

How to Untie the Gordian Knot?

The Peaceful and Innovative Approach for the Universal Solution over Spent Nuclear Fuel Management

Kee-chan Song

Korea Atomic Energy Research Institute (KAERI)

Daejeon Korea

Since the first introduction of the nuclear power plant, Kori Unit 1 in 1978 Korea has relied on the nuclear energy to sustainably support electricity for the economic development. The four nuclear complexes which deploy twenty reactors, four CANDU's in Wolsung and sixteen in other sites, are the steam engines for the economic growth. As illustrated in Figure 1, all four complexes are located along the coastal areas. This was simply due to the easiness to transport parts for the reactor construction and the easiness to access the cooling sea water. The other industries have been also developed along the coastal area. In 2009 Korea became the world top 9 for the international trade. The global trading becomes the heart of the business sector in Korea. This inevitably develops the cluster of major cities along the coastal areas. Busan became the 2nd largest city with the biggest harbor to become a real hub for the export and import. Many metro cities are developed along Busan to manufacture steel, chemical substances, petroleum, car making, and ship building. These industries traditionally classified as a manufacturing industry requires a lot of energy. To meet the huge demand from the conventional manufacturing industry and the new comer, information technology and high tech electronics sectors nuclear power plants have been introduced in the South Eastern part of Korea. The other complex Yonggwang is located in the South Western part of Korea to support the steel manufacturing and chemical engineering business in that area. In summary the nuclear power has contributed as a heart for the economy of Korea for the last three decades and nowadays the complexes are surrounded with major cities and industries.

1. Issues on Spent Nuclear Fuel Accumulation and Management

Ambitious Nuclear Generation Program

Unfortunately, the active operation of nuclear power plants inevitably by-produces radioactive wastes, both of low and high levels. As of the end of the year 2008, Korea already has more than 10,000 tU at reactor sites as summarized in Table 1. As illustrated in Figure 2, around 700 tU is generated annually. That is partly due to the four CANDU's which produces around 100 tU annually from each one. The ordinary 1,000 MWe PWR generates around 20 tU. This trend will be dramatically changed when Korea follows the official track to add more nuclear power plants in the near term. According to the Green Growth Plan announced officially by the National Government in 2008, Korea will end up with 38 reactors in operation in 2030. This means that the nuclear share will reach 59%.

Huge Spent Nuclear Fuel Arising and Heavy Population Density

It is not yet certain to predict the long term deployment plan for nuclear reactors beyond the year 2030. However, experts foresee that at least by 2050 the electricity demand will steadily increase in Korea and reach the saturation in 2050. To cope with the increase more reactors are assumed to be introduced between 2030 and 2050. Even after 2050 new reactors will be deployed to replace old ones which will be retired after their expected life times, between 50 and 60 years. In the middle of this century the total

Paper presented at a U.S.-ROK Workshop on Nuclear Energy and Nonproliferation, Center for U.S.-Korea Policy, The Henry L. Stimson Center, and Korea Atomic Energy Research Institute, Washington DC, January 20, 2010.

accumulation of spent nuclear fuel in Korea will hit the 50,000 tU. By the end of this century the total accumulation from PWRs and CANDUs will be more than 100,000 tU. Including the accumulation of CANDU spent nuclear fuel, the total will be around 110,000 to 120,000 tU as illustrated in Figure 3 which is almost twice of the capacity of the halted Yucca Mountain repository, 63,000 tU. The distance between Yucca Mountain and the nearest big city Las Vegas is 100 miles. However, the distance between Busan and Daegu depicted in Figure 1 is less than 80 miles. In between two cities more than 10 million people live together. This really tells us the difficulty that Korea is facing with at this moment for the proper management of spent nuclear fuel.

Difficulty for Transportation

To transport spent nuclear fuel from a reactor site to another place has been a serious social and technical issue around the world. Many Germans have been unhappy about the land transportation of spent nuclear fuel and high- and low-level radioactive wastes across the border and the nation. For Korea transportation will be a really serious issue. To transport spent nuclear fuel a transport cask which can accommodate around 14 PWR assemblies is used. Even though the net weight of 14 PWR assemblies is in the order of ten tons, the total weight of a transportation cask is more than 120 tons. All national roads in Korea can endure the maximum loading of 40 tons much less than the weight of a transportation cask. Especially a bridge is the weakest spot for the heavy loading. In practice it is impossible to transport a cask by road. Then there are only two alternatives for the transportation of spent nuclear fuel by rail and by ship.

Unfortunately however the most railway systems in Korea are for passengers. Even though there are a certain routes to transport heavy material such as cement, those railways are very limited. Even though a new railway is constructed from four nuclear reactor sites to a future spent nuclear fuel management facility, many new systems inevitably should pass by big cities because the current reactor sites are very close to those big cities. This will certainly escalate the debates over the spent nuclear fuel transportation nation-wide.

The practical way is to use ship transportation. During the construction of a nuclear reactor, the site operated the temporary harbor for 3,000 ton ships to transport all equipment and components of a reactor. This becomes the standard to build a reactor in Korea. For ship transportation, the temporary harbor can be transformed for a good service of transportation of spent nuclear fuel. As long as a new complex for spent nuclear fuel management is located along a coastal area, the sea transportation will do the job. Once spent nuclear fuel is safely delivered to the harbor, it can be transported along a very special short distance load which can endure the weight of a heavy transportation cask. However, this will obviously limit any potential complex site to a coastal area. From now on, we can assume that any spent nuclear fuel management facility either in the form of a centralized spent fuel storage one, a final repository, or a recycling one will be located along the coastal area in Korea for this practical reason.

Difficulty to Find a Reasonable Site for Disposal

As stated, the site securing for the spent fuel management is in practice a difficult mission. KAERI has steadily developed the reference disposal concept KRS (Korean Reference Repository System) for direct disposal of spent nuclear fuel in crystalline rocks in Korea. In fact the most popular stable geological medium is a crystalline rock like gneiss and granite populated with heavy fracture networks. Like the world famous Swedish KBS-3V concept, the KRS is adopting the concept of the vertical borehole emplacement of spent nuclear fuel in a waste container surrounded with bentonite layers. The bentonite known to retard heavy isotope such as TRUs (Transurinic Elements) whose half lives are very long will have a phase change at the temperature around 120 degree in Celsius. With a proper engineering margin, when a disposal concept is studied the maximum allowable temperature inside bentonite is set to be 100 degree in Celsius. The spent nuclear fuel especially PWR one emits significant decay heat. Therefore, in a typical geologic condition the distance between two boreholes will be around 6 to 8 meters which the distance between two disposal tunnels are 40 meters. This certainly requires a lot of underground area to dispose of spent nuclear fuel. For example, the average density per square meter area for PWR spent fuel is 5.5 kg.

Therefore if 100,000 tU spent fuel is targeted to be disposed of 19 square kilometer underground area is needed if the geologic condition is perfectly immaculate. Unfortunately in the real world it is impossible to identify the massive host rock without any defect. Typically extra 30% is required not to use the area heavily fractured. That means that 25 square kilometer underground area is essential for a repository. Then what would be the size on the ground surface for that facility? In Yucca Mountain the distance from a repository to the nearest biosphere is five miles. It will be extremely difficult to find a candidate in a coastal area to suit for these criteria in many countries such as Korea. Also, the dry climate in Yucca Mountain is perfectly good for the isolation of radioactive materials. However, on the contrary, the annual precipitation in Korea is around 1,450 mm with an extremely heavy occasional flooding in summer. Therefore, it will be a real challenge to identify a hosting repository site along a heavily populated coastal line in Korea which suits all geo-hydraulic conditions.

Summary of Issues

Figure 6 summarizes all issues discussed in this paper. As illustrated, all four nuclear complexes are closely located with big cities, which limit further extension of their current storage capacities. Due to the practical difficulties on road and railway transportation, the ship transportation will be a pragmatic approach. There will be no technical challenge to accomplish that mission. However it would limit the accessibility to the in-land areas so that potential spent nuclear fuel management facility is located on the coastal area.

2. Innovative Solution for the Management of Spent Nuclear Fuel

Many states in the world have tried hard to deal with the spent nuclear fuels for many decades. Most of the programs cannot get real accomplishment due to the following reasons:

Current Situation

- (1) There is no proof to assure long term safety over a direct disposal repository in many countries.
- (2) There is no good two way communication between the implementers and other stakeholders such as local communities in many cases.
- (3) There is serious demand to assure the environmental friendliness in all cases.
- (4) There is financial burden to implement a certain option for spent nuclear fuel in many cases.
- (5) There is no significant technology advance to reduce the volume and the risk of radioactive materials. And
- (6) There is no practical choice to minimize the level of radioactivities from long lived fission products and TRUs after thousand years since emplace for the final disposal.

Combination of Options

In practice, it will be impossible to find a single option to solve the problem of spent fuel management. Instead, the potential combination of options for short-, mid-, and long-term management as illustrated in Figure 7 might be a pragmatic solution. The market strongly supports the important role of the storage as a short term option. Also, the final disposal option is essential to handle wastes, either in the form of spent nuclear fuel or any solid wastes from reprocessing and the recycling.

Then the real questions will be as follows:

- (1) What will be the mid-term options to minimize the burden of waste disposal?
- (2) Do we really need the mid-term options? and
- (3) What would be the characteristics of the mid-term solutions from the view points of economy, proliferation resistance, the technical feasibility, and environmental friendliness?

Request to Solve the Global Problem with Financially Acceptable Way

We unfortunately do not know what would be the best for the commercialization of mid-term options at this stage, even though many states have worked on technology development at this time. We are not at that stage yet. Traditionally, the United States and France have worked on the wet type advanced nuclear fuel cycle technologies such as UREX, TRUOX, COEX, and GARNEX because for the domestic application in these states they did not have to worry much about the proliferation issues. In that sense those technologies might have certain difficulty to solve the global issues on the spent nuclear fuel arising unless there is a very good competitive international service for all countries concerning about the spent nuclear fuel accumulation. In practice it will be challenging to assure inexpensive service charge for foreign countries if there are facilities located in the United States and France due to the expensive transportation cost between service providers and consumers.

The optimum solution might be to develop proliferation resistant technologies and at the time of commercialization to set up the global norms to avoid any potential breakout scenarios from that facility. Technically instead of wet processes, dry processes can serve better role for non-proliferation. A certain dry processes such as pyro-processing (hereafter pyro) as depicted in Figure 8 have been known to assure proliferation characteristics.

The pyro technology has a long tradition especially in the field of aluminum industries. The ARCO listed in the DJII 30 is the master of the pyro to produce the aluminum ingots.

Basic Principle and Its Proliferation Resistance of Pyro

The scientific base for the pyro is very straightforward using the difference in the electro-potential scientifically known as Gibb's free energy of different elements. Due to the common characteristics of heavy TRUs the energy gaps among TRU elements are small, and the gap among fission products are also tiny. However, there is a significant difference between the gaps for TRUs and fission products. That is the basis of separation between TRUs and fission products via pyro. In theory, one may argue by using the same principle each element of TRUs can be selectively separated. If this is true then it will create the concern over potential proliferation as happened for the PUREX process. However, the practical separation of any significant amount of fissile material from other TRUs is not feasible due to the similarity in Gibb's free energy levels. The whole process is equivalent to the electric circuit with a certain resistance. All components in pyro act as a resistance with a certain uncertainty. If the system becomes big, the uncertainty also increases. That creases uncertainty in the voltage, in our terminology the Gibb's free energy. One can easily understand it if one can remember the very simple Ohm's law. In addition, to reach a certain energy level from the ground one requires a certain fluctuation at early stage so that the so called step function type, sharp increase which can tune the energy level very sharply to the target value is not achievable practically at least at the early stage. Moreover all pyro processes happen inside a hot cell. Therefore as long as the watch dog has a full authority to monitor any potential abrupt material flow from a hot cell to outside, all fissile materials which are the essence for the non-proliferation concern will reside inside a hot cell, which is not easy to access due to its intrinsic radiation when hot materials stay inside.

3. Suggestions for Joint Cooperation and Five Pillars

Initial Joint Actions from Korea and the United States

As discussed, we are facing with a real global challenge for the proper management of spent nuclear fuels. If it is a just problem of the limited number of states the current wet technology might handle the problem. However many emerging states such as UAE, Turkey, Vietnam and others would like to introduce the new fleets of reactors. Pyro technology has showed its great potential in other industries. It also has its own intrinsic proliferation resistant features. To assure its merits and to find better ways to handle its potential disadvantages along with all international political and legal issues for its final global

commercialization, many key subjects about pyro are strongly recommended to be reviewed at the international level. I believe that Korea and the United States can act as international leaders for this fact finding research from the Year of 2010. Then with a certain success both states can invite other states with the same concerns on spent nuclear fuel management in the near future.

Key Subjects

There are many interesting key subjects for the joint cooperative works between Korea and the United States.

- (1) Economic viability,
- (2) Proliferation resistance,
- (3) Next Generation Safeguards Initiative(NGSI),
- (4) Environmental friendliness,
- (5) Technical feasibility,
- (6) Development of norms to prevent potential breakout, and
- (7) Legal system for the multi-lateral agreement

Affirmative Role of the Cold Test Facility, PRIDE in KAERI

These are areas not only for the further scientific development but also to get the support from international society. As illustrated in Figure 9, it requires a team approach from scientific achievement, social supports based on its authenticity as well as the care for the fairness. These are the real nature for the future success. The PRIDE(PyROprocess Integrated inactive Demonstration) facility under construction in KAERI can serve as a technical hub to promote the technical feasibility, safeguardability, and non-proliferation. International scholars along with key members from prominent watchdogs can work together to test the principles of pyro, to find a practical way for the concept of “Safeguards by Design”, to apply the NGSI for better implementation, and very importantly to build up the mutual trust and team works among all stakeholders.

Korea – US Joint Study

Korea would like to have full strategic cooperation with the United States to really understand all pros and cons of the pyro and to advance the technical levels. The current hot issues over the cost, technical as well as socio-political matters can be deeply studied throughout the joint team work to finally develop the global technical and socio-political norms to handle the international dilemma over the spent nuclear fuel. It will be a good opportunity not only for Korea and the United States to solve the nuclear issues but also for many allies and new emerging states which are deeply interested in nuclear options without any solid recipe to handle potential spent nuclear fuel.

Five Pillars

For the joint bi-lateral and global research works, five pillars are proposed:

- (1) Deliberative approach to get full support internationally and domestically
- (2) Step by step decision for the assurance of transparency and non-proliferation
- (3) Good initiative to check and balance among the wet & dry recycling initiatives
- (4) Global partner to create all norms for universal solution on spent nuclear fuel issues

- (5) Fully open minded to understand pros and cons of the innovative nuclear fuel cycle technologies in the field of economics, environmental-friendliness, and feasibility with other partners

As explained already, the issues on the pyro are not just a matter of science. It requires the strong agreement from domestic, regional and global societies. To accomplish it the first two pillars, the deliberative approach and the step by step decision mechanism proven to be the best approaches for the success are proposed. It will certainly enhance the transparency for the planning, implementation and discussions over many cumbersome subjects. The third pillar is to have a strong check and balance system to properly identify the optimum solution for the nuclear fuel cycles. Traditionally many Western states overemphasize the importance of the advanced wet processes. Even though the wet processes have a certain advantages, it also inherits the problem in the proliferation so that it might not be an option for the global solution. The value of the dry process is strongly recommended for the future detailed study. Fourthly, we need a strong leader to solve the everlasting spent nuclear fuel problems. From now on Korea and the United States work as a team to develop the final puzzle to solve the spent nuclear fuel issues. Finally and the most importantly we cannot go anywhere without the true mutual trust. I truly stresses the importance of the environment and the value of the mutual trust. Both Korea and the United States have the same vision for non-proliferation. Based on this solid ground we should understand the real needs of each other. The United States has been in the 'War against Terror' and Korea has been fighting to find a 'Practical Way' to reduce the burden of the spent nuclear fuel arising. If we really understand why my true friend is concerned about the specific issues, it will be a little bit easy to identify a proper mechanism to jointly work together. With many lessons throughout the history now it is a real time to trust the value of the mutual friendship between two countries. The joint effort will surely act as a cornerstone to tackle the everlasting dilemma over the global spent nuclear fuel accumulation.

Table 1 Current Status of Spent Nuclear Fuel Arising in Korea

(As of the end of 2008: tU)

Reactor	Site	Capacity	Stored	Year of Saturation
PWR	Kori(4)	2,253	1,685	2016
	Yonggwang(6)	2,686	1,623	2021
	Uljin(6)	1,642	1,294	2018
PHWR	Wolsong(4)	5,980	5,481	2017
Total		12,561	10,083	-

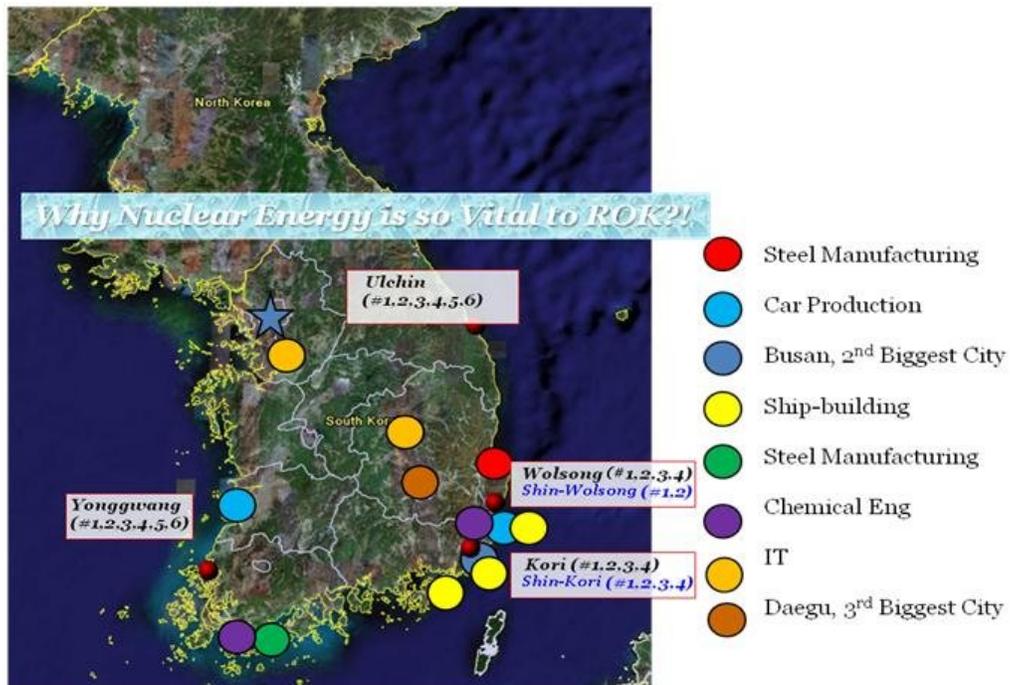


Figure 1 Deployment of Nuclear Power Plants and Manufacturing Business in Korea

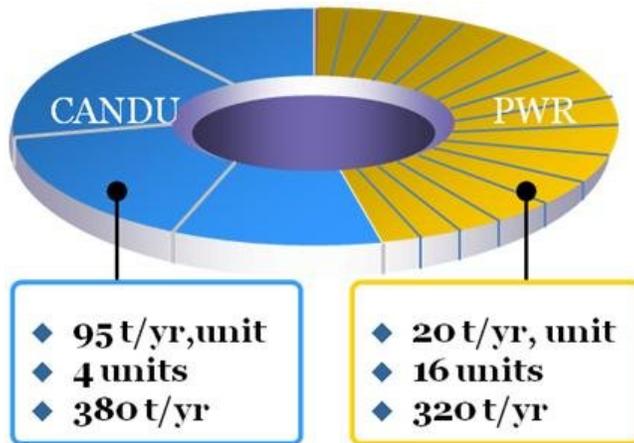


Figure 2 Spent Nuclear Fuel Arising from a PWR and a CANDU

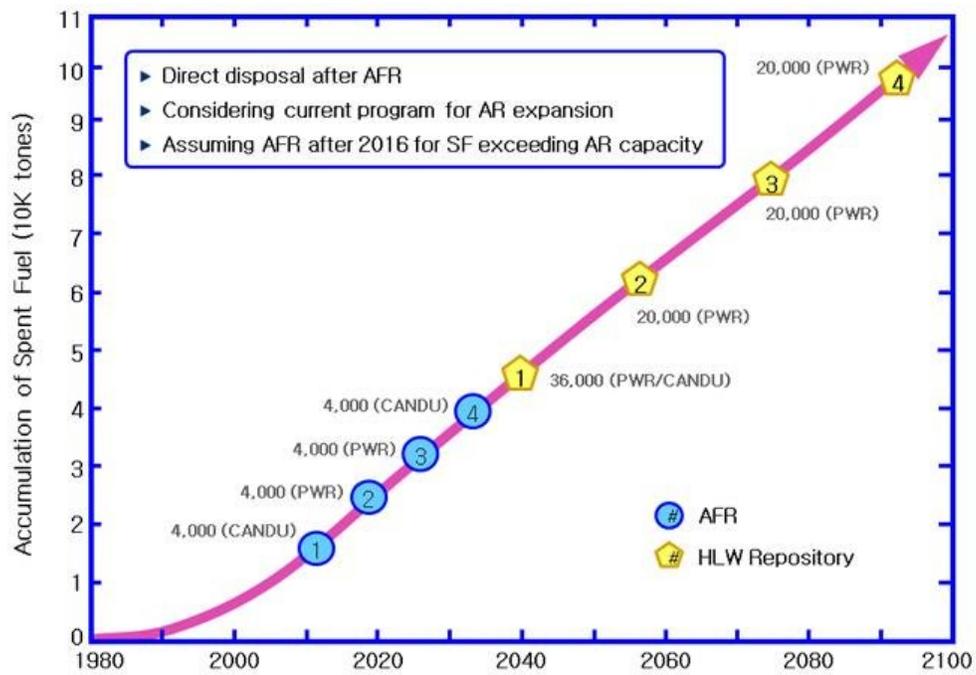


Figure 3 Long-term Project of the Accumulation of Spent Nuclear Fuel and the Potential Introduction of Management Facilities



Figure 4 The Korea Reference System for Direct Disposal of Spent Nuclear Fuel

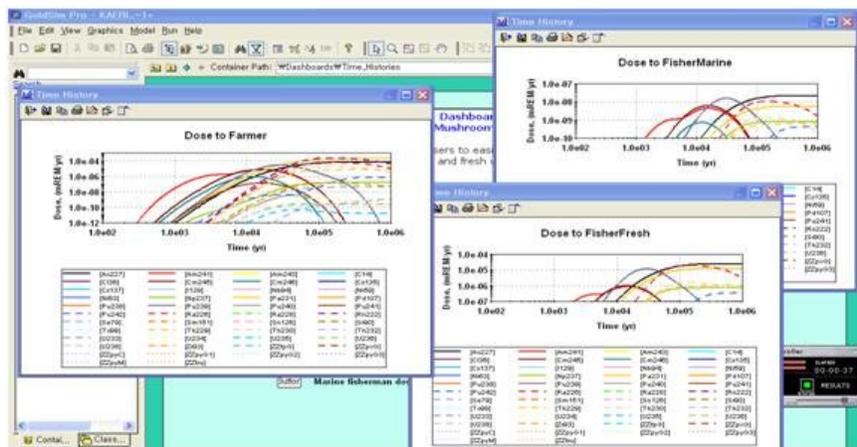


Figure 5 Long-term Post Closure Radiological Impact of a Potential Repository in Korea

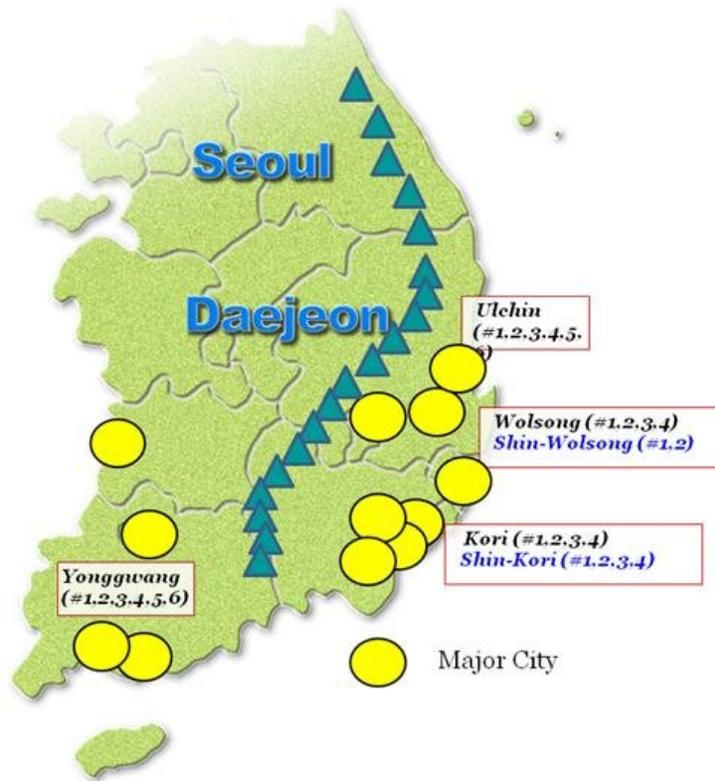


Figure 6 Illustration of Summary for Issues over Spent Fuel Management in Korea



Figure 7 Practical Approach for the Management of Spent Nuclear Fuel, Combination of Short-, Mid-, and Long-term Options

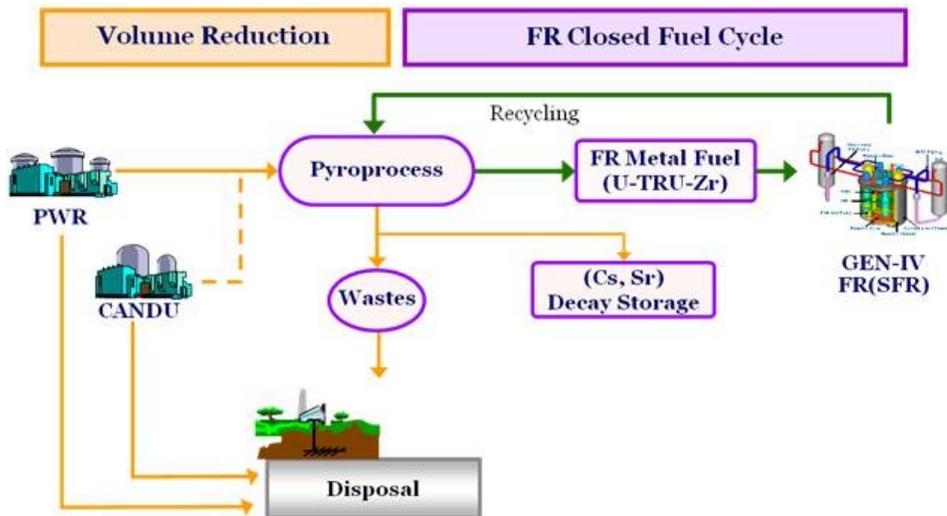


Figure 8 The Concept of the Advanced Nuclear Fuel Cycle, Combination of Pyroprocessing and the Gen-IV Fast Reactor

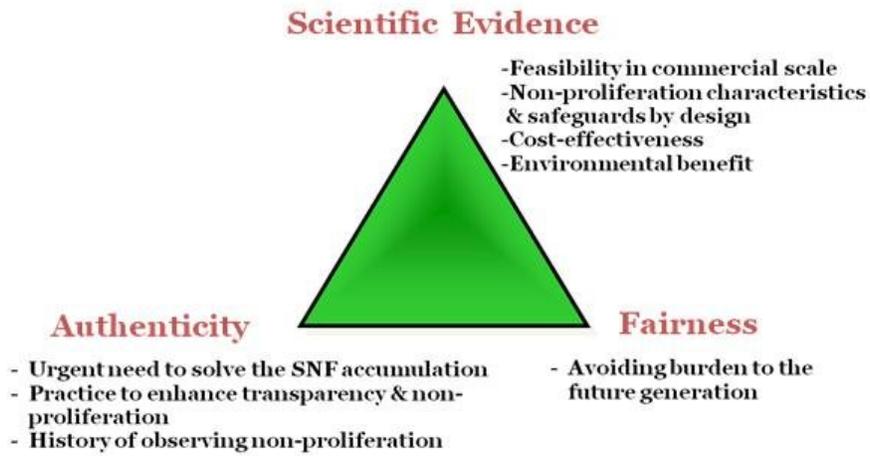


Figure 9 Three Roots to Make a Real Success for the Success in the Spent Nuclear Fuel Management

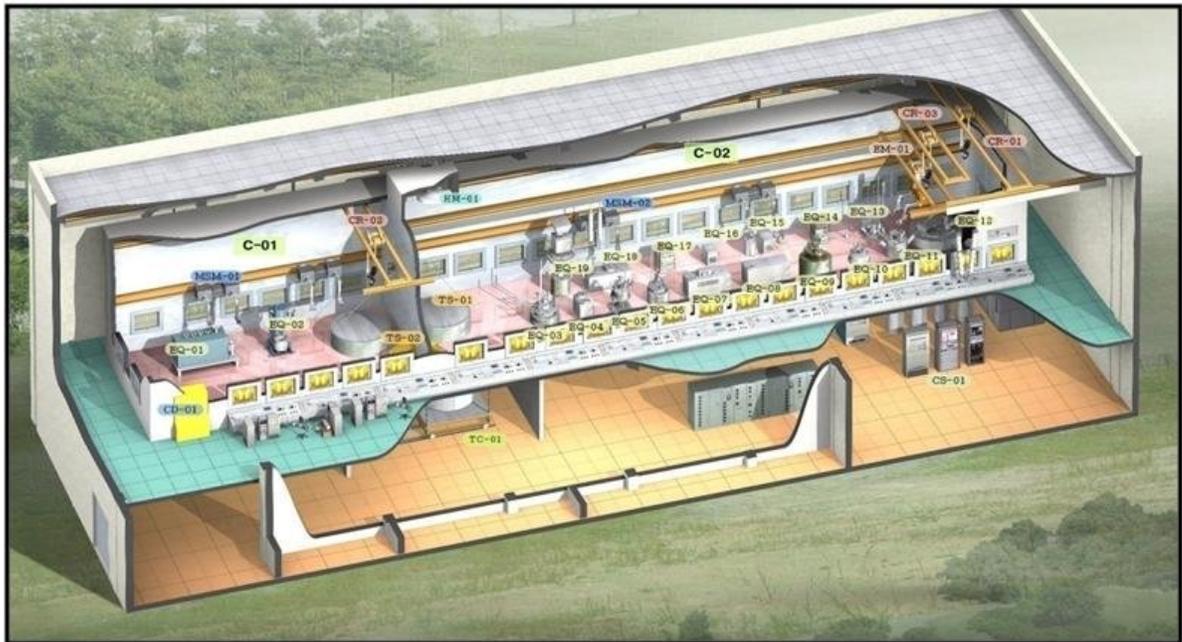


Figure 10 The Schematic View of the PRIDE in KAERI, Korea



Same Vision for
PR-PP and PSI



Understanding
Needs of Partners



Identifying Proper
Mechanisms



Mutual Trust



Going Together: Participation

Figure 11 Visions for Joint Study for the Advanced Nuclear Fuel Cycle