be shown as Figure 5.6, in circular plane with normalized ratios. This result gives three important indications; (1) Technology and economics are regarded as less important than the others, (2) Acceptances both in domestic and in multilateral should be considered as more important, and (3) The others which are traditionally considered as important factors are still significant.

First, it is noticeable that the weightings as for the criterions in technology (3.2%) and economics (7.4%) are just about 10% because this result is opposite to a general perception widely used in preliminary feasibility studies on national policy or project. Considering the contrary of this result, the expert group has recognized that both criteria are apt to be changed over time in a long-term perspective. In addition, multilateral option can give merits on the economy of scale and risk management. Current evaluations on these criteria may have uncertainties thus it needs to consider other criteria within a holistic approach on the matter of multilateral SNF management. It is also necessary to invest resources on the multilateral management options for SNFs even though it seems challenging or financial-risky in current perspective.

Second, the domestic (17.0%) and multilateral (12.3%) acceptances are regarded as important factors for promoting multilateral SNF management. It is generally believed that public acceptance is one of key factors for SNF management because many efforts trying to seek a site for SNF management have been failed with low acceptances. In multilateral options, a hosting country will take burdens of managing SNFs thus it would be reasonable to

promote if any volunteer has an intention for hosting the multilateral facility. In addition, some kinds of clear incentives can help to introduce a hosting country. It is deserved to consider that South Australian state government recently shows a potential intention for hosting a disposal facility for international SNFs.

Third, it can clear again that the purpose of this study is for managing SNFs in safe, secure, proliferation-resistant and environmental-friendly. All of these criteria are weighted in 60%, and they are featured as not to be changed easily over time even though possible risks on SNF management are related to these factors. In safety criteria, system resilience takes the second rank among all twenty sub-criterions. It is well reflected that the perception of expert group on accidental risks raised by gigantic external forces like the Tsunami happened in 2011. The most important factor is proliferation-resistance since proliferation risk has been consistently suggested as a key concern in the reprocessing process.

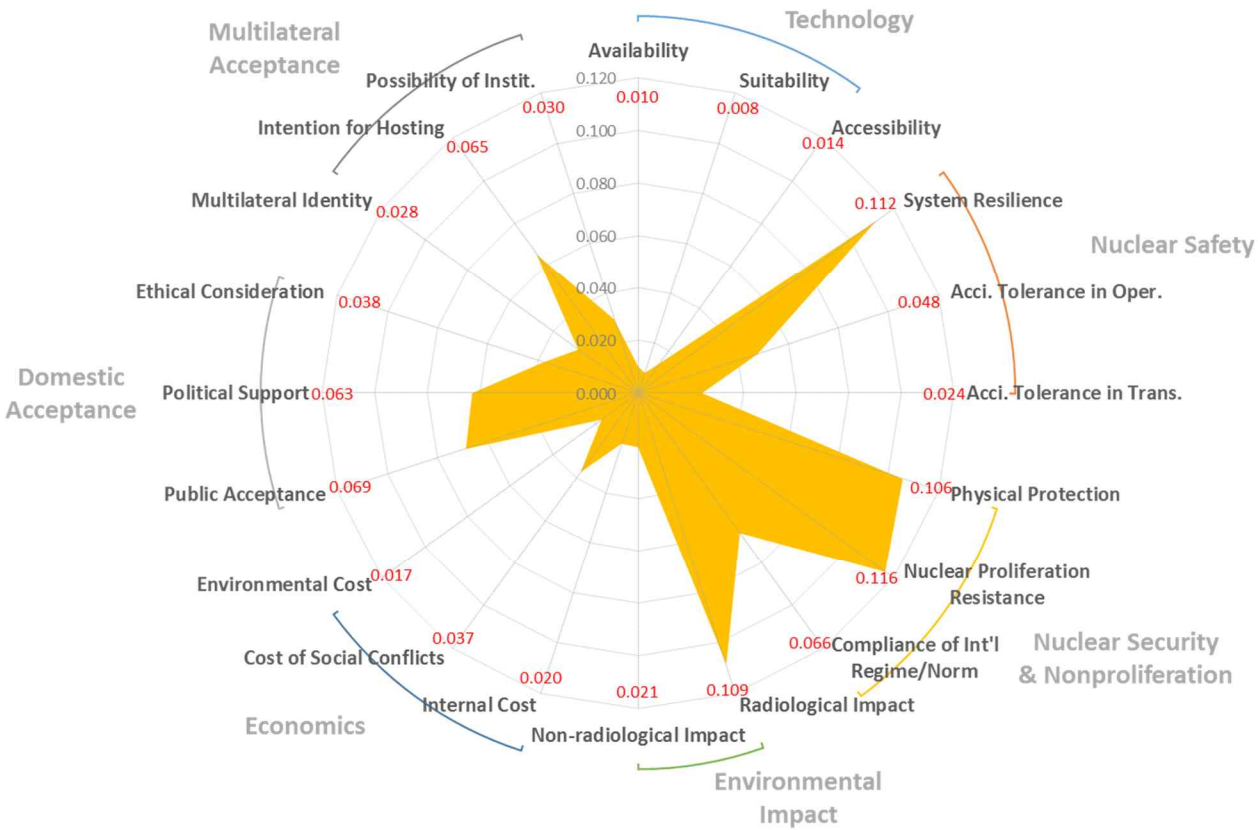

Figure 5.6 Weights on evaluation criteria in collective opinion

Table 5.2 Weights on evaluation criteria in collective opinion

Weight on top-tier criteria		Weight on second-tier criteria		C.I.	C.R.	Overall weight
Technology	0.032	Availability	0.318	0.027	0.046	0.010
		Suitability	0.250			0.008
		Accessibility	0.431			0.014
Nuclear safety	0.184	System resilience	0.608	0.002	0.003	0.112
		Acci. tolerance (O)	0.259			0.048
		Acci. tolerance (T)	0.133			0.024
Security & nonproliferation	0.288	Physical protection	0.368	0.000	0.000	0.106
		Proliferation resistance	0.403			0.116
		Compliance of int'l regime/norm	0.229			0.066
Environmental impact	0.129	Radiological impact	0.841	0.000		0.109
		Non-radiological impact	0.159			0.021
Economics	0.074	Internal cost	0.271	0.004	0.007	0.020
		Cost of social conflicts	0.499			0.037
		Environmental cost	0.230			0.017
Domestic acceptance	0.170	Public acceptance	0.405	0.000	0.000	0.069
		Political support	0.372			0.063
		Ethical consideration	0.223			0.038
Multilateral acceptance	0.123	Multilateral identity	0.228	0.000	0.001	0.028
		Intention for hosting	0.532			0.065
		Possibility of institutionalization	0.240			0.030
C.I.	0.082					
C.R.	0.062					

Table 5.3 Weights on multilateral options according to sub-criteria in collective opinion

	Technology			Nuclear safety			Security & nonproliferation			Environmental impact		Economics			Domestic acceptance			Multilateral acceptance		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C1	C2	C3	C1	C2	C3	C1	C2	C3
Regional SNF repository	0.528	0.506	0.605	0.620	0.752	0.473	0.501	0.639	0.585	0.694	0.566	0.374	0.355	0.498	0.360	0.224	0.277	0.288	0.293	0.430
Regional repro. & storage	0.318	0.329	0.166	0.192	0.117	0.260	0.212	0.141	0.185	0.159	0.213	0.282	0.247	0.262	0.265	0.319	0.297	0.323	0.324	0.267
Multilateral P&T	0.154	0.164	0.228	0.188	0.130	0.267	0.287	0.219	0.230	0.147	0.221	0.345	0.397	0.240	0.375	0.458	0.426	0.389	0.383	0.303
C.I.	0.000	0.004	0.001	0.000	0.000	0.000	0.001	0.005	0.000	0.001	0.001	0.000	0.015	0.001	0.004	0.007	0.002	0.001	0.000	0.001
C.Ratio	0.000	0.008	0.002	0.000	0.000	0.001	0.002	0.008	0.000	0.001	0.001	0.001	0.026	0.002	0.007	0.012	0.003	0.002	0.001	0.001

In the perspectives of each three multilateral options, it is necessary to clarify the relations between selected option and each factors. If it clarifies those connections, the customized strategies for improving preference can be possible, that is a purpose of sensitivity analysis. To make clear the effect of changes in factors, it varies only one weight of criterion from -100% to 100% of current value while the others keep holding relative ratios. In this approach, the original preferences will be changed according to the weight adjustments of each seven criteria, and it allows to figure out which factors have strong influences over overall preferences or not.

First, in the case of regional SNF repository, this option is the most preferred one in 50.6%. As for a sensitivity to evaluation factors, Figure 5.7 shows that the slopes of each changing factors are different in degree and tendency. This option has strong positive relations with criterions on nuclear safety, environmental impact, nuclear security and nonproliferation and technology in order, whereas the others are in opposite relations. There is a notable thing that technology and economics have the lowest values in their slope, and it means these two criteria would not have decisive effects on resultant preference of regional SNF repository. Moreover, it points out that the issues on domestic acceptance and safety should be managed as important factors.

Second, the option of regional reprocessing and storage occupies the lowest rank with 22.1% of preference. As shown in Figure 5.8, it has strong positive relations with domestic acceptance, multilateral acceptance, economics and technology in order. On the other hand, nuclear security and

nonproliferation, safety, environmental impact are in negative relations. In this option, technology and economics seem to be unable to introduce insignificant changes in the overall preference, and it indicates that the factors of domestic acceptance and security and nonproliferation should be considered as important.

Third, the multilateral P&T option is rated as 27.3% in overall preference. Figure 5.9 shows that this option has proportional relation with domestic acceptance, multilateral acceptance and economics, while inverse relations with other criterions. Like as mentioned in the above, technology and economics have mere influences on the result, and it highlights the significance of domestic acceptance and safety for bringing about noticeable changes.

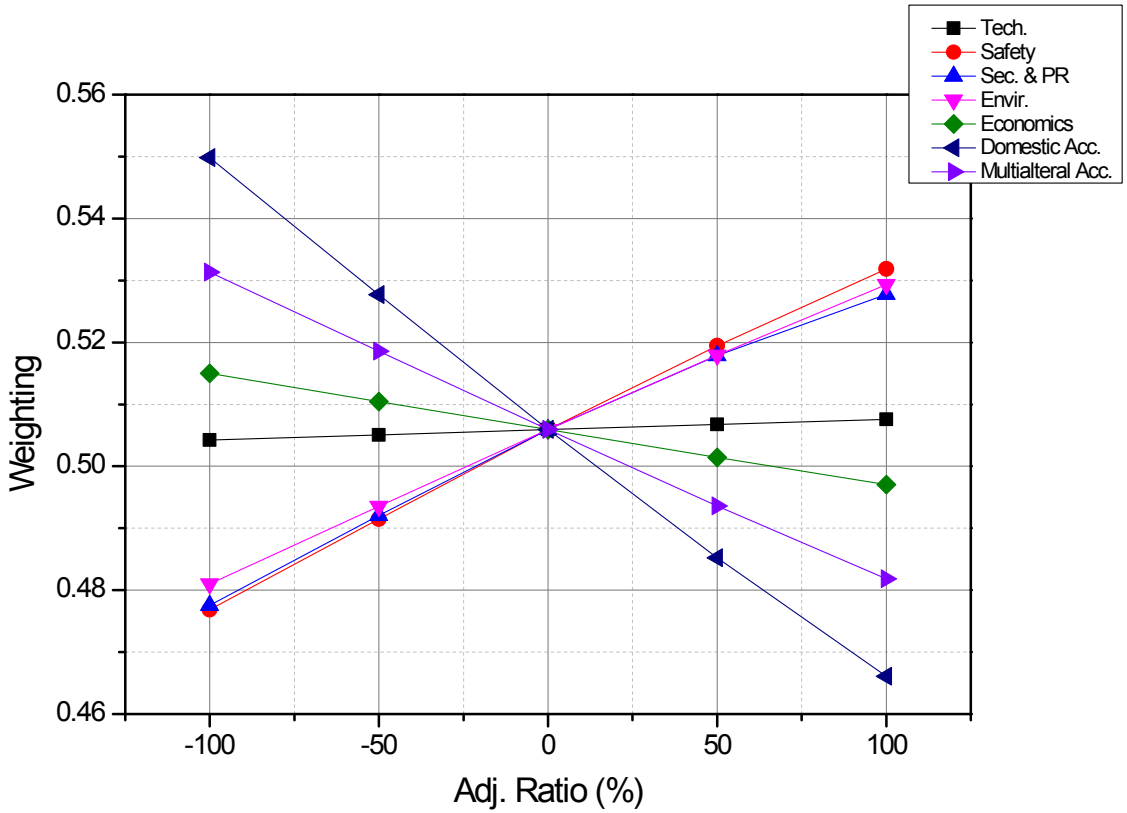

Figure 5.7 Sensitivity analysis on regional SNF repository

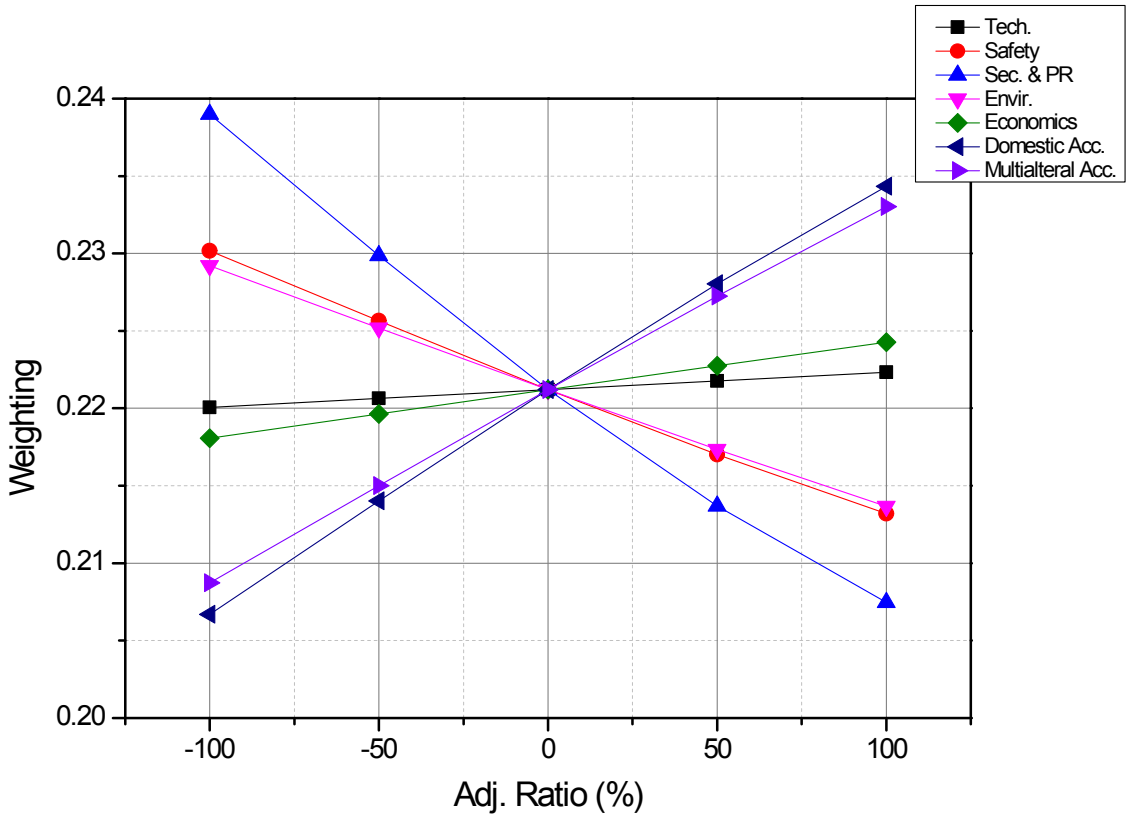

Figure 5.8 Sensitivity analysis on regional reprocessing and storage

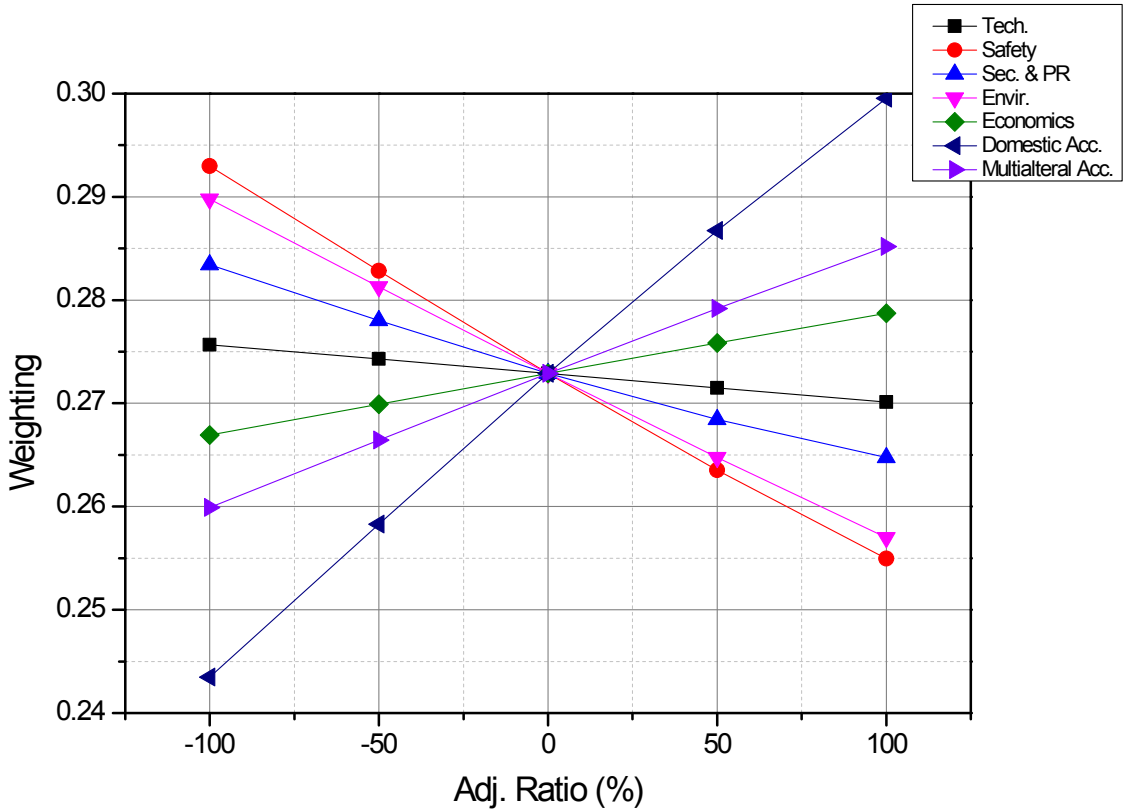

Figure 5.9 Sensitivity analysis on multilateral P&T

Sub-groups in different academic background

The twelve experts can be classified in accordance with their academic background. Four of them are based on social or political background, and the others are regarded as experts in engineering or science. Comparing the results reorganized in each groups, there is not different in the order of preference on multilateral options, just in degree. The remarkable thing is that social/political experts are more supporting (35%) on multilateral P&T option than the other group (24%). This is originated from the fact that multilateral P&T option gains higher ratings in domestic and multilateral acceptances, which are considered as sociopolitical factors.

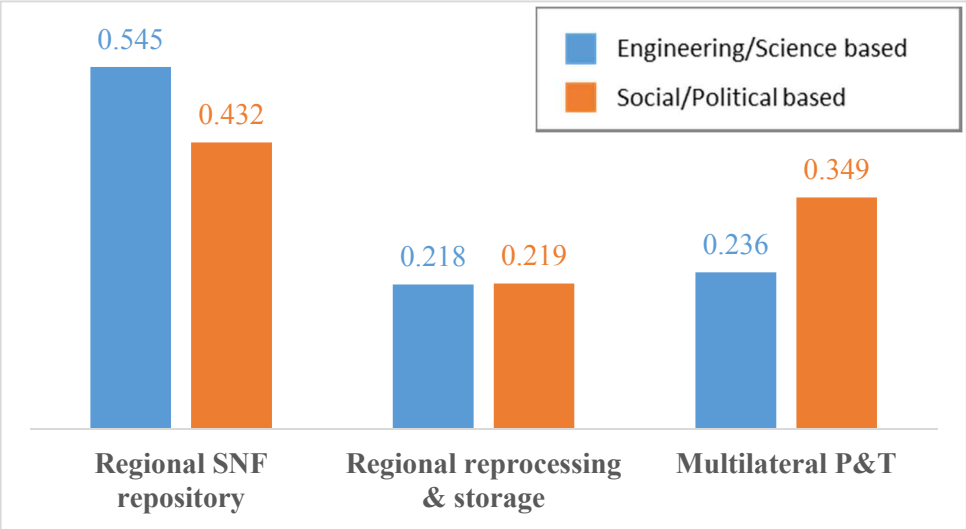

Figure 5.10 Comparison of preferences on multilateral options between two sub-groups

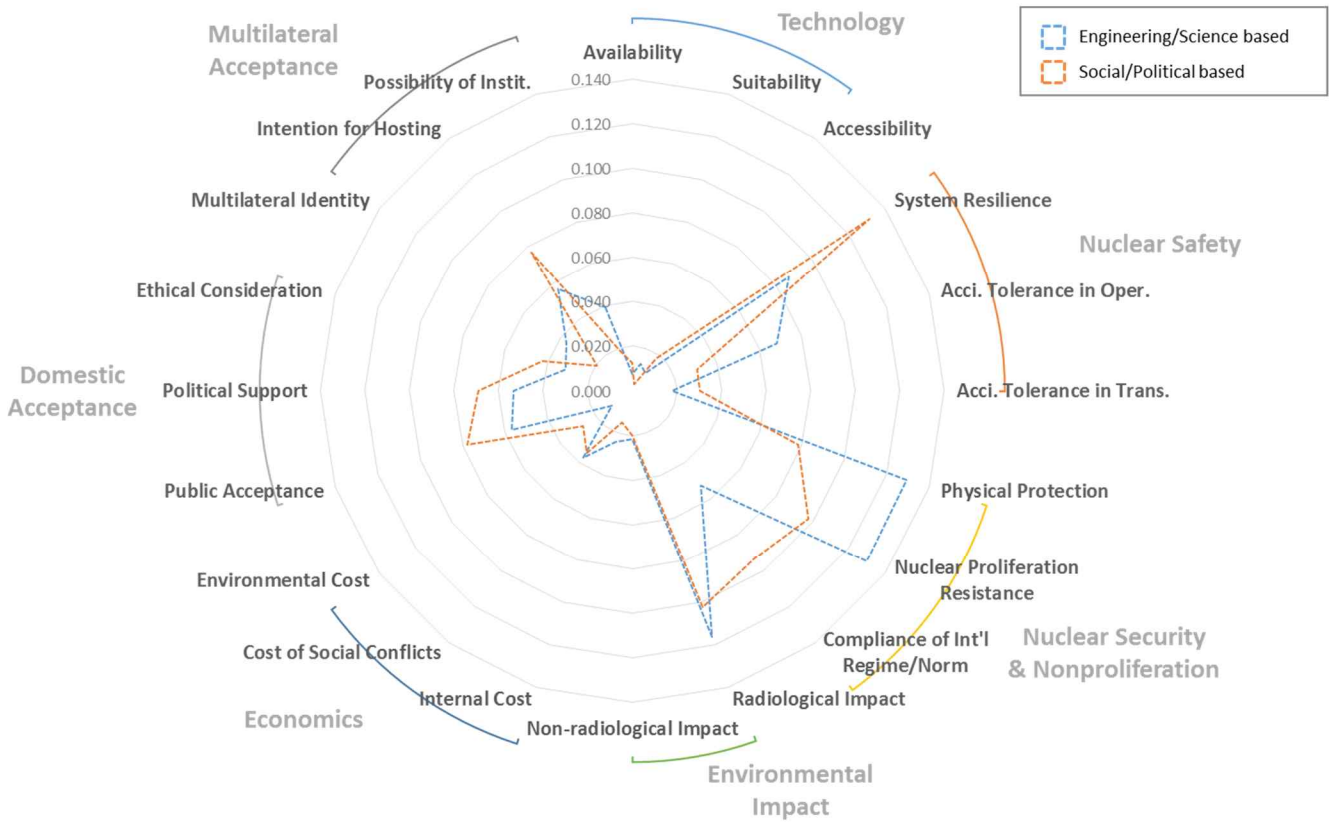

Figure 5.11 Weights on evaluation criteria in comparison of two sub-groups

Table 5.4 Weights on evaluation criteria in opinion of engineering/science group

Weight on top-tier criteria		Weight on second-tier criteria		C.I.	C.R.	Overall weight
Technology	0.029	Availability	0.249	0.035	0.060	0.007
		Suitability	0.425			0.012
		Accessibility	0.326			0.010
Nuclear safety	0.173	System resilience	0.502	0.007	0.013	0.087
		Acci. tolerance (O)	0.394			0.068
		Acci. tolerance (T)	0.103			0.018
Security & nonproliferation	0.312	Physical protection	0.415	0.001	0.002	0.130
		Proliferation resistance	0.417			0.130
		Compliance of int'l regime/norm	0.168			0.052
Environmental impact	0.138	Radiological impact	0.843	0.000		0.116
		Non-radiological impact	0.157			0.022
Economics	0.073	Internal cost	0.332	0.002	0.004	0.024
		Cost of social conflicts	0.510			0.037
		Environmental cost	0.158			0.011
Domestic acceptance	0.142	Public acceptance	0.402	0.000	0.001	0.057
		Political support	0.375			0.053
		Ethical consideration	0.223			0.032
Multilateral acceptance	0.132	Multilateral identity	0.274	0.001	0.002	0.036
		Intention for hosting	0.428			0.057
		Possibility of institutionalization	0.298			0.039
C.I.	0.103					
C.R.	0.078					

Table 5.5 Weights on evaluation criteria in opinion of social/political group

Weight on top-tier criteria		Weight on second-tier criteria		C.I.	C.R.	Overall weight
Technology	0.034	Availability	0.373	0.017	0.029	0.013
		Suitability	0.091			0.003
		Accessibility	0.536			0.018
Nuclear safety	0.193	System resilience	0.684	0.000	0.000	0.132
		Acci. tolerance (O)	0.158			0.030
		Acci. tolerance (T)	0.158			0.030
Security & nonproliferation	0.269	Physical protection	0.290	0.001	0.002	0.078
		Proliferation resistance	0.364			0.098
		Compliance of int'l regime/norm	0.346			0.093
Environmental impact	0.122	Radiological impact	0.836	0.000		0.102
		Non-radiological impact	0.164			0.020
Economics	0.076	Internal cost	0.193	0.007	0.013	0.015
		Cost of social conflicts	0.452			0.034
		Environmental cost	0.355			0.027
Domestic acceptance	0.189	Public acceptance	0.411	0.007	0.013	0.078
		Political support	0.364			0.069
		Ethical consideration	0.224			0.042
Multilateral acceptance	0.116	Multilateral identity	0.167	0.000	0.000	0.019
		Intention for hosting	0.665			0.077
		Possibility of institutionalization	0.167			0.019
C.I.	0.085					
C.R.	0.064					

Table 5.6 Weights on multilateral options according to sub-criteria in opinion of engineering/science group

	Technology			Nuclear safety			Security & nonproliferation			Environmental impact		Economics			Domestic acceptance			Multilateral acceptance		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C1	C2	C3	C1	C2	C3	C1	C2	C3
Regional SNF repository	0.592	0.443	0.694	0.705	0.770	0.477	0.536	0.648	0.579	0.714	0.633	0.290	0.355	0.501	0.528	0.228	0.320	0.282	0.353	0.429
Regional repro. & storage	0.299	0.394	0.167	0.143	0.106	0.257	0.197	0.156	0.221	0.141	0.195	0.296	0.267	0.250	0.214	0.373	0.305	0.367	0.355	0.303
Multilateral P&T	0.109	0.164	0.139	0.152	0.124	0.267	0.267	0.196	0.199	0.145	0.173	0.415	0.378	0.250	0.257	0.400	0.375	0.352	0.292	0.268
C.I.	0.004	0.002	0.004	0.000	0.000	0.001	0.001	0.001	0.001	0.000	0.002	0.002	0.005	0.000	0.000	0.000	0.002	0.000	0.001	0.002
C.Ratio	0.007	0.003	0.007	0.001	0.001	0.001	0.002	0.002	0.002	0.001	0.003	0.003	0.009	0.000	0.000	0.000	0.003	0.000	0.001	0.003

Table 5.7 Weights on multilateral options according to sub-criteria in opinion of social/political group

	Technology			Nuclear safety			Security & nonproliferation			Environmental impact		Economics			Domestic acceptance			Multilateral acceptance		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C1	C2	C3	C1	C2	C3	C1	C2	C3
Regional SNF repository	0.384	0.625	0.369	0.480	0.714	0.464	0.419	0.596	0.571	0.662	0.459	0.496	0.354	0.494	0.167	0.213	0.201	0.294	0.192	0.424
Regional repro. & storage	0.331	0.218	0.134	0.277	0.143	0.268	0.246	0.103	0.118	0.188	0.233	0.250	0.220	0.276	0.299	0.247	0.271	0.245	0.250	0.219
Multilateral P&T	0.285	0.157	0.497	0.244	0.143	0.268	0.335	0.301	0.311	0.150	0.307	0.254	0.426	0.230	0.534	0.540	0.528	0.461	0.558	0.357
C.I.	0.011	0.013	0.001	0.000	0.000	0.000	0.002	0.036	0.007	0.001	0.000	0.000	0.038	0.004	0.027	0.038	0.002	0.017	0.010	0.017
C.Ratio	0.019	0.022	0.002	0.000	0.000	0.000	0.003	0.063	0.013	0.002	0.000	0.000	0.066	0.007	0.047	0.066	0.004	0.029	0.017	0.029

As for the comparison in sub-criteria shown in Figure 5.11, two groups are also not different in overall tendency but in degree. This implies that the AHP method is not highly dependent on features of respondents only if they have professional knowledge and experiences on the key issue. As listed in Table 5.8, both groups show similar preferences in top ranked criterions. The eight of ten criterions are in common, whereas the differences can be featured by each groups; Engineering/science group is apt to prefer practical factors to construct multilateral SNF management while social/political group considers potential risks in related societies.

Table 5.8 Comparison of top ranked criterions in two sub-groups

Ranking	Engineering/science group	Social/political group
1	Proliferation resistance	System resilience
2	Physical protection	Radiological impact
3	Radiological impact	Proliferation resistance
4	System resilience	Compliance of int'l regime/norm
5	Accident tolerance in operation	Physical protection
6	Public acceptance	Public acceptance
7	Intention of hosting	Intention of hosting
8	Political support	Political support
9	Compliance of int'l regime/norm	Ethical considerations
10	Possibility of institutionalization	Cost of social conflicts

This chapter has been evaluated the multilateral options for SNF management to select the most reasonable one, and examined weightings on criteria to prioritize key factors on this issue. According to the expert opinion, regional SNF repository is selected as the most reasonable option. In addition,

the weightings on evaluation criteria imply to break the generalized perception, and to consider measures for enhancing acceptances on multilateral SNF management. However, this does not mean that other options are useless. This study examines the pros and cons of each multilateral options thus these can be promoted as a dual-track approach. Therefore, it is necessary to consider specific measures for supporting these multilateral options both in a regional perspective and in ROK.

Chapter 6 Practical Implications

In previous chapter, it examined the multilateral management options for SNFs in Northeast Asian region, and those options were evaluated by the selected experts. The results can be accepted as the deducted preferences on three options would reflect the necessity and adequacy for establishing a multilateral framework on SNF management in Northeast Asia. The multilateral cooperation can be applied to Northeast Asian region, and it is able to contribute to the SNF management in each regional countries. As a study concerning the policies on SNF management, this study is to present ideas for practical implications acceptable to Northeast Asian region

First of all, it requires to consider a concrete strategic plan for achieving multilateral SNF management. A roadmap as a systemized plan, which is consisted of mission, vision, core value and strategic object, is widely used in the field of business management, and this concept can be applied to the establishment of multilateral cooperation. Furthermore, an analysis on policy environment will help to promote the introduction of multilateral SNF management for Northeast Asian and its member states.

6.1 Application to Northeast Asian region

The problem of SNF management is becoming more serious around the world and especially in Northeast Asia. To introduce multilateral management options for SNFs to Northeast Asian region, it must understand the internal and external

conditions for policy environment exactly, and then it can prepare for what is to come. That is why a specific roadmap is required.

A roadmap starts with mission which declares the purpose of multilateral cooperation and serves as the standard for further cooperation. Introducing the multilateral options for SNF management in Northeast Asia, it is clearly expected that they will contribute to sustainable use of civilian nuclear power, and achieve SNF management in safe, secure and proliferation-resistant. Moreover, the multilateral cooperation on this matter can serve both as a confidence building measure easing the tensions in Northeast Asian region, and as a basement for continuous collaborations among the regional countries. All of these can be regarded as the mission for constructing the multilateral cooperation. Vision provides the framework for roadmap by describing what it needs to accomplish in order to continue achieving the goal, SNF management in Northeast Asian region. In this regard, its vision for multilateral cooperation would be suggested to construct a consortium for studying and promoting the multilateral options. Provision of feasible multilateral options for managing SNFs in this region can be pursued through the multilateral consortium. Using the result of expert survey deducted in the previous chapter, the core values can be introduced. This study considers seven evaluation criteria as key factors but two of them, technology and economics, are regarded as less important than the others. For a long-term sustainability, the values for multilateral cooperation should be unchangeable or less changeable. Thus the following factors are considered as core values serving as guides for activities performed by the multilateral cooperation.

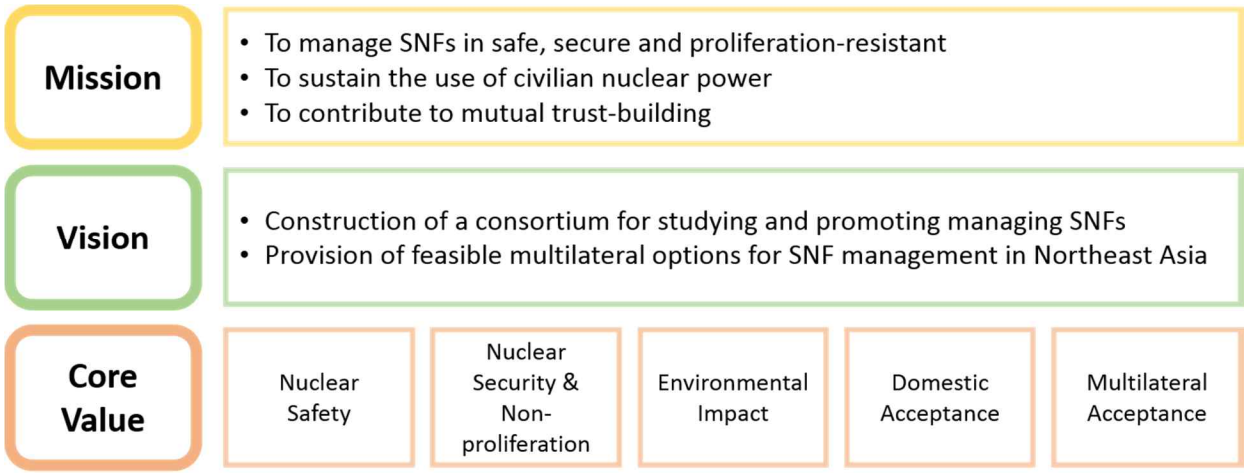

Figure 6.1 Mission, vision and core values of multilateral cooperation for SNF management in Northeast Asia

To introduce a multilateral consortium in the region, it is necessary to establish concrete strategies to achieve the goal of SNF management. These strategies define how it can succeed in reaching its mission and help to keep its condition in top form. Both internal and external environment assessment is needed as an input for developing strategies, and in this regard a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is widely utilized.

The policy environment for SNF management in Northeast Asia is assessed by SWOT analysis as shown in Table 6.1. As for the internal strengths, first of all, it be indicated the rapid growths and R&D activities on nuclear power industry, which are mainly driven by four major nuclear power states. In addition, there are national requests for accumulated SNFs in each countries thus these might be a strong driving force or motivation for finding multilateral solutions. However, the problem of SNF management is going to be too urgent to have an enough time for preparing a domestic solution in each states. Moreover, some countries have poor geological conditions for long-term disposal of SNFs, and others are restricted to access to the sensitive technologies such as reprocessing. Even if all the above weaknesses are excluded, traditional tensions in the region which has a historical background might inhibit a mutual cooperation. Considering the external opportunities and threats, the issue of multilateral SNF management is obtaining consensus in the global perspective because of not only necessities from existing nuclear states but also demands from newcomers. In addition, the recent proposals suggested by Russian Federation and Australian State Government can be regarded as a beneficial chance to refine feasible multilateral options. In contrast, the

multilateral cooperation can be threaten by the fact that there is no precedence of multilateral SNF management around the world. Various concerns on nuclear safety, security and nonproliferation are also suggested as potential risks for introducing the multilateral options. Based on this SWOT analysis, it is possible to consider possible strategies according to its position in the SWOT matrix. The combination of the internal and the external elements creates the following four intersections:

- ***SO (Strengths-Opportunities) strategy*** is to use internal strengths to capitalize on external opportunities.
- ***WO (Weaknesses-Opportunities) strategy*** is to improve internal weaknesses by using external opportunities.
- ***ST (Strengths-Threats) strategy*** is to use internal strengths to avoid external threats.
- ***WT (Weaknesses-Threats) strategy*** aims to avoid threats and to minimize weaknesses.

Each of three multilateral options considered in the previous chapters can be attained by one of above strategies. Firstly, in the case of regional SNF repository, it is evaluated as the simplest disposal option with less transportations then others but it needs a stable geological condition. According to the SWOT matrix, this option can be promoted by a WO strategy because the vulnerabilities related to a siting process and long-term burdens of SNF can be overcame by voluntary hosting intentions on the multilateral facilities. For

example, the recent preliminary study proposed by the South Australian state government considers the disposal of international SNF and intermediate wastes not only to earn economic benefits but to strengthen its leverage on nuclear industry. The government also consider the fuel leasing option to create a synergy with the disposal service. If a country voluntarily contributes to provide a site for SNF disposal, this multilateral option can be promoted easier than the others. Therefore this option requires a WO strategy to be introduced to Northeast Asian region, and it would be important to cooperate with a country with the strong intention of hosting multilateral SNF disposal facility.

For the multilateral P&T which is a multilateral option secondly preferred, a ST strategy can be applied. Anticipated threats on nuclear safety, security and nonproliferation issues are originated from the radioactive characteristics of SNF. In this case, the innovative technologies allow to eliminate these threats through P&T technologies that can reduce radioactivity and volume of SNFs. Moreover, as evaluated in the previous chapter, this option is rated as the most positive in domestic and multilateral acceptances thus it can be expected to overcome a chronic problem of public acceptance on this issue. It also requires starting from the cooperation in R&D stage, and this challenging task can provide an equivalent opportunity to cooperate with others. In several states including European states, Japan and China, researches on P&T have been performed in the early stages so further R&D activities are required.

As thirdly preferred, the regional reprocessing and storage can be promoted by a ST strategy because it is possible to use internal features to avoid external threats on the regional SNF management. Similar to the P&T option,

it is able to respond to the risks on managing SNFs with advantages in reducing SNF burden and introducing a joint control for safety, security and safeguards. On the contrary, it highly depends on the states with commercial reprocessing capacities such as Japan and China although the other factors are evaluated as much as the P&T case. Considering the actual promotion, this option can compete or cooperate with the proposal for nuclear fuel leasing and take-back services. For instance, Russian federation has been proposed a concept of fuel cycle services including a guaranteed fuel supply, and a take-back of SNF for storage and reprocessing. In this context, Tenex, a Russian state-owned company, has tried to develop a process to recycle repeatedly for maximizing utility of resources [84].

In the other intersections of the SWOT matrix, SO and WT strategies can be considered to apply two extreme cases; the multilateral initiative can be the most offensive stance as SO, and a nuclear phase-out is the most defensive position of WT. To introduce the multilateral options for managing SNFs to Northeast Asian region, it is necessary to cope with all possible strategies except the nuclear phase-out scenario. As a long-term roadmap for introducing multilateral SNF management options in Northeast Asia, the establishment of multilateral consortium with consents from members is required, then it should examine transitions to feasible multilateral options both of WO and ST strategies. These can be pursued as strategic objects for reactive and proactive measures for SNF management in the region. The former is to manage the cumulated SNF, while the latter is to prepare feasible options for SNFs generated in the future. To react the urgency of SNF management, an option

that can be applied in simple way should be considered as a reactive measure thus this study suggests the option of multilateral SNF repository for this purpose. The other options needs more time and efforts for their applications so it is reasonable to prepare them as measures against the SNFs arisen later. The roadmap suggested in this study will contribute to prepare feasible options for SNF management as a collective measure in the region, and it allows each member states to consider the multilateral options in parallel with the domestic options.

Table 6.1 SWOT analysis on multilateral SNF management in Northeast Asia

	Strengths: • Major nuclear power states (in capacity and potential) • Nat'l driving forces in SNF management • Strong R&D activities	**Weaknesses:** • Urgency in SNF management • Differences in access to sensitive technology • Regional tensions/conflicts • Difficulty in siting procedures
Opportunities: • Int'l consensus on multilateral SNF management • Proposals from AUS and RUS • Newcomers' demands on the backend fuel cycle service	**SO strategy** • Cooperation for consensus building on SNF management	**WO strategy** • Regional SNF repository
Threats: • Risks on nuclear security and proliferation • Characteristics of SNF (Radioactivity, volume) • Lack of precedence	**ST strategy** • Multilateral P&T • Regional reprocessing and storage	**WT strategy** • Nuclear phase-out in Northeast Asian region

6.2 Policy recommendations for Republic of Korea

Until a recent date, the government of ROK has maintained a stance of "wait-and-see" as a domestic policy for decades so the problem of SNF management in the ROK became more serious. It can be said that this passive attitude of the government has been occurred due to the sequential failures for introducing a domestic SNF disposal facility [85]. Even in promoting a public policy, it is important to obtain acceptances from the public and local residents, then what about the policy on SNF management? There is no other factors regarded more important than the public acceptance in the case of SNF management policy, thus various measures for enhancing public supports are required.

In recent, the government of ROK has announced the Master Plan for management of high-level waste [86]. The main gist of the Master Plans is following:

1) Selecting a domestic site for HLW management through a stepwise and consent-based procedure
2) Considering international storage and disposal options to provide against uncertainties in the domestic siting process
3) Preparing the HLW management facilities such as underground research laboratory (URL), interim storage and geological repository on time
4) Developing key technologies for HLW management including transportation, storage, disposal and recycling, and encouraging international cooperation for joint researches

5) Improving transparency and reliability on HLW management policy through continuous communication with the local inhabitants

These five tasks aims to prepare the applicable options for HLW management, and Figure 6.2 shows well details of this plan. According to current schedule, a site selection process will begin next year, and then constructions of interim storage and repository will be started in 2029. Before operating an interim storage, accumulated SNFs will be separately kept in on-site storages. International joint researches are optionally considered as a supplementary approaches of domestic policy. In this regard, it is possible to discover problems of the current master plan. The first deadlock can begin at a siting step because a time of 12 years is not enough to obtain public acceptance in comparing with the foreign cases. In addition, it would be hard to accept the fact that a potential site will contain the facilities of both interim storage and repository in same area. The other problem is on schedule, which is under a strong time pressure without considering any contingency plan. If any interruption is occurred, sequential steps will be jeopardized. Lastly, it needs to specify suggestions on international cooperation in more detail. All these problems can inhibit to proceed the plan in sequential.

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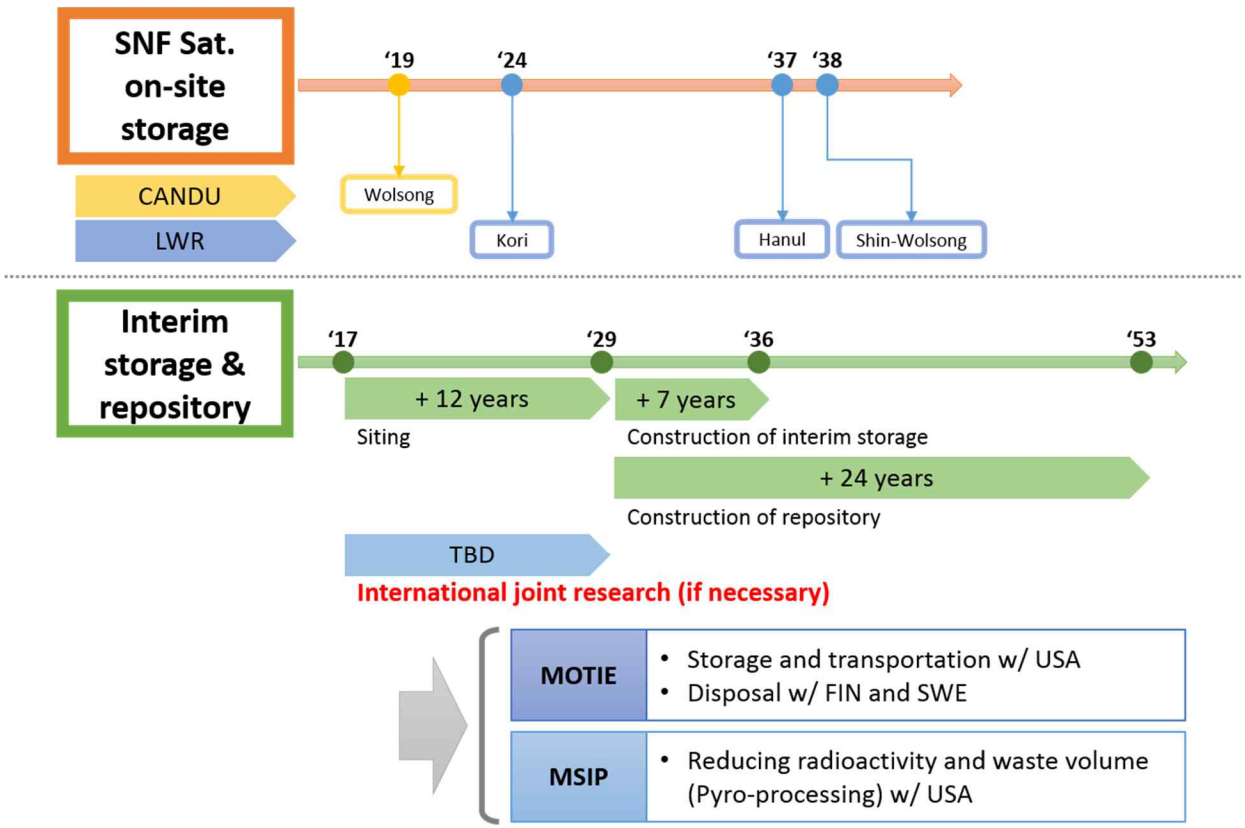

Figure 6.2 Current master plan for HLW management in the ROK

According to the flow for promoting a domestic HLW management plan in Figure 6.3, the first decision step on a siting will influence to determine whether the plan will be a success or not. Unless a site is confirmed, the service extension of on-site storages should be considered but it is also not an easy task. In the current legislations, there is a discrepancy in interpretation of some legal terms on kinds of on-site storage facilities. In this process, if the extension of on-site storage period is allowable, a siting step will be restarted afterward. Otherwise, that request cannot be approved by oppositions of local communities, then there is no choice but shut-down of nuclear power plants in the worst case. This deadlock is the most concerned matter in the current plan, thus it is necessary to examine how to solve, or how to prevent the anticipated problem. In several studies, it has been indicated that it is necessary to enhance the public acceptance for strengthening a policy adaption in the issues of radioactive management. The procedure of "Decide-Announce-Defend" (DAD) approach has been widely used in promoting various national policies but this approach needs to be corrected to apply to the SNF management policy [87,88]. The low acceptance is based on the fact that there is no option that can be considered except the plan proposed by high level decision makers. To enhance public acceptance, it requires to suggest additional options which can reflect public opinion. In this regard, it is important to prepare alternatives or back-up plans of the current plan, and multilateral options can be applied.

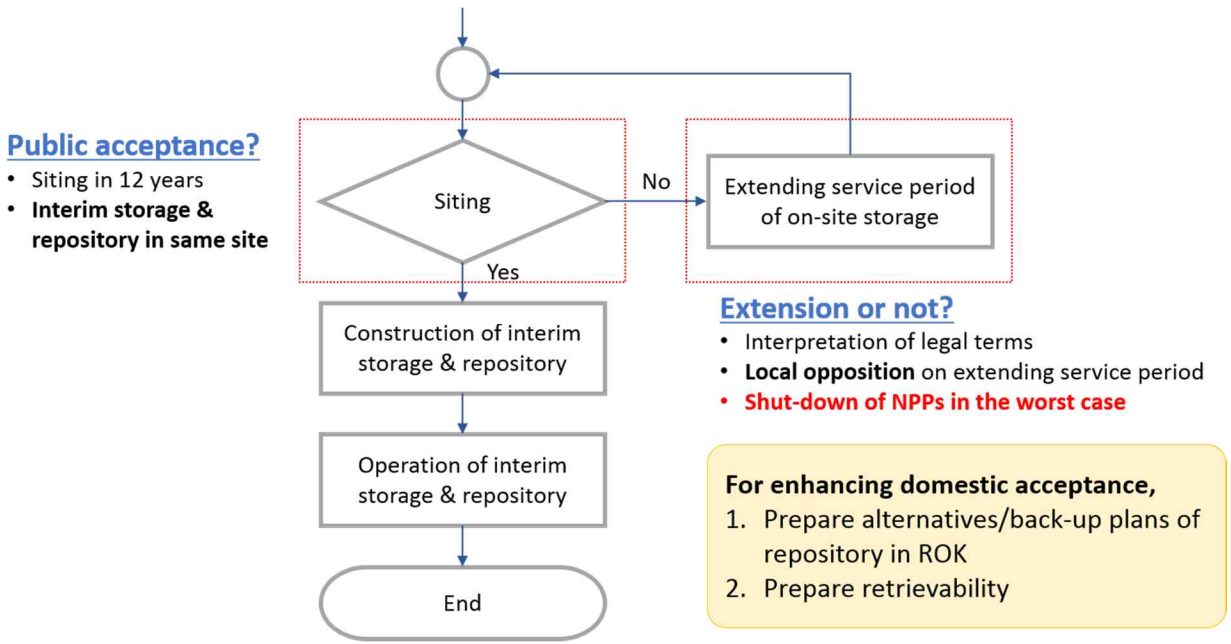

Figure 6.3 Flow chart for promoting current master plan for HLW management in the ROK

In case of ROK, if multilateral options are promoted in parallel with the domestic strategy for SNF management, the improvement of public acceptance can be achieved by providing alternatives to current national strategy to widen choices for national SNF management plan. To select feasible multilateral options for the ROK, the options should be practically applicable to the ROK, and beside, the ROK can contribute substantially to develop the multilateral options. Furthermore, multilateral options can manage SNFs in perspectives from a short-term to long-term period, thus both reactive and proactive measures are demanded. Among the multilateral SNF management options discussed in previous chapters, this study selects the option of regional SNF repository and multilateral P&T options to combine with the ROK's domestic policy.

As a reactive measure for resolving the urgent problem of SNF management, the regional SNF repository is chosen as an optimum option because it is currently regarded as the most feasible option. Furthermore, the Australian proposal gives chance to develop this option more practical, which can be promoted by the WO strategy. If a practical cooperation for regional SNF repository is established, this option can be considered redundant or back-up for the domestic plan with enhancing the public acceptances on siting steps. Considering the national SNF statuses in each countries, not only ROK but Japan and Taiwan might be attracted to participate in this cooperation. In addition, USA and IAEA can be related to this multilateral option as key observers in the international aspects. All the participants need to contribute in financial investment for construction and operation of the multilateral facility,

and to cooperate in preparation of key elements such as transportation, storage and disposal technologies. As a contribution plan of ROK for participating this option, especially in promotion of the Australian proposal, the ROK can discuss a technical cooperation on fuel fabrication since the Australian proposal is to expand its scope to fuel-leasing in the frontend cycle. This kind of technical collaboration can be regarded as a basis for mutual benefits, then it helps the ROK to join the multilateral cooperation.

In a long-term perspective, it is necessary to prepare a proactive measure for SNFs which are anticipated to occur from now on. To maximize its effectiveness on SNF management, it needs to develop innovative technologies for minimizing the burdens of SNF disposal in domestic territory. Thus, the multilateral P&T is selected for this purpose, and it is expected to obtain public supports on the policy promotion with introduction of the concept of retrievability to the current plan. This allows flexibilities on a whole steps of deciding, debating and promoting processes. For this option, Japan, Taiwan, China and ROK have interests in its development and utilization, thus all these countries are considered as key member states. In addition to them, USA has a common interest for this cooperation because USA tries to devote enormous efforts for an innovative technologies for SNF management, and the P&T is expected as a feasible solution for this purpose. Lastly, the IAEA is considered as an important observer for the same reason as before. As an option applying in future, this approach can accept the requirements on amount of time and investment for its practicality. In technical aspects, joint R&D and mutual verification on new technologies on P&T are required necessarily, and this

condition can be utilized as a practical basement of the ROK's leverage. That means the ROK can contribute its assets to develop the multilateral P&T though hosting of a site for multilateral feasibility study on P&T from lab-scale to pilot-scale.

For introducing these multilateral options to the ROK, there are some requirements or preparations for its introduction to the domestic plan. First, it needs to stipulate these multilateral options in the Master plan for HLW management. To promote national policies, only a documented and publicized plan can obtain its long-term driving forces in budget and manpower. In addition, these multilateral options should be considered as redundant or back-up options for the domestic approach. The effectiveness in enhancing public acceptances is already mentioned in previous section. Next, in the legislation steps, it requires to legislate multilateral requirements such as a basis for funding and specific terms on the multilateral options. Furthermore, considering the relation with USA, it needs to discuss the prior consent necessary for the ROK's transboundary nuclear activities with the USA. Third, it is highly recommended the ROK to establish a new authorized agency for managing the whole backend fuel cycle including SNF disposal, recycling and P&T. In current, this issue is separately connected to several government ministries of MOTIE, MISP and MOFA, so it is difficult to resolve differences in opinions among the government branches. For the goal of SNF management with both domestic and multilateral options, it would be effectively achieved and integrated only through an independent agency over those branches. At last, there are many think-tanks around the world, which gather a group of

professional in order to consider various problems and work out ways to resolve them, and the same is true for nuclear policy. The issue of nuclear fuel cycle is so convoluted that its policies requires to be examined continuously and extensively. However, in the ROK, none of independent research institutes on nuclear policy is operational. Preparing a SNF management policy combining the domestic and the multilateral options, therefore, this study suggests to establish a think-tank for gathering a group of experts. As a sustainable and proficient research environment, it would be expected that periodic policy reviews and analysis of policy environment for the ROK's SNF management are achieved. Moreover, this organization can promote domestic feasibility studies on the multilateral options compatible with the domestic strategy before activating a multilateral consortium suggested in the prior section.

Based on these four preparations, the multilateral options chosen in this study can be compatible with the national master plan in the ROK. In addition, establishment of a multilateral consortium will provide a measure of consensus-building, then it can take over the feasibility studies performed in each states for specification and application of potential options. Thus all of these policy recommendations should be examined in parallel, both regionally and domestically.

Chapter 7 Conclusion

7.1 Summary and findings

The purpose of this study is to identify both practical and feasible multilateral options for spent fuel management applicable to the Northeast Asian region where nuclear electricity has been playing major role in building energy security, economy and industrial infrastructure. To achieve the goal of this study, the thesis is focused to answer following research questions: 1) what are the possible multilateral options for SNF management in Northeast Asia, and then how they can be evaluated on practicality and feasibility, 2) which multilateral option can be preferred, and what criteria should be considered as significant, and 3) what are the strategic plans for introducing multilateral options to Northeast Asia and the ROK. To find the answers, it examines possible cases of multilateral SNF management, then it selects three of them; "regional SNF repository", "regional reprocessing and storage", and "multilateral P&T". To evaluate these multilateral options, the multi-criterial evaluation approaches are reviewed the issues of SNF management and its multilateralization are involved various factors. In this step, the AHP is chosen as a key research methodology, which is featured in followings: theoretical background, objectiveness on weight derivation, consistency check, and collecting group opinion.

It evaluates the qualitative and quantitative criteria, which relate to spent nuclear fuel management and its multilateralization, as a whole through the AHP method that is one of the multi-criteria decision making approaches. For

applying the AHP method, it arranges various evaluation factors used in the previous researches on the SNF management or the innovative nuclear fuel cycle system, then it deducts the common factors. Moreover, it includes the multilateral characteristics based on the definition and basic principles of multilateralism in International Relation. The resultant criteria covers the area of technology, nuclear safety, security and nonproliferation, environmental impact, economics, domestic acceptance, and multilateral acceptance. For more details, twenty sub-criteria of each top criterions are defined as the evaluation criteria. As for possible alternatives for SNF management, it chooses the following three multilateral options with considering the diversity of key technologies and strategic feasibilities.

As the first of practical and feasible multilateral options, a "regional SNF repository" aims to dispose of SNFs in a joint repository facility which satisfies geological conditions on the long-term stability. This option can be regarded as the simplest measure since it does not manipulate SNFs to extract some materials or to modify their original forms. It also can be featured as that not only limited to nuclear power countries but any countries without operating nuclear power plants can be a host state only if there are suitable sites and contributions of voluntary countries. The second multilateral option is defined as "regional reprocessing and storage", which is utilizing commercial reprocessing capacities in Northeast Asian region and then managing separated plutonium and uranium within a joint facility for long-term storage. Resultant vitrified HLW and ILW will be returned to the member country of origin. This approach utilizes the multilateral framework as a stable supplying system for

ensuring the commercial reprocessing services without access to the sensitive technologies. Furthermore, enhanced security measures and safeguards can be expected by the joint control of sensitive materials produced by reprocessing. The last option is defined as "P&T" that is based on innovative technologies developed recently on a laboratory-scale. Assuming its scale-up for industrialization, a P&T center is operated to eliminate the final disposal burdens of SNF through with decontamination of high level wastes, leaving behind only intermediate and low level wastes. Both ILW and LLW will be returned to the country of origin as significant disposal experience with them have established both safety and security assurance. However, it needs significant amounts of time and money to promote from R&D step to commercialization thus a multilateral cooperation can be effective in its progress.

Based on the selected criteria, three postulated multilateral options are examined on the relative merits by the AHP method with global experts. This thesis led to an evaluation model which provides expert consensus for practical and feasible multilateral SNF management approaches.

Table 7.1 Summarized result of collective opinion in expert survey

Multilateral option	Preference (%)	Rank of multilateral option according to each criterions																			
		Technology			Nuclear safety			Security & nonprolifer.			Enviro. impact		Economics			Domestic acceptance			Multilateral acceptance		
		A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1	E2	E3	F1	F2	F3	G1	G2	G3
Regional SNF repository	**50.6**	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2	3	3	3	3	1
Regional reprocess. & storage	**22.1**	2	2	3	2	3	3	3	3	3	2	3	3	3	2	3	2	2	2	2	3
Multilateral P&T	**27.3**	3	3	2	3	2	2	2	2	2	3	2	2	1	3	1	1	1	1	1	2
Weight on 1st-tier criteria (%)		3.2			18.4			28.8			12.9		7.4			17.0			12.3		

A1: Availability, A2: Suitability, A3: Accessibility / B1: System resilience, B2: Accident tolerance (O), B3: Accident tolerance (T) / C1: Physical protection, C2: Proliferation resistance, C3: Int'l regime/norm / D1: Radiological impact, D2: Non- radiological impact / E1: Internal cost, E2: Cost of social conflict, E3: Environ. cost / F1: Public acceptance, F2: Political support, F3: Ethical consideration / G1: Multilateral identification, G2: Intention for hosting, G3: Institutionalization

As shown in Table 7.1, from the results of expert survey for assessing in practical and professional, the option of "regional SNF repository" is found to be the most preferred in current for multilateral SNF management in Northeast Asia. Then "innovative P&T" is the found to be the second preference, leaving "regional reprocessing and storage" as the least preferred option. A "regional SNF repository" option receives the highest ratings by experts in almost all criteria. The result explains why this option has been explored most in the past. The ongoing proposal by the South Australian State government may prove the first multinational solution. As the second preferred option, a "multilateral P&T" is favorably evaluated in the sections of public acceptance, political support, ethical consideration and multilateral identity while a "regional reprocessing and storage" is relatively high only in the technology criteria. The difference between latter two options is explained by the fact that the "multilateral P&T" can eliminate the disposal burdens of HLW fundamentally. In addition the P&T option can also allow technical cooperation because this option is based on innovative technologies requiring significant R&D efforts for several decades.

The most notable point is that the factors considered as important by the expert group are different from general perception as often found in public policy-making. The feasibilities in technology and economics would be considered as important factors for deciding a national policy, R&D investment, or long-term planning. The experts placed higher weight on nuclear safety, security and nonproliferation, public acceptance and the intention of hosting the multilateral SNF management facilities. Considering required time and features of multilateral SNF management, experts predict that public acceptance and

siting as the requirement for long-term policy should be considered more important than technology and economics.

If the multilateral management options for SNFs in Northeast Asian region are introduced, they will contribute to restoring public support for nuclear power by managing SNFs with due attention to nuclear safety, security and nonproliferation. For this reason, the multilateral cooperation on SNF management can serve both as a confidence building measure to enhance regional cooperation in Northeast Asian region. In case of ROK, the advent of multilateral options can change national policy for SNF management with the improvement of public acceptance by providing sustainable solutions to the current policy for national SNF repository development plan. Therefore, it is recommended that the results of this study should be continuously updated to actively respond to the changes of policy environments on SNF management.

7.2 Future work

In the aspect of research methodology used in this study, the evaluation and survey processes can obtain more validity of results if it can involve a larger group of professionals in AHP. In this context, further studies targeting broadened expert group should be followed with the multi-criteria evaluation model proposed by this study. In addition, the AHP evaluations can be repeated to update changes in national demand, policy and qualification of options. For future discussions on multilateral approaches, these procedures should be performed in both in multilateral and in national levels, in parallel.

It should be noted that several researches have pointed out inherent limitations of the AHP method. They mainly indicate the problems of priority inversion occurred by adding new alternatives [89] and of inconsistency raised by measuring scales [90,91]. Moreover, there are several methods for collective decision making in the AHP according to the facts whether it classifies survey respondents, or uses interval-values instead of individual raw data. In this study, all experts are regarded in equal for simplicity, thus each responses received from different experts are rated as equivalent. If it assumes, then applies different perspectives on the classification of respondents, more complex but refined results can be deduced, thus it is remained for a follow-up study.

Among key assumptions used in this study, the condition of independence for all evaluation options and factors is the prerequisite for applying a generalized AHP method. This independence assumption needs to be validated by examining sensitivity among options and factors. However, in real cases, some of factors would relate with others in direct or indirect ways thus a more refined measure is utilized. As one of advanced MCDM techniques, ANP (Analytic Network Process) method is recently founded on the practical perception that all decision making problems cannot be constructed hierarchically because of its interconnections or dependences among elements in different levels [92,93]. It means that the ANP method can consider complex interrelationships in decision levels and evaluation factors. To establish a general and simplified model, this dissertation assumes that a policy decision making, especially in applying top-down approaches, is a framework with a unidirectional hierarchy relation which supports the theoretical basis of AHP

method. In contrast, the ANP allows to simulate the interactional relationships among actors, element, and alternatives so it would be proper to consider interactions such as public hearings or feedback processes in a policy promotion. Therefore, an additional analysis based on the ANP method can improve the results of this study with considering interconnections in options of multilateral SNF management. Furthermore, comparison of the two approaches will also offer a practical choice of analytic methods on this matter.

It is significant to prepare proper measures for dealing with anticipated problems. In this regard, future studies would aim to develop applicable scenarios for introducing multilateral options to Northeast Asia and the ROK. Based on current SNF management plans in each countries, it requires multilateral scenarios to promote in parallel with both short-term and long-term plans. Thus, subsequent studies should be performed to analyze concreate multilateral scenarios and their key factors.

In the case of ROK, the studies for coordinating the domestic and multilateral policies on SNF management needs to be continuously supported. CANDU SNFs is left outside this thesis research scope even though it is one of important issues for the final waste management for several countries including ROK. Therefore, future work needs to consider management options of CANDU fuels, which might change preferences on feasible multilateral options and key factors, and that can be an important research topic

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Abbreviation

ABACC	Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials
ADS	Accelerator-driven Systems
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CANDU	CANada Deuterium Uranium
CI	Consistency Index
CR	Consistency Ratio
DAD	Decide-Announce-Defend
DUPIC	Direct Use of Pressurized water reactor spent fuel In CANDU
ELECTRE	ELimination and Choice Expressing Reality
EURATOM	EURopean ATOMic energy community
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILW	Intermediate Level Waste
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
JAEC	Japan Atomic Energy Commission
KEEI	Korea Energy Economics Institute

KIET	Korea Institute for industrial Economics and Trade
KINS	Korea Institute of Nuclear Safety
KISTEP	Korea Institute of S&T Evaluation and Planning
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MA	Minor Actinides
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
MOFA	Ministry of Foreign Affairs
MOTIE	Ministry of Trade, Industry and Energy
MOX	Mixed Oxide Fuel
MSIP	Ministry of Science, ICT and Future Planning
NEA	Nuclear Energy Agency
NGO	Non-Governmental Organization
NPT	Non-Proliferation Treaty
OECD	Organization for Economic Cooperation and Development
P&T	Partitioning and Transmutation
PHWR	Pressurized Heavy Water Reactor
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PUREX	Plutonium-URanium EXtraction
R&D	Research and Development

RI	Random Index
ROK	Republic of Korea
SFR	Sodium-cooled Fast Reactor
SNF	Spent Nuclear Fuel
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TRU	TRans-Uranium
UNDIR	United Nations Institute for Disarmament Research
WNA	World Nuclear Association

Appendix 1. Questionnaires for Expert Survey

Analytic Hierarchy Process (AHP) Survey Questions for Experts on Multilateral Spent Nuclear Fuel Management in Northeast Asia

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Northeast Asian countries with high population densities including Japan, Korea, are Taiwan are encountering persisting public opposition to options for spent nuclear fuel management, ranging from permanent disposal, recycling as well as direct geological disposal. At some nuclear plants, spent nuclear fuels are filling up all available space which eventually can force to shut down plants. Situation is far better in China where plants are built recently and population density is much lower. International communities have been calling for multilateral approaches as a long-term solution. I have described three multilateral approached, as defined herein.

Thank you for your kindness in taking time to answer to our survey to identify preferred approaches and important factors. Here is a set of questionnaires that I would like to ask your reply which will be analyzed, anonymously, for the feasibility study on multilateral spent nuclear fuel (SNF) management in Northeast Asia. The main purpose of this survey is to assess importance of important factors, which are related to scenario selection for SNF management in this region, in hierarchical, and to estimate the weights of each elements.

All your responses in this survey will not be disclosed and will only be used for statistical analysis for this academic study. Completion of the survey would take approximately 30~40 minutes. Thank you for your time and kind input to this study.

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Information of Respondent

Please fill out the form below.

Nationality	
Type of Organization (Government, Industry, University, R&D, NGO and Other)	
Work Experience (in years)	

Area of Expertise (Please mark [√] all that applies)		
[ ] Nuclear Safety	[ ] Nuclear Security	[ ] Nonproliferation
[ ] Nuclear Fuel cycle	[ ] Disarmament	[ ] Int'l Relation
[ ] Political Science	[ ] Economics	
[ ] Etc :		

Questionnaires on Multilateral SNF Management in Northeast Asia

Please mark [√] on which criteria you think more important/adequate than the other and how much you think it relatively important in comparison with the other on the matter of SNF management in Northeast Asian region. Kindly assist in completing the following pair-wise comparisons.

The order of this questionnaires would be following; ① Adequacy evaluation of three selected scenarios according to sub-criteria, ② Importance rating among the detailed criteria, ③ Importance rating among the higher criteria, and ④ Supplementary comment

If you have anything you cannot understand, please feel free to ask me anytime.

Table 1. The fundamental scale of absolute numbers

Intensity Scale	Definition	Description
1	Equal	Two activities contribute equally to the objective
3	Slightly adequate/important	Experience and judgement slightly favor one activity over another
5	Strongly adequate/important	Experience and judgement strongly favor one activity over another
7	Very adequate/important	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extremely adequate/important	The evidence favoring one activity over another is of the highest possible order of affirmation

A. Questions in the Form of Pair-wise Comparison - **Please check one for each comparison!**

Category 1. Technology

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

Availability	The key technology applied to selected scenario should be fully developed or verified to utilize for SNF management (geological repository, reprocessing, long-term storage, participation and transmutation).									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Suitability	The key technology must be suitable/appropriate for the purpose of SNF management. In addition, its technological features in operation and management should be well connected/combined with existing systems in the long term.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Accessibility	The key technology can be more affordable when it has less difficulties/obstacles in access to target technology or its development and application.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for technology

Criteria	9	7	5	3	1	3	5	7	9	Criteria
Availability										Suitability
Availability										Accessibility
Suitability										Accessibility

Category 2. Nuclear Safety

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

System integrity	The nuclear system for SNF management should maintain its safety in case of external events or natural disasters occur (considering geological, hydrological characteristics and etc.).									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Accident tolerance in operation	The target nuclear system can be assessed as safe when the system minimize/avoid the accidental damage (or its risk) occurred in operation.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Accident tolerance in transportation	The target nuclear system can be assessed as safe when the system minimize/avoid the accidental damage (or its risk) occurred in domestic/transnational transportation.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for nuclear safety

Criteria	9	7	5	3	1	3	5	7	9	Criteria
System integrity										Accident tolerance in operation
System integrity										Accident tolerance in transportation
Accident tolerance in operation										Accident tolerance in transportation

Category 3. Nuclear Security and Nonproliferation

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

Physical Protection	The nuclear security level can be enhanced with appropriate measures against theft of nuclear materials or sabotage to nuclear facilities for SNF management.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Nuclear Proliferation Resistance	Proper means/measures which prevent misuse/diversion of sensitive material and technology can strengthen the nuclear proliferation resistance.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Compliance of International Regime/Norm	It could observe/comply existing international regime/norms, and cooperate with international organization to achieve the goal of nuclear security and nonproliferation in the anticipated SNF management system.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for nuclear security and nonproliferation

Criteria	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Criteria**
Physical Protection										Nuclear Proliferation Resistance
Physical Protection										Compliance of International Regime/Norm
Nuclear Proliferation Resistance										Compliance of International Regime/Norm

Category 4. Environmental Impact

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

Radiological Impact	The operation of SNF management system must minimize various radiological impacts on the environment. It includes ionizing radiation, heat, or nuclide leakage from the target facilities.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Non-radiological Impact	The construction/operation of SNF management system must reduce various non-radiological impacts on the environment. It includes noise, dust, or non-availability of land arisen from related activities.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for environmental impact

Criteria	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Criteria**
Radiological Impact										Non-radiological Impact

Category 5. Economics

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

Internal Cost	This cost is all tangible expenses for construction, operation, maintenance and transportation in the SNF management system. These cover management of accident risk, establishment of safety regulation (The lower is more adequate).									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Cost of Social Conflicts	This is a part of external cost for the SNF management system. It would cover management of accident risk, establishment of safety regulation and resolution of local conflict over siting issue (The lower is more adequate).									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Environmental Cost	This cost corresponds to the values required/consumed for managing SNF; costs for long-term management, disadvantages to territorial use and natural/energy resource utilization (The lower is more adequate).									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for economics

Criteria	9	7	5	3	1	3	5	7	9	Criteria
Internal Cost										Cost of Social Conflicts
Internal Cost										Environmental Cost
Cost of Social Conflicts										Environmental Cost

Category 6. Domestic Acceptance in member states

⮟ Pair-wise comparison among three scenarios according to second-tier criteria

Public Acceptance	The success or failure for participating the regional/multilateral cooperation for SNF management rests on public acceptability in each member states. Especially in case of siting issue, the local acceptance in proposed area would be the most important factor									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Political Support	It would be advantageous for promoting the regional/multilateral cooperation when strong political will/support from governments can be obtained. The Driving force of cooperation is highly based on the political decisions.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Ethical Consideration	The process for achieving the goal of SNF management and the resultants should be fair/ethical among member states, and between generations.									
Scenario	9	7	5	3	1	3	5	7	9	Scenario
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

⮟ Pair-wise comparison among the second-tier criteria for domestic acceptance in member states

Criteria	9	7	5	3	1	3	5	7	9	Criteria
Public Acceptance										Political Support
Public Acceptance										Ethical Consideration
Political Support										Ethical Consideration

Category 7. Multilateral Acceptance

▼ Pair-wise comparison among three scenarios according to second-tier criteria

Multilateral Identity	When the target cooperation scenario has the unity (not a dichotomous/differential approach) in role, position and benefit, then it can be evaluated as an ideal regional/multilateral cooperation.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Intention for Hosting	A scenario can be feasible/practical in proportion to the strong intention to host regional/multilateral facility for SNF management. The easier selecting/finding candidate to host the facility, the more advantageous policy implementation can be.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T
Possibility of Institutionalization	The systemized and sustainable cooperation would be maintained with the low possibility on betrayal and breakaway of member states, then it can be evaluated as institutionalized cooperative system.									
Scenario	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Scenario**
Regional SNF Repository										Regional Reprocessing & Storage
Regional SNF Repository										Multilateral P&T
Regional Reprocessing & Storage										Multilateral P&T

▼ Pair-wise comparison among the second-tier criteria for multilateral acceptance

Criteria	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Criteria**
Multilateral Identity										Intention for Hosting
Multilateral Identity										Possibility of Institutionalization
Intention for Hosting										Possibility of Institutionalization

Pair-wise comparison among the top-tier criteria for multilateral SNF management in Northeast Asia

Criteria	9	7	5	3	1	3	5	7	9	Criteria
Technology										Nuclear Safety
Technology										Nuclear Security and Nonproliferation
Technology										Environmental Impact
Technology										Economics
Technology										Domestic Acceptance in Member States
Technology										Multilateral Acceptance
Nuclear Safety										Nuclear Security and Nonproliferation
Nuclear Safety										Environmental Impact
Nuclear Safety										Economics
Nuclear Safety										Domestic Acceptance in Member States
Nuclear Safety										Multilateral Acceptance
Nuclear Security and Nonproliferation										Environmental Impact
Nuclear Security and Nonproliferation										Economics
Nuclear Security and Nonproliferation										Domestic Acceptance in Member States
Nuclear Security and Nonproliferation										Multilateral Acceptance
Environmental Impact										Economics
Environmental Impact										Domestic Acceptance in Member States
Environmental Impact										Multilateral Acceptance
Economics										Domestic Acceptance in Member States
Economics										Multilateral Acceptance
Domestic Acceptance in Member States										Multilateral Acceptance

B. Supplementary Questions (Optional)

Q1. Do you think the evaluation criteria suggested in this survey are adequate? If any criteria need to be added or deleted, please identify on your feedback.

Q2. Do you think the three scenarios for multilateral cooperation suggested in this survey representative? If you think that anything is required to complement or modify, please write on your feedback.

Q3. Please describe your opinion on the issue of multilateral SNF management cooperation in Northeast Asia. (Including obstacles, key factors to overcome, or prospects of the cooperation in this region)

Thank you very much for your answers!

Appendix 2. Results of Expert Survey

1. Collective opinion of expert group

- Re-arranged by the geometric mean values of raw data
- All twelve experts' responses (Expert A to L)

Response analysis

Pair-wise comparison among the top-tier criteria

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance
Technology	1.000	0.226	0.175	0.254	0.381	0.178	0.166
Nuclear safety	4.427	1.000	1.000	1.552	3.323	1.000	1.108
Security & Nonproliferation	5.711	1.000	1.000	2.627	3.737	2.371	4.076
Environmental impact	5.711	0.644	0.381	1.000	2.141	0.803	1.108
Economics	5.711	0.301	0.268	0.467	1.000	0.272	0.525
Domestic acceptance	5.624	1.000	0.422	1.246	3.680	1.000	1.552
Multilateral acceptance	6.015	0.903	0.245	0.903	1.904	0.644	1.000
Total	**34.199**	**5.074**	**3.490**	**8.048**	**16.166**	**6.268**	**9.534**

Normalized matrix

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance	Total	Average	Consistency Measure
Technology	0.029	0.045	0.050	0.032	0.024	0.028	0.017	**0.225**	**0.032**	**7.341**
Nuclear safety	0.129	0.197	0.286	0.193	0.206	0.160	0.116	**1.287**	**0.184**	**7.438**
Security & Nonproliferation	0.167	0.197	0.286	0.326	0.231	0.378	0.427	**2.014**	**0.288**	**7.565**
Environmental impact	0.167	0.127	0.109	0.124	0.132	0.128	0.116	**0.904**	**0.129**	**7.531**
Economics	0.167	0.059	0.077	0.058	0.062	0.043	0.055	**0.521**	**0.074**	**7.537**
Domestic acceptance	0.164	0.197	0.121	0.155	0.228	0.160	0.163	**1.187**	**0.170**	**7.556**
Multilateral acceptance	0.176	0.178	0.070	0.112	0.118	0.103	0.105	**0.862**	**0.123**	**7.478**
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**		C.I.	**0.082**
									R.I.	**1.320**
									C.Ratio	**0.062**

1. Technology

Pair-wise comparison among second-tier criteria

Technology	Availability	Suitability	Accessibility
Availability	1.000	1.607	0.582
Suitability	0.622	1.000	0.725
Accessibility	1.719	1.380	1.000
Total	3.341	3.987	2.307

Normalized matrix

Technology	Availability	Suitability	Accessibility	Total	Average	Consistency Measure
Availability	0.299	0.403	0.252	0.955	0.318	3.053
Suitability	0.186	0.251	0.314	0.751	0.250	3.039
Accessibility	0.514	0.346	0.434	1.294	0.431	3.069
Total	1.000	1.000	1.000		C.I.	0.027
					R.I.	0.580
					C.Ratio	0.046

Pair-wise comparison among three scenarios according to second-tier criteria

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.677	3.389
Regional repro. & storage	0.596	1.000	2.082
Multilateral P&T	0.295	0.480	1.000
Total	1.891	3.157	6.471

Normalized matrix

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.529	0.531	0.524	1.584	0.528	3.000
Regional repro. & storage	0.315	0.317	0.322	0.954	0.318	3.000
Multilateral P&T	0.156	0.152	0.155	0.463	0.154	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.403	3.393
Regional repro. & storage	0.713	1.000	1.825
Multilateral P&T	0.295	0.548	1.000
Total	2.008	2.950	6.218

Normalized matrix

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.498	0.475	0.546	1.519	0.506	3.014
Regional repro. & storage	0.355	0.339	0.294	0.988	0.329	3.008
Multilateral P&T	0.147	0.186	0.161	0.493	0.164	3.004
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.008

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.816	2.534
Regional repro. & storage	0.262	1.000	0.765
Multilateral P&T	0.395	1.308	1.000
Total	1.657	6.123	4.298

Normalized matrix

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.604	0.623	0.589	1.816	0.605	3.004
Regional repro. & storage	0.158	0.163	0.178	0.499	0.166	3.001
Multilateral P&T	0.238	0.214	0.233	0.684	0.228	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

2. Nuclear safety

Pair-wise comparison among second-tier criteria

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in
System resilience	1.000	2.498	4.327
Acci. tolerance in operation	0.400	1.000	2.080
Acci. tolerance in	0.231	0.481	1.000
Total	1.631	3.979	7.407

Normalized matrix

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in	Total	Average	Consistency Measure
System resilience	0.613	0.628	0.584	1.825	0.608	3.007
Acci. tolerance in operation	0.245	0.251	0.281	0.778	0.259	3.003
Acci. tolerance in	0.142	0.121	0.135	0.398	0.133	3.001
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

Pair-wise comparison among three scenarios according to second-tier criteria

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.184	3.351
Regional repro. & storage	0.314	1.000	1.000
Multilateral P&T	0.298	1.000	1.000
Total	1.612	5.184	5.351

Normalized matrix

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.620	0.614	0.626	1.861	0.620	3.001
Regional repro. & storage	0.195	0.193	0.187	0.575	0.192	3.000
Multilateral P&T	0.185	0.193	0.187	0.565	0.188	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	6.525	5.666
Regional repro. & storage	0.153	1.000	0.918
Multilateral P&T	0.177	1.089	1.000
Total	1.330	8.614	7.584

Normalized matrix

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.752	0.757	0.747	2.257	0.752	3.001
Regional repro. & storage	0.115	0.116	0.121	0.352	0.117	3.000
Multilateral P&T	0.133	0.126	0.132	0.391	0.130	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.873	1.723
Regional repro. & storage	0.534	1.000	1.000
Multilateral P&T	0.581	1.000	1.000
Total	2.114	3.873	3.723

Normalized matrix

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.473	0.484	0.463	1.419	0.473	3.001
Regional repro. & storage	0.252	0.258	0.269	0.779	0.260	3.001
Multilateral P&T	0.275	0.258	0.269	0.801	0.267	3.001
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

3. Nuclear security and nonproliferation

Pair-wise comparison among second-tier criteria

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm
Physical protection	1.000	0.919	1.593
Proliferation resistance	1.088	1.000	1.778
Compliance of int'l reg./norm	0.628	0.563	1.000
Total	2.716	2.481	4.370

Normalized matrix

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm	Total	Average	Consistency Measure
Physical protection	0.368	0.370	0.364	1.103	0.368	3.000
Proliferation resistance	0.401	0.403	0.407	1.210	0.403	3.000
Compliance of int'l reg./norm	0.231	0.227	0.229	0.687	0.229	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Pair-wise comparison among three scenarios according to second-tier criteria

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.251	1.838
Regional repro. & storage	0.444	1.000	0.701
Multilateral P&T	0.544	1.427	1.000
Total	1.988	4.678	3.539

Normalized matrix

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.503	0.481	0.519	1.504	0.501	3.004
Regional repro. & storage	0.223	0.214	0.198	0.635	0.212	3.002
Multilateral P&T	0.274	0.305	0.283	0.861	0.287	3.002
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.122	3.232
Regional repro. & storage	0.243	1.000	0.583
Multilateral P&T	0.309	1.715	1.000
Total	1.552	6.838	4.815

Normalized matrix

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.644	0.603	0.671	1.918	0.639	3.019
Regional repro. & storage	0.156	0.146	0.121	0.424	0.141	3.004
Multilateral P&T	0.199	0.251	0.208	0.658	0.219	3.007
Total	1.000	1.000	1.000		C.I.	0.005
					R.I.	0.580
					C.Ratio	0.008

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.160	2.537
Regional repro. & storage	0.316	1.000	0.803
Multilateral P&T	0.394	1.246	1.000
Total	1.711	5.406	4.339

Normalized matrix

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.585	0.585	0.585	1.754	0.585	3.000
Regional repro. & storage	0.185	0.185	0.185	0.555	0.185	3.000
Multilateral P&T	0.230	0.230	0.230	0.691	0.230	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

4. Environmental impact

Pair-wise comparison among second-tier criteria

Environmental impact	Radiological impact	비방사능 영향
Radiological impact	1.000	5.276
Non-radiological impact	0.190	1.000
Total	1.190	6.276

Normalized matrix

Environmental impact	Radiological impact	Non-radiological impact	Total	Average	Consistency measure
Radiological impact	0.841	0.841	1.681	0.841	2.000
Non-radiological impact	0.159	0.159	0.319	0.159	2.000
Total	1.000	1.000		C.I.	0.000
				R.I.	
				C.Ratio	

Pair-wise comparison among three scenarios according to second-tier criteria

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.544	4.544
Regional repro. & storage	0.220	1.000	1.116
Multilateral P&T	0.220	0.896	1.000
Total	1.440	6.440	6.660

Normalized matrix

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.694	0.706	0.682	2.082	0.694	3.003
Regional repro. & storage	0.153	0.155	0.168	0.476	0.159	3.001
Multilateral P&T	0.153	0.139	0.150	0.442	0.147	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.001

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.759	2.472
Regional repro. & storage	0.363	1.000	1.000
Multilateral P&T	0.405	1.000	1.000
Total	1.767	4.759	4.472

Normalized matrix

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.566	0.580	0.553	1.698	0.566	3.002
Regional repro. & storage	0.205	0.210	0.224	0.639	0.213	3.001
Multilateral P&T	0.229	0.210	0.224	0.663	0.221	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.001

5. Economics

Pair-wise comparison among second-tier criteria

Economics	Internal cost	Cost of social conflicts	Environmental cost
Internal cost	1.000	0.595	1.076
Cost of social conflicts	1.680	1.000	2.387
Environmental cost	0.930	0.419	1.000
Total	3.610	2.014	4.462

Normalized matrix

Economics	Internal cost	Cost of social conflicts	Environmental cost	Total	Average	Consistency Measure
Internal cost	0.277	0.295	0.241	0.814	0.271	3.007
Cost of social conflicts	0.465	0.496	0.535	1.497	0.499	3.013
Environmental cost	0.258	0.208	0.224	0.690	0.230	3.006
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.007

Pair-wise comparison among three scenarios according to second-tier criteria

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.290	1.115
Regional repro. & storage	0.775	1.000	0.795
Multilateral P&T	0.897	1.258	1.000
Total	2.672	3.549	2.910

Normalized matrix

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.374	0.364	0.383	1.121	0.374	3.001
Regional repro. & storage	0.290	0.282	0.273	0.845	0.282	3.001
Multilateral P&T	0.336	0.355	0.344	1.034	0.345	3.001
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.215	1.061
Regional repro. & storage	0.823	1.000	0.521
Multilateral P&T	0.943	1.918	1.000
Total	2.766	4.133	2.582

Normalized matrix

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.362	0.294	0.411	1.066	0.355	3.031
Regional repro. & storage	0.298	0.242	0.202	0.741	0.247	3.022
Multilateral P&T	0.341	0.464	0.387	1.192	0.397	3.036
Total	1.000	1.000	1.000		C.I.	0.015
					R.I.	0.580
					C.Ratio	0.026

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.987	1.987
Regional repro. & storage	0.503	1.000	1.147
Multilateral P&T	0.503	0.872	1.000
Total	2.007	3.859	4.134

Normalized matrix

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.498	0.515	0.481	1.494	0.498	3.003
Regional repro. & storage	0.251	0.259	0.277	0.787	0.262	3.002
Multilateral P&T	0.251	0.226	0.242	0.719	0.240	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

6. Domestic acceptance

Pair-wise comparison among second-tier criteria

Domestic acceptance	Public acceptance	Political support	Ethical consideration
Public acceptance	1.000	1.067	1.859
Political support	0.937	1.000	1.629
Ethical consideration	0.538	0.614	1.000
Total	2.475	2.681	4.488

Normalized matrix

Domestic acceptance	Public acceptance	Political support	Ethical consideration	Total	Average	Consistency Measure
Public acceptance	0.404	0.398	0.414	1.216	0.405	3.001
Political support	0.379	0.373	0.363	1.115	0.372	3.001
Ethical consideration	0.217	0.229	0.223	0.669	0.223	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Pair-wise comparison among three scenarios according to second-tier criteria

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.236	1.052
Regional repro. & storage	0.809	1.000	0.644
Multilateral P&T	0.950	1.552	1.000
Total	2.759	3.788	2.697

Normalized matrix

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.362	0.326	0.390	1.079	0.360	3.009
Regional repro. & storage	0.293	0.264	0.239	0.796	0.265	3.007
Multilateral P&T	0.344	0.410	0.371	1.125	0.375	3.010
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.007

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.623	0.549
Regional repro. & storage	1.605	1.000	0.617
Multilateral P&T	1.823	1.621	1.000
Total	4.428	3.244	2.166

Normalized matrix

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.226	0.192	0.253	0.671	0.224	3.009
Regional repro. & storage	0.362	0.308	0.285	0.956	0.319	3.014
Multilateral P&T	0.412	0.500	0.462	1.373	0.458	3.019
Total	1.000	1.000	1.000		C.I.	0.007
					R.I.	0.580
					C.Ratio	0.012

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.877	0.693
Regional repro. & storage	1.141	1.000	0.655
Multilateral P&T	1.442	1.526	1.000
Total	3.583	3.403	2.348

Normalized matrix

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.279	0.258	0.295	0.832	0.277	3.003
Regional repro. & storage	0.318	0.294	0.279	0.891	0.297	3.004
Multilateral P&T	0.403	0.449	0.426	1.277	0.426	3.005
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

7. Multilateral acceptance

Pair-wise comparison among second-tier criteria

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization
Multilateral identity	1.000	0.440	0.930
Intention for hosting	2.275	1.000	2.275
Possibility of institutionalization	1.076	0.440	1.000
Total	4.350	1.879	4.204

Normalized matrix

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization	Total	Average	Consistency Measure
Multilateral identity	0.230	0.234	0.221	0.685	0.228	3.000
Intention for hosting	0.523	0.532	0.541	1.596	0.532	3.001
Possibility of institutionalization	0.247	0.234	0.238	0.719	0.240	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Pair-wise comparison among three scenarios according to second-tier criteria

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.850	0.776
Regional repro. & storage	1.176	1.000	0.793
Multilateral P&T	1.289	1.261	1.000
Total	3.465	3.112	2.569

Normalized matrix

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.289	0.273	0.302	0.864	0.288	3.002
Regional repro. & storage	0.339	0.321	0.309	0.969	0.323	3.002
Multilateral P&T	0.372	0.405	0.389	1.167	0.389	3.003
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.878	0.787
Regional repro. & storage	1.139	1.000	0.819
Multilateral P&T	1.270	1.221	1.000
Total	3.410	3.099	2.606

Normalized matrix

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.293	0.283	0.302	0.879	0.293	3.001
Regional repro. & storage	0.334	0.323	0.314	0.971	0.324	3.001
Multilateral P&T	0.373	0.394	0.384	1.150	0.383	3.001
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.553	1.476
Regional repro. & storage	0.644	1.000	0.851
Multilateral P&T	0.678	1.175	1.000
Total	2.321	3.728	3.327

Normalized matrix

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.431	0.417	0.444	1.291	0.430	3.002
Regional repro. & storage	0.277	0.268	0.256	0.801	0.267	3.001
Multilateral P&T	0.292	0.315	0.301	0.908	0.303	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.001

2. Collective opinions of sub-groups

2.1. Engineering/Science based experts

- Re-arranged by the geometric mean values of raw data
- Eight experts' responses (Expert A, B, E, F, G, H, J and K)

Response analysis

Pair-wise comparison among the top-tier criteria

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance
Technology	1.000	0.218	0.149	0.169	0.447	0.200	0.169
Nuclear safety	4.583	1.000	1.000	1.732	2.236	1.000	1.000
Security & Nonproliferation	6.708	1.000	1.000	2.236	5.196	3.873	3.873
Environmental impact	6.708	0.577	0.447	1.000	3.000	1.000	1.000
Economics	6.708	0.447	0.192	0.333	1.000	0.258	0.447
Domestic acceptance	5.000	1.000	0.258	1.000	3.873	1.000	1.000
Multilateral acceptance	5.916	1.000	0.258	1.000	2.236	1.000	1.000
Total	**36.623**	**5.243**	**3.305**	**7.470**	**17.988**	**8.331**	**8.489**

Normalized matrix

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance	Total	Average	Consistency Measure
Technology	0.027	0.042	0.045	0.023	0.025	0.024	0.020	**0.205**	**0.029**	**7.509**
Nuclear safety	0.125	0.191	0.303	0.232	0.124	0.120	0.118	**1.212**	**0.173**	**7.485**
Security & Nonproliferation	0.183	0.191	0.303	0.299	0.289	0.465	0.456	**2.186**	**0.312**	**7.788**
Environmental impact	0.183	0.110	0.135	0.134	0.167	0.120	0.118	**0.967**	**0.138**	**7.728**
Economics	0.183	0.085	0.058	0.045	0.056	0.031	0.053	**0.511**	**0.073**	**7.530**
Domestic acceptance	0.137	0.191	0.078	0.134	0.215	0.120	0.118	**0.992**	**0.142**	**7.726**
Multilateral acceptance	0.162	0.191	0.078	0.134	0.124	0.120	0.118	**0.926**	**0.132**	**7.577**
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**		C.I.	**0.103**
									R.I.	**1.320**
									C.Ratio	**0.078**

1. Technology

Pair-wise comparison among second-tier criteria

Technology	Availability	Suitability	Accessibility
Availability	1.000	0.754	0.585
Suitability	1.326	1.000	1.710
Accessibility	1.710	0.585	1.000
Total	4.036	2.339	3.295

Normalized matrix

Technology	Availability	Suitability	Accessibility	Total	Average	Consistency Measure
Availability	0.248	0.322	0.177	0.748	0.249	3.050
Suitability	0.329	0.428	0.519	1.275	0.425	3.088
Accessibility	0.424	0.250	0.304	0.977	0.326	3.071
Total	1.000	1.000	1.000		C.I.	0.035
					R.I.	0.580
					C.Ratio	0.060

Pair-wise comparison among three scenarios according to second-tier criteria

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.172	4.983
Regional repro. & storage	0.460	1.000	3.004
Multilateral P&T	0.201	0.333	1.000
Total	1.661	3.505	8.987

Normalized matrix

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.602	0.620	0.554	1.776	0.592	3.014
Regional repro. & storage	0.277	0.285	0.334	0.897	0.299	3.008
Multilateral P&T	0.121	0.095	0.111	0.327	0.109	3.003
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.007

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.058	2.877
Regional repro. & storage	0.945	1.000	2.265
Multilateral P&T	0.348	0.442	1.000
Total	2.293	2.499	6.142

Normalized matrix

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.436	0.423	0.468	1.328	0.443	3.005
Regional repro. & storage	0.412	0.400	0.369	1.181	0.394	3.004
Multilateral P&T	0.152	0.177	0.163	0.491	0.164	3.002
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.583	4.583
Regional repro. & storage	0.218	1.000	1.316
Multilateral P&T	0.218	0.760	1.000
Total	1.436	6.342	6.899

Normalized matrix

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.696	0.723	0.664	2.083	0.694	3.017
Regional repro. & storage	0.152	0.158	0.191	0.500	0.167	3.004
Multilateral P&T	0.152	0.120	0.145	0.417	0.139	3.003
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.007

2. Nuclear safety

Pair-wise comparison among second-tier criteria

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in
System resilience	1.000	1.442	4.327
Acci. tolerance in operation	0.693	1.000	4.327
Acci. tolerance in	0.231	0.231	1.000
Total	1.924	2.673	9.653

Normalized matrix

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in	Total	Average	Consistency Measure
System resilience	0.520	0.539	0.448	1.507	0.502	3.022
Acci. tolerance in operation	0.360	0.374	0.448	1.183	0.394	3.019
Acci. tolerance in	0.120	0.086	0.104	0.310	0.103	3.005
Total	1.000	1.000	1.000		C.I.	0.007
					R.I.	0.580
					C.Ratio	0.013

Pair-wise comparison among three scenarios according to second-tier criteria

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.779	4.779
Regional repro. & storage	0.209	1.000	0.918
Multilateral P&T	0.209	1.089	1.000
Total	1.419	6.867	6.697

Normalized matrix

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.705	0.696	0.714	2.114	0.705	3.002
Regional repro. & storage	0.148	0.146	0.137	0.430	0.143	3.000
Multilateral P&T	0.148	0.159	0.149	0.455	0.152	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	7.454	6.031
Regional repro. & storage	0.134	1.000	0.880
Multilateral P&T	0.166	1.136	1.000
Total	1.300	9.590	7.911

Normalized matrix

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.769	0.777	0.762	2.309	0.770	3.002
Regional repro. & storage	0.103	0.104	0.111	0.319	0.106	3.000
Multilateral P&T	0.128	0.118	0.126	0.372	0.124	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.933	1.719
Regional repro. & storage	0.517	1.000	1.000
Multilateral P&T	0.582	1.000	1.000
Total	2.099	3.933	3.719

Normalized matrix

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.476	0.492	0.462	1.430	0.477	3.002
Regional repro. & storage	0.246	0.254	0.269	0.770	0.257	3.001
Multilateral P&T	0.277	0.254	0.269	0.800	0.267	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.001

3. Nuclear security and nonproliferation

Pair-wise comparison among second-tier criteria

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm
Physical protection	1.000	1.043	2.365
Proliferation resistance	0.959	1.000	2.608
Compliance of int'l reg./norm	0.423	0.383	1.000
Total	2.382	2.426	5.974

Normalized matrix

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm	Total	Average	Consistency Measure
Physical protection	0.420	0.430	0.396	1.246	0.415	3.003
Proliferation resistance	0.403	0.412	0.437	1.251	0.417	3.003
Compliance of int'l reg./norm	0.178	0.158	0.167	0.503	0.168	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Pair-wise comparison among three scenarios according to second-tier criteria

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.596	2.115
Regional repro. & storage	0.385	1.000	0.704
Multilateral P&T	0.473	1.420	1.000
Total	1.858	5.016	3.819

Normalized matrix

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.538	0.517	0.554	1.609	0.536	3.004
Regional repro. & storage	0.207	0.199	0.184	0.591	0.197	3.001
Multilateral P&T	0.255	0.283	0.262	0.800	0.267	3.002
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.979	3.455
Regional repro. & storage	0.251	1.000	0.765
Multilateral P&T	0.289	1.308	1.000
Total	1.541	6.287	5.220

Normalized matrix

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.649	0.633	0.662	1.944	0.648	3.003
Regional repro. & storage	0.163	0.159	0.147	0.469	0.156	3.001
Multilateral P&T	0.188	0.208	0.192	0.587	0.196	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.762	2.762
Regional repro. & storage	0.362	1.000	1.170
Multilateral P&T	0.362	0.855	1.000
Total	1.724	4.616	4.932

Normalized matrix

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.580	0.598	0.560	1.738	0.579	3.005
Regional repro. & storage	0.210	0.217	0.237	0.664	0.221	3.002
Multilateral P&T	0.210	0.185	0.203	0.598	0.199	3.002
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

4. Environmental impact

Pair-wise comparison among second-tier criteria

Environmental impact	Radiological impact	비방사능 영향
Radiological impact	1.000	5.367
Non-radiological impact	0.186	1.000
Total	1.186	6.367

Normalized matrix

Environmental impact	Radiological impact	Non-radiological impact	Total	Average	Consistency measure
Radiological impact	0.843	0.843	1.686	0.843	2.000
Non-radiological impact	0.157	0.157	0.314	0.157	2.000
Total	1.000	1.000		C.I.	0.000
				R.I.	
				C.Ratio	

Pair-wise comparison among three scenarios according to second-tier criteria

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	5.203	4.779
Regional repro. & storage	0.192	1.000	1.000
Multilateral P&T	0.209	1.000	1.000
Total	1.401	7.203	6.779

Normalized matrix

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.714	0.722	0.705	2.141	0.714	3.002
Regional repro. & storage	0.137	0.139	0.148	0.423	0.141	3.000
Multilateral P&T	0.149	0.139	0.148	0.436	0.145	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.455	3.455
Regional repro. & storage	0.289	1.000	1.201
Multilateral P&T	0.289	0.833	1.000
Total	1.579	5.288	5.656

Normalized matrix

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.633	0.653	0.611	1.898	0.633	3.007
Regional repro. & storage	0.183	0.189	0.212	0.585	0.195	3.002
Multilateral P&T	0.183	0.157	0.177	0.518	0.173	3.002
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

5. Economics

Pair-wise comparison among second-tier criteria

Economics	Internal cost	Cost of social conflicts	Environmental cost
Internal cost	1.000	0.699	1.968
Cost of social conflicts	1.432	1.000	3.482
Environmental cost	0.508	0.287	1.000
Total	2.940	1.986	6.450

Normalized matrix

Economics	Internal cost	Cost of social conflicts	Environmental cost	Total	Average	Consistency Measure
Internal cost	0.340	0.352	0.305	0.997	0.332	3.005
Cost of social conflicts	0.487	0.504	0.540	1.530	0.510	3.008
Environmental cost	0.173	0.145	0.155	0.473	0.158	3.002
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.004

Pair-wise comparison among three scenarios according to second-tier criteria

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.919	0.744
Regional repro. & storage	1.088	1.000	0.669
Multilateral P&T	1.344	1.495	1.000
Total	3.432	3.415	2.413

Normalized matrix

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.291	0.269	0.308	0.869	0.290	3.003
Regional repro. & storage	0.317	0.293	0.277	0.887	0.296	3.004
Multilateral P&T	0.392	0.438	0.414	1.244	0.415	3.005
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.201	1.043
Regional repro. & storage	0.833	1.000	0.637
Multilateral P&T	0.959	1.570	1.000
Total	2.792	3.771	2.680

Normalized matrix

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.358	0.318	0.389	1.066	0.355	3.011
Regional repro. & storage	0.298	0.265	0.238	0.801	0.267	3.009
Multilateral P&T	0.344	0.416	0.373	1.133	0.378	3.012
Total	1.000	1.000	1.000		C.I.	0.005
					R.I.	0.580
					C.Ratio	0.009

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.006	2.006
Regional repro. & storage	0.498	1.000	1.000
Multilateral P&T	0.498	1.000	1.000
Total	1.997	4.006	4.006

Normalized matrix

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.501	0.501	0.501	1.502	0.501	3.000
Regional repro. & storage	0.250	0.250	0.250	0.749	0.250	3.000
Multilateral P&T	0.250	0.250	0.250	0.749	0.250	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

6. Domestic acceptance

Pair-wise comparison among second-tier criteria

Domestic acceptance	Public acceptance	Political support	Ethical consideration
Public acceptance	1.000	1.103	1.757
Political support	0.907	1.000	1.732
Ethical consideration	0.569	0.577	1.000
Total	2.476	2.680	4.489

Normalized matrix

Domestic acceptance	Public acceptance	Political support	Ethical consideration	Total	Average	Consistency Measure
Public acceptance	0.404	0.411	0.391	1.207	0.402	3.001
Political support	0.366	0.373	0.386	1.125	0.375	3.001
Ethical consideration	0.230	0.215	0.223	0.668	0.223	3.001
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.001

Pair-wise comparison among three scenarios according to second-tier criteria

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.466	2.054
Regional repro. & storage	0.405	1.000	0.833
Multilateral P&T	0.487	1.201	1.000
Total	1.892	4.667	3.886

Normalized matrix

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.528	0.528	0.528	1.585	0.528	3.000
Regional repro. & storage	0.214	0.214	0.214	0.643	0.214	3.000
Multilateral P&T	0.257	0.257	0.257	0.772	0.257	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.602	0.577
Regional repro. & storage	1.661	1.000	0.918
Multilateral P&T	1.732	1.089	1.000
Total	4.393	2.691	2.496

Normalized matrix

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.228	0.224	0.231	0.683	0.228	3.000
Regional repro. & storage	0.378	0.372	0.368	1.118	0.373	3.000
Multilateral P&T	0.394	0.405	0.401	1.200	0.400	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.986	0.907
Regional repro. & storage	1.014	1.000	0.765
Multilateral P&T	1.103	1.308	1.000
Total	3.117	3.294	2.671

Normalized matrix

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.321	0.299	0.339	0.960	0.320	3.004
Regional repro. & storage	0.325	0.304	0.286	0.915	0.305	3.003
Multilateral P&T	0.354	0.397	0.374	1.125	0.375	3.004
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

7. Multilateral acceptance

Pair-wise comparison among second-tier criteria

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization
Multilateral identity	1.000	0.669	0.880
Intention for hosting	1.495	1.000	1.495
Possibility of institutionalization	1.136	0.669	1.000
Total	3.632	2.337	3.375

Normalized matrix

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization	Total	Average	Consistency Measure
Multilateral identity	0.275	0.286	0.261	0.822	0.274	3.001
Intention for hosting	0.412	0.428	0.443	1.283	0.428	3.002
Possibility of institutionalization	0.313	0.286	0.296	0.895	0.298	3.002
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Pair-wise comparison among three scenarios according to second-tier criteria

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.784	0.784
Regional repro. & storage	1.275	1.000	1.066
Multilateral P&T	1.275	0.938	1.000
Total	3.551	2.722	2.850

Normalized matrix

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.282	0.288	0.275	0.845	0.282	3.000
Regional repro. & storage	0.359	0.367	0.374	1.101	0.367	3.000
Multilateral P&T	0.359	0.345	0.351	1.055	0.352	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.025	1.170
Regional repro. & storage	0.975	1.000	1.258
Multilateral P&T	0.855	0.795	1.000
Total	2.830	2.820	3.428

Normalized matrix

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.353	0.364	0.341	1.058	0.353	3.001
Regional repro. & storage	0.345	0.355	0.367	1.066	0.355	3.001
Multilateral P&T	0.302	0.282	0.292	0.875	0.292	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.001

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.506	1.506
Regional repro. & storage	0.664	1.000	1.201
Multilateral P&T	0.664	0.833	1.000
Total	2.328	3.339	3.707

Normalized matrix

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.430	0.451	0.406	1.287	0.429	3.005
Regional repro. & storage	0.285	0.300	0.324	0.909	0.303	3.003
Multilateral P&T	0.285	0.249	0.270	0.804	0.268	3.003
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

2.2. Social/Political based experts

- Re-arranged by the geometric mean values of raw data
- Four experts' responses (Expert C, D, I and L)

Response analysis

Pair-wise comparison among the top-tier criteria

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance
Technology	1.000	0.231	0.195	0.333	0.342	0.164	0.164
Nuclear safety	4.327	1.000	1.000	1.442	4.327	1.000	1.186
Security & Nonproliferation	5.130	1.000	1.000	2.924	3.000	1.710	4.217
Environmental impact	5.130	0.693	0.342	1.000	1.710	0.693	1.186
Economics	5.130	0.231	0.333	0.585	1.000	0.281	0.585
Domestic acceptance	6.082	1.000	0.585	1.442	3.557	1.000	2.080
Multilateral acceptance	6.082	0.843	0.237	0.843	1.710	0.481	1.000
Total	**32.881**	**4.999**	**3.692**	**8.570**	**15.646**	**5.330**	**10.418**

Normalized matrix

	Technology	Nuclear safety	Security & Nonproliferation	Environmental impact	Economics	Domestic acceptance	Multiateral acceptance	Total	Average	Consistency Measure
Technology	0.030	0.046	0.053	0.039	0.022	0.031	0.016	**0.237**	**0.034**	**7.330**
Nuclear safety	0.132	0.200	0.271	0.168	0.277	0.188	0.114	**1.349**	**0.193**	**7.483**
Security & Nonproliferation	0.156	0.200	0.271	0.341	0.192	0.321	0.405	**1.885**	**0.269**	**7.557**
Environmental impact	0.156	0.139	0.093	0.117	0.109	0.130	0.114	**0.857**	**0.122**	**7.520**
Economics	0.156	0.046	0.090	0.068	0.064	0.053	0.056	**0.534**	**0.076**	**7.567**
Domestic acceptance	0.185	0.200	0.158	0.168	0.227	0.188	0.200	**1.326**	**0.189**	**7.570**
Multilateral acceptance	0.185	0.169	0.064	0.098	0.109	0.090	0.096	**0.812**	**0.116**	**7.526**
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**		C.I.	**0.085**
									R.I.	**1.320**
									C.Ratio	**0.064**

1. Technology

Pair-wise comparison among second-tier criteria

Technology	Availability	Suitability	Accessibility
Availability	1.000	5.000	0.577
Suitability	0.200	1.000	0.200
Accessibility	1.732	5.000	1.000
Total	2.932	11.000	1.777

Normalized matrix

Technology	Availability	Suitability	Accessibility	Total	Average	Consistency Measure
Availability	0.341	0.455	0.325	1.120	0.373	3.041
Suitability	0.068	0.091	0.113	0.272	0.091	3.009
Accessibility	0.591	0.455	0.563	1.608	0.536	3.052
Total	1.000	1.000	1.000		C.I.	0.017
					R.I.	0.580
					C.Ratio	0.029

Pair-wise comparison among three scenarios according to second-tier criteria

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.000	1.568
Regional repro. & storage	1.000	1.000	1.000
Multilateral P&T	0.638	1.000	1.000
Total	2.638	3.000	3.568

Normalized matrix

Availability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.379	0.333	0.440	1.152	0.384	3.026
Regional repro. & storage	0.379	0.333	0.280	0.993	0.331	3.022
Multilateral P&T	0.242	0.333	0.280	0.855	0.285	3.019
Total	1.000	1.000	1.000		C.I.	0.011
					R.I.	0.580
					C.Ratio	0.019

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.466	4.718
Regional repro. & storage	0.405	1.000	1.186
Multilateral P&T	0.212	0.843	1.000
Total	1.617	4.310	6.903

Normalized matrix

Suitability	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.618	0.572	0.683	1.874	0.625	3.049
Regional repro. & storage	0.251	0.232	0.172	0.654	0.218	3.015
Multilateral P&T	0.131	0.196	0.145	0.472	0.157	3.013
Total	1.000	1.000	1.000		C.I.	0.013
					R.I.	0.580
					C.Ratio	0.022

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.646	0.775
Regional repro. & storage	0.378	1.000	0.258
Multilateral P&T	1.291	3.873	1.000
Total	2.669	7.519	2.033

Normalized matrix

Accessibility	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.375	0.352	0.381	1.108	0.369	3.002
Regional repro. & storage	0.142	0.133	0.127	0.402	0.134	3.001
Multilateral P&T	0.484	0.515	0.492	1.491	0.497	3.003
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

2. Nuclear safety

Pair-wise comparison among second-tier criteria

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in
System resilience	1.000	4.327	4.327
Acci. tolerance in operation	0.231	1.000	1.000
Acci. tolerance in	0.231	1.000	1.000
Total	1.462	6.327	6.327

Normalized matrix

Nuclear safety	System resilience	Acci. tolerance in operation	Acci. tolerance in	Total	Average	Consistency Measure
System resilience	0.684	0.684	0.684	2.052	0.684	3.000
Acci. tolerance in operation	0.158	0.158	0.158	0.474	0.158	3.000
Acci. tolerance in	0.158	0.158	0.158	0.474	0.158	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Pair-wise comparison among three scenarios according to second-tier criteria

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.732	1.968
Regional repro. & storage	0.577	1.000	1.136
Multilateral P&T	0.508	0.880	1.000
Total	2.085	3.612	4.104

Normalized matrix

System resilience	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.480	0.480	0.480	1.439	0.480	3.000
Regional repro. & storage	0.277	0.277	0.277	0.831	0.277	3.000
Multilateral P&T	0.244	0.244	0.244	0.731	0.244	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	5.000	5.000
Regional repro. & storage	0.200	1.000	1.000
Multilateral P&T	0.200	1.000	1.000
Total	1.400	7.000	7.000

Normalized matrix

Acci. tolerance in operation	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.714	0.714	0.714	2.143	0.714	3.000
Regional repro. & storage	0.143	0.143	0.143	0.429	0.143	3.000
Multilateral P&T	0.143	0.143	0.143	0.429	0.143	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.732	1.732
Regional repro. & storage	0.577	1.000	1.000
Multilateral P&T	0.577	1.000	1.000
Total	2.155	3.732	3.732

Normalized matrix

Acci. tolerance in	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.464	0.464	0.464	1.392	0.464	3.000
Regional repro. & storage	0.268	0.268	0.268	0.804	0.268	3.000
Multilateral P&T	0.268	0.268	0.268	0.804	0.268	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

3. Nuclear security and nonproliferation

Pair-wise comparison among second-tier criteria

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm
Physical protection	1.000	0.760	0.880
Proliferation resistance	1.316	1.000	1.000
Compliance of int'l reg./norm	1.136	1.000	1.000
Total	3.452	2.760	2.880

Normalized matrix

Security & nonproliferation	Physical protection	Proliferation resistance	Compliance of int'l reg./norm	Total	Average	Consistency Measure
Physical protection	0.290	0.275	0.306	0.871	0.290	3.002
Proliferation resistance	0.381	0.362	0.347	1.091	0.364	3.003
Compliance of int'l reg./norm	0.329	0.362	0.347	1.039	0.346	3.002
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Pair-wise comparison among three scenarios according to second-tier criteria

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.613	1.326
Regional repro. & storage	0.620	1.000	0.693
Multilateral P&T	0.754	1.442	1.000
Total	2.374	4.056	3.020

Normalized matrix

Physical protection	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.421	0.398	0.439	1.258	0.419	3.004
Regional repro. & storage	0.261	0.247	0.230	0.737	0.246	3.002
Multilateral P&T	0.318	0.356	0.331	1.004	0.335	3.003
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.003

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.583	2.646
Regional repro. & storage	0.218	1.000	0.258
Multilateral P&T	0.378	3.873	1.000
Total	1.596	9.456	3.904

Normalized matrix

Proliferation resistance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.626	0.485	0.678	1.789	0.596	3.125
Regional repro. & storage	0.137	0.106	0.066	0.309	0.103	3.020
Multilateral P&T	0.237	0.410	0.256	0.903	0.301	3.073
Total	1.000	1.000	1.000		C.I.	0.036
					R.I.	0.580
					C.Ratio	0.063

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	4.327	2.080
Regional repro. & storage	0.231	1.000	0.333
Multilateral P&T	0.481	3.000	1.000
Total	1.712	8.327	3.413

Normalized matrix

Compliance of int'l reg./norm	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.584	0.520	0.609	1.713	0.571	3.025
Regional repro. & storage	0.135	0.120	0.098	0.353	0.118	3.005
Multilateral P&T	0.281	0.360	0.293	0.934	0.311	3.015
Total	1.000	1.000	1.000		C.I.	0.007
					R.I.	0.580
					C.Ratio	0.013

4. Environmental impact

Pair-wise comparison among second-tier criteria

Environmental impact	Radiological impact	비방사능 영향
Radiological impact	1.000	5.097
Non-radiological impact	0.196	1.000
Total	1.196	6.097

Normalized matrix

Environmental impact	Radiological impact	Non-radiological impact	Total	Average	Consistency measure
Radiological impact	0.836	0.836	1.672	0.836	2.000
Non-radiological impact	0.164	0.164	0.328	0.164	2.000
Total	1.000	1.000		C.I.	0.000
				R.I.	
				C.Ratio	

Pair-wise comparison among three scenarios according to second-tier criteria

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	3.708	4.213
Regional repro. & storage	0.270	1.000	1.316
Multilateral P&T	0.237	0.760	1.000
Total	1.507	5.468	6.529

Normalized matrix

Radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.664	0.678	0.645	1.987	0.662	3.005
Regional repro. & storage	0.179	0.183	0.202	0.563	0.188	3.001
Multilateral P&T	0.158	0.139	0.153	0.450	0.150	3.001
Total	1.000	1.000	1.000		C.I.	0.001
					R.I.	0.580
					C.Ratio	0.002

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.968	1.495
Regional repro. & storage	0.508	1.000	0.760
Multilateral P&T	0.669	1.316	1.000
Total	2.177	4.284	3.255

Normalized matrix

Non-radiological impact	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.459	0.459	0.459	1.378	0.459	3.000
Regional repro. & storage	0.233	0.233	0.233	0.700	0.233	3.000
Multilateral P&T	0.307	0.307	0.307	0.922	0.307	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

5. Economics

Pair-wise comparison among second-tier criteria

Economics	Internal cost	Cost of social conflicts	Environmental cost
Internal cost	1.000	0.481	0.481
Cost of social conflicts	2.080	1.000	1.442
Environmental cost	2.080	0.693	1.000
Total	5.160	2.174	2.923

Normalized matrix

Economics	Internal cost	Cost of social conflicts	Environmental cost	Total	Average	Consistency Measure
Internal cost	0.194	0.221	0.164	0.579	0.193	3.009
Cost of social conflicts	0.403	0.460	0.493	1.356	0.452	3.020
Environmental cost	0.403	0.319	0.342	1.064	0.355	3.016
Total	1.000	1.000	1.000		C.I.	0.007
					R.I.	0.580
					C.Ratio	0.013

Pair-wise comparison among three scenarios according to second-tier criteria

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	2.027	1.913
Regional repro. & storage	0.493	1.000	1.000
Multilateral P&T	0.523	1.000	1.000
Total	2.016	4.027	3.913

Normalized matrix

Internal cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.496	0.503	0.489	1.488	0.496	3.001
Regional repro. & storage	0.245	0.248	0.256	0.749	0.250	3.000
Multilateral P&T	0.259	0.248	0.256	0.763	0.254	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.236	1.088
Regional repro. & storage	0.809	1.000	0.386
Multilateral P&T	0.919	2.590	1.000
Total	2.728	4.826	2.474

Normalized matrix

Cost of social conflicts	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.367	0.256	0.440	1.062	0.354	3.076
Regional repro. & storage	0.297	0.207	0.156	0.660	0.220	3.050
Multilateral P&T	0.337	0.537	0.404	1.278	0.426	3.102
Total	1.000	1.000	1.000		C.I.	0.038
					R.I.	0.580
					C.Ratio	0.066

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.968	1.968
Regional repro. & storage	0.508	1.000	1.316
Multilateral P&T	0.508	0.760	1.000
Total	2.016	3.728	4.284

Normalized matrix

Environmental cost	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.496	0.528	0.459	1.483	0.494	3.012
Regional repro. & storage	0.252	0.268	0.307	0.827	0.276	3.007
Multilateral P&T	0.252	0.204	0.233	0.689	0.230	3.006
Total	1.000	1.000	1.000		C.I.	0.004
					R.I.	0.580
					C.Ratio	0.007

6. Domestic acceptance

Pair-wise comparison among second-tier criteria

Domestic acceptance	Public acceptance	Political support	Ethical consideration
Public acceptance	1.000	1.000	2.080
Political support	1.000	1.000	1.442
Ethical consideration	0.481	0.693	1.000
Total	2.481	2.693	4.522

Normalized matrix

Domestic acceptance	Public acceptance	Political support	Ethical consideration	Total	Average	Consistency Measure
Public acceptance	0.403	0.371	0.460	1.234	0.411	3.019
Political support	0.403	0.371	0.319	1.093	0.364	3.016
Ethical consideration	0.194	0.257	0.221	0.672	0.224	3.010
Total	1.000	1.000	1.000		C.I.	0.007
					R.I.	0.580
					C.Ratio	0.013

Pair-wise comparison among three scenarios according to second-tier criteria

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.439	0.386
Regional repro. & storage	2.280	1.000	0.439
Multilateral P&T	2.590	2.280	1.000
Total	5.870	3.718	1.825

Normalized matrix

Public acceptance	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.170	0.118	0.212	0.500	0.167	3.025
Regional repro. & storage	0.388	0.269	0.240	0.898	0.299	3.052
Multilateral P&T	0.441	0.613	0.548	1.602	0.534	3.085
Total	1.000	1.000	1.000		C.I.	0.027
					R.I.	0.580
					C.Ratio	0.047

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.656	0.508
Regional repro. & storage	1.524	1.000	0.340
Multilateral P&T	1.968	2.943	1.000
Total	4.492	4.599	1.848

Normalized matrix

Political support	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.223	0.143	0.275	0.640	0.213	3.044
Regional repro. & storage	0.339	0.217	0.184	0.741	0.247	3.061
Multilateral P&T	0.438	0.640	0.541	1.619	0.540	3.124
Total	1.000	1.000	1.000		C.I.	0.038
					R.I.	0.580
					C.Ratio	0.066

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.693	0.405
Regional repro. & storage	1.442	1.000	0.481
Multilateral P&T	2.466	2.080	1.000
Total	4.908	3.773	1.886

Normalized matrix

Ethical consideration	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.204	0.184	0.215	0.602	0.201	3.003
Regional repro. & storage	0.294	0.265	0.255	0.814	0.271	3.004
Multilateral P&T	0.502	0.551	0.530	1.584	0.528	3.007
Total	1.000	1.000	1.000		C.I.	0.002
					R.I.	0.580
					C.Ratio	0.004

7. Multilateral acceptance

Pair-wise comparison among second-tier criteria

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization
Multilateral identity	1.000	0.251	1.000
Intention for hosting	3.979	1.000	3.979
Possibility of institutionalization	1.000	0.251	1.000
Total	5.979	1.503	5.979

Normalized matrix

Multilateral acceptance	Multilateral identity	Intention for hosting	Possibility of institutionalization	Total	Average	Consistency Measure
Multilateral identity	0.167	0.167	0.167	0.502	0.167	3.000
Intention for hosting	0.665	0.665	0.665	1.996	0.665	3.000
Possibility of institutionalization	0.167	0.167	0.167	0.502	0.167	3.000
Total	1.000	1.000	1.000		C.I.	0.000
					R.I.	0.580
					C.Ratio	0.000

Pair-wise comparison among three scenarios according to second-tier criteria

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.000	0.760
Regional repro. & storage	1.000	1.000	0.439
Multilateral P&T	1.316	2.280	1.000
Total	3.316	4.280	2.199

Normalized matrix

Multilateral identity	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.302	0.234	0.346	0.881	0.294	3.028
Regional repro. & storage	0.302	0.234	0.200	0.735	0.245	3.025
Multilateral P&T	0.397	0.533	0.455	1.384	0.461	3.047
Total	1.000	1.000	1.000		C.I.	0.017
					R.I.	0.580
					C.Ratio	0.029

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	0.669	0.394
Regional repro. & storage	1.495	1.000	0.386
Multilateral P&T	2.541	2.590	1.000
Total	5.036	4.259	1.780

Normalized matrix

Intention for hosting	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.199	0.157	0.221	0.577	0.192	3.011
Regional repro. & storage	0.297	0.235	0.217	0.749	0.250	3.016
Multilateral P&T	0.504	0.608	0.562	1.675	0.558	3.033
Total	1.000	1.000	1.000		C.I.	0.010
					R.I.	0.580
					C.Ratio	0.017

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T
Regional SNF repository	1.000	1.627	1.432
Regional repro. & storage	0.615	1.000	0.508
Multilateral P&T	0.699	1.968	1.000
Total	2.313	4.595	2.940

Normalized matrix

Possibility of institutionalization	Regional SNF repository	Regional repro. & storage	Multilateral P&T	Total	Average	C.M.
Regional SNF repository	0.432	0.354	0.487	1.273	0.424	3.042
Regional repro. & storage	0.266	0.218	0.173	0.656	0.219	3.022
Multilateral P&T	0.302	0.428	0.340	1.070	0.357	3.037
Total	1.000	1.000	1.000		C.I.	0.017
					R.I.	0.580
					C.Ratio	0.029

초 록

오늘날 원자력 에너지는 화석연료 고갈과 온실가스 배출에 대응한 현실적 대안으로서 자리매김하고 있으며, 후쿠시마 사고 이 후에도 많은 국가들에서는 원전을 지속적으로 이용, 확대하려는 계획을 추진 중에 있다. 이러한 원전의 이용은 필연적으로 사용후핵연료의 발생으로 이어지지만, 전 세계적으로 누적 사용후핵연료의 최종 관리는 처분 또는 재처리를 통해 매우 제한적으로 수행되고 있을 뿐이다. 원자력 안전, 핵안보 사고의 피해 확산 또는 위험성 등을 고려한다면, 원전 고밀 지역인 동북아 지역에서의 사용후핵연료 관리 문제는 더욱 중요할 수 밖에 없다. 특히 한국, 대만, 일본의 경우 높은 인구밀도와 불안정한 지질학적 조건으로 사용후핵연료의 직접 처분 방안을 추진하기 어렵고, 상용 재처리는 민감 기술로서 통제되고 제한적으로만 허용되기에 당면한 사용후핵연료 문제를 해결하기에는 충분하지 못한 실정이다. 오늘날 대만의 경우 소내 저장조 용량이 2016년 내 포화되어 원전 가동을 중지해야 하는 위기를 맞고 있으며, 한국의 경우도 2024년 포화시점으로 같은 문제가 예상되며, 일본의 경우도 마찬가지의 어려움이 예상된다. 이러한 맥락에서 핵연료주기부문의 다자협력 방안이 다수 논의된 바 있으며, 2000년대에 나온 제안들 중 국제핵연료은행, 국제우라늄농축센터 등은 현재 실제로 추진 중으로 핵연료주기 서비스 공급 안정에 기여하고 있다.

사용후핵연료 관리 방안에 관한 기존 국내 연구들은 포화시점에 대응하기 위한 대내적 차원 또는 양자적 협력을 통한 해결책을 모색해온 반면, 국제적 관점의 연구들에서는 다자 협력을 포함한 다양한 해결법을 주목해온 바 있다. 또한 대안 평가에 활용되었던 평가기준들은 다양한 인자들을 총체적으로 고려하지 못했거나, 다자 특

성을 포함하지 않았기에 사용후핵연료 다자관리 방안을 위한 새로운 논의에 부적합한 것으로 판단하였다. 이에 본 연구는 동북아 지역의 사용후핵연료 관리를 위한 실현 가능한 방안들을 검토하고 제안하는 것을 그 목적으로 한다. 따라서 본 논문의 연구 질문은 ① "동북아 사용후핵연료 관리를 위한 다자협력 방안들은 무엇이며 이를 어떻게 평가할 것인가?" ② "선호되는 다자 방안은 무엇이며 주요 평가 기준은 무엇인가?" ③ "다자관리 방안을 동북아 및 한국에 도입하기 위한 전략은 무엇인가?" 이다. 이에 대한 답을 찾기 위해, 다기준 의사결정 방법 중 하나인 분석적 계층화 과정을 통해 사용후핵연료의 관리와 그 다자화와 관련된 정성적, 정량적 요인들을 총체적으로 평가하였다. 그 적용을 위해 사용후핵연료 관리 또는 신규 핵연료주기 시스템 연구들에서 사용된 평가기준들을 정리하여 공통 요인으로 도출하고 다자주의의 정의와 원칙에 기반한 특징을 반영하여 기술성, 안전성, 안보 및 비확산성, 환경 영향성, 경제성, 대내적 수용성, 다자 수용성의 총 일곱 개 상위 평가기준과 각 하위 평가기준들 20가지를 정의하였다. 또한 동북아 지역에 적용 가능한 사용후핵연료 관리 다자협력 방안들 중 핵심 기술의 차별성과 실현 가능성 등을 고려한 세 가지 방안을 평가 대상으로 선정하였다.

첫 번째는 지역 사용후핵연료 처분 방안으로, 장기 처분에 적합한 지질학적 요건만 만족한다면 가장 단순하게 추진할 수 있는 해결책이다. 또한 현재 원전을 운영 중에 있지 않은 국가라 하더라도 조건에 부합하면 해당 시스템을 유치할 수 있는 것으로 특징된다. 두 번째는 지역 재처리 및 저장 방안으로, 동북아 지역 내 상용 재처리 역량을 활용하고 분리된 플루토늄, 우라늄, 마이너 악티나이드 등을 공동 저장관리 하는 것이다. 이는 민감 기술에 대한 접근 없이 서비스 공급을 안정적으로 보장하면서 공정 후 민감 물질들을 공동 관리함으로써 핵확산 저항성을 보장하는 협력이라 할 수 있다. 마지

막 방안은 핵종 분리변환에 대한 다자 시스템으로, 고준위폐기물의 중저준위화 공정을 통해 최종 처분 부담을 줄이는 혁신 기술에 기반한 접근법이다. 다만 해당 기술이 연구개발 단계에 있어 상용화까지는 상당 시간과 비용이 필요하기에 다국간 협력을 통해 추진할 것이 요구된다.

본 연구는 선정된 평가기준들과 다자관리 방안들을 활용하여 사용후핵연료 다자관리 방안 평가에 활용할 수 있는 모델을 제시하였다. 실질적인 평가를 위해 국내·외 전문가를 대상으로 설문을 수행한 결과, 현 시점에서 가장 적합한 다자관리 방안은 “지역 사용후핵연료 처분”이었으며, “다자 핵종 분리변환”과 “지역 재처리 및 저장” 순서로 선호되었다. “지역 사용후핵연료 처분”은 대다수 기준에서 가장 높은 평가를 받았으며, 이는 현재 구체적으로 논의되고 있는 호주 제안과도 연결된다는 점에서 주목할 만 하다. “다자 핵종 분리변환”은 대중수용성, 정치적 지지, 윤리적 고려 및 다자 정체성 항목에서 높은 평가를 받았으며, “지역 재처리 및 저장” 방안이 기술성에서만 상대적으로 나은 평가를 받은 것과 차별되는 점이다. 이는 “다자 핵종 분리 변환”이 혁신 기술에 기반하지만, 사용후핵연료 문제의 근본 원인을 제거할 수 있다는 점과 비차등적 협력이 가능하다는 점에서 상대적으로 나은 평가를 받은 것으로 파악된다. 가장 주목할만한 점으로는 전문가 집단의 평가에 있어서 중요하게 고려된 요소들이 일반적 인식과 달랐다는 점이다. 즉, 국가 중장기 정책 및 연구개발 투자 등에 있어서는 기술성과 경제성이 중요한 평가요인으로 고려되는데, 본 연구에서는 원자력 안전, 안보, 비확산성과 대중수용성 및 다자시설에 대한 유치 의사 확보 등이 더 중요한 요소로서 고려되었다. 이는 사용후핵연료 관리의 시간과 다자협력의 특성을 감안한다면 현재의 경제성, 기술성 보다는 장기적 정책 추진의 필수조건인 대중수용성과 부지 마련을 더 중요하게 고려되어야

함을 시사한다.

동북아 사용후핵연료를 위한 다자관리 방안은, 지역 내 사용후핵연료 관리를 위한 대응 또는 예방적 조치로서 역할하며 지역 내 원자력 안전, 안보, 핵비확산 수준 향상에 기여할 것이다. 또한 동북아 국가들 간 신뢰구축 방안으로서 역할 함으로써 지역 내 긴장을 완화하고 지속적인 협력 기반으로 활용될 수 있을 것이다. 한국의 대내적 관점에서는 이러한 다자관리 방안들이 국내 정책과 병행 추진된다면, 서로간 상호보완 역할과 다양한 선택지 제공을 통해 사용후핵연료 관리 정책에 대한 대중수용성 증진을 도모할 수 있을 것이다. 마지막으로, 사용후핵연료 관리에 대한 정책 환경 변화에 능동적으로 대응하기 위해서는 본 연구에서 제안된 다기준 평가 모델을 지속적으로 활용할 것을 강조한다.

주요어: 후행 핵연료주기, 사용후핵연료 관리, 동북아 지역, 다기준 평가, 분석적 계층화 과정, 다자관리 방안
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