The Advanced Nuclear Fuel Cycle System in Korea
Volume 01 / Winter 2008
NEWSLETTER

In Focus

Sustainability of Nuclear Energy Is Nuclear Energy the Future?

The recent surges in energy demand worldwide are causing serious problems: global warming from excess greenhouse gas emissions is one; the exhaustion of natural resources from their reckless usage is another. In order to address these problems, many countries are focusing on nuclear power as an alternative energy source to the currently entrenched fossil fuels. Thus, countries with existing nuclear power programs are considering expansion, while developing countries are vying to initiate such programs in their own territories.

Nevertheless, it is difficult to conclude at this point whether nuclear power has established itself as a sustainable energy source for the future. Many countries still hesitate when planning to expand their nuclear power generation capacity; some countries even object to maintaining their current levels. Such views reflect the widespread concerns over the risks posed by radiation to public health, the aftermath of accidents that might occur at nuclear power plants, and the risk of proliferation, which may facilitate the deadly use of nuclear technology and materials.

In this first issue of *The Advanced Nuclear Fuel Cycle System in Korea,* two energy experts, Hans-Holger Rogner and Frank Barnaby, discuss whether nuclear energy is capable of fulfilling its role as a sustainable energy source for the future. Hans-Holger Rogner is the Section Head, Planning and Economic Studies Section of the International Atomic Energy Agency (IAEA), and Frank Barnaby is a consultant on nuclear issues to the Oxford Research Group, an independent nongovernmental organization working to promote a more sustainable approach to security for the UK and the world. Please note that their views do not necessarily represent those of the Korea Atomic Energy Research Institute (KAERI).

NUCLEAR POWER: THE WAY FORWARD TO SUSTAINABLE ENERGY SUPPLIES

Written by Hans-Holger Rogner

For

Sustainable development, as defined in 1987 by the Brundtland Commission, known formally as the World Commission on Environment and Development (WCED), is "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition requires that we judge today's options not only based on the immediate political, economic, or environmental implications, but also from the perspective of future generations, who will benefit from our successes in achieving sustainable

/ Continued on page 02

NUCLEAR POWER: NOT THE ANSWER TO A SUSTAINABLE ENERGY FUTURE

Written by Frank Barnaby

Against

There is a pressing need for development in much of the world, and energy is essential for this development to occur. Reducing poverty, increasing standards of living, improving health care, and raising productivity—both industrial and agricultural—all require reliable and secure access to sources of energy. According to the International Energy Agency (IEA), global energy demand is projected to be 50% higher in 2030 than it is today; and about 70% of this growth in demand is likely to come from the developing countries.

/ Continued on page 05

development, or suffer from our failures.

In other words, central to the concept of sustainable development is the maintenance or augmentation of the assets (natural, man-made, and human/social assets) available to future generations, while at the same time, minimizing the depletion of our finite resources and not exceeding the limits of the global ecosystem. In my opinion, the development of nuclear power broadens the natural resource base available for energy production, increases human and man-made capital, and, when safely handled, has little impact on ecosystems.

Economics

New nuclear power plants (NPPs) are more expensive to construct than their fossil-fuel-based alternatives, particularly gas-fired power plants. In liberalized energy markets that emphasize short payback periods, the high capital costs of NPPs and long amortization periods are major disadvantages relative to fossil-fuel-based, particularly gas-fired, power plants.

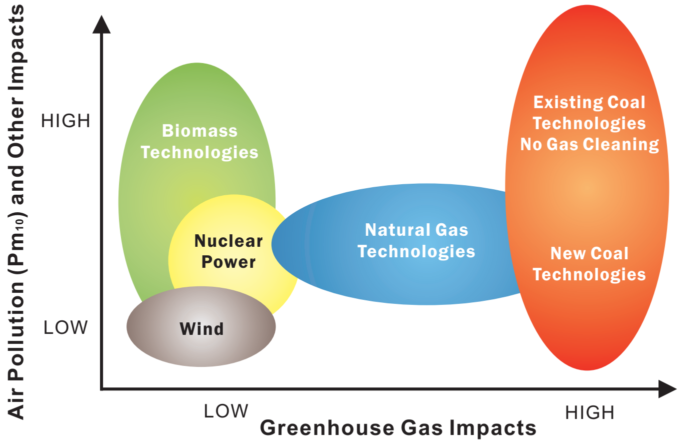
On the other hand, NPPs are cheap to operate: the existing operating NPPs, for which the initial capital investments are largely depreciated, are among the lowest cost generators. Not surprisingly, interest has grown in extending NPP operating lifetimes from their initial licensed lifetimes of 30–40 years, and actual license extensions of up to 60 years are already a reality.

In addition, nuclear electricity generating costs are less sensitive to changes in fuel prices than are fossil-fuel-based electricity generating costs; a doubling of uranium prices would result in only a 4–5% increase in the generating cost, while for natural gas, such an increase would translate into 60–70% higher generating costs. Recent increases in international fossil fuel market prices have eliminated the margins for natural gas and coal, leaving nuclear power as the least-cost electricity generation option for base-load electricity generation.

Externalities

External costs are those borne by the public and not the beneficiaries of electricity generation, such as the health costs due to a highly polluting power plant. Substantial progress has been made in recent decades in internalizing many previously external environmental and health costs through, for example, regulations for pollution control, nuclear safety, mine safety, oil tanker operation, and, more recently, the new markets for carbon emissions trading created by the entry into force of the Kyoto Protocol. Once such costs are internalized, they are taken into account in private investment decisions and in consumer choices.

In this regard, nuclear power generally compares well, as it has already internalized its costs to a greater extent than alternative technologies (Refer to Fig. 1). Current nuclear-based electricity generation costs in most countries incorporate all the safety costs down the fuel chain as well as the costs of eventual decommissioning and waste management, including the disposal of low-, intermediate-, and high-level radioactive waste.

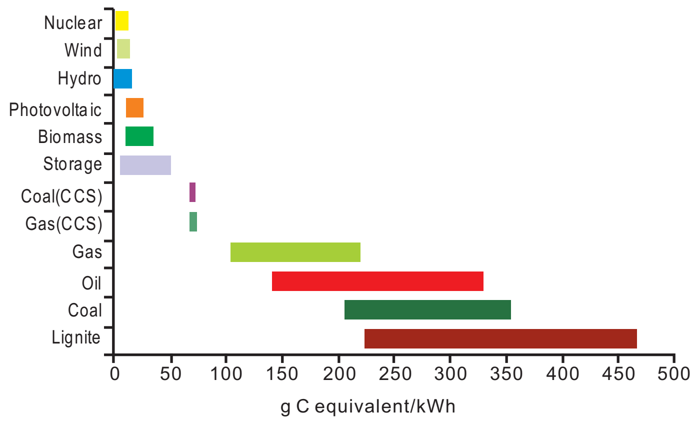


Source: European Commission 2003

Fig 1. Relative Environmental Impacts

Environment

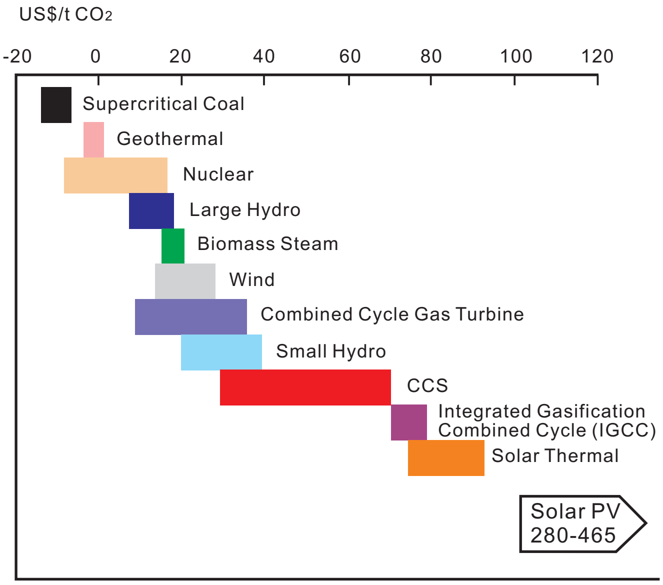
The complete nuclear power chain—from resource extraction to waste disposal, including reactor and facility construction and decommissioning—emits only 2–6 g of carbon equivalent per kilowatt hour (gCeq/kWh). This is around the same as that for wind and solar power when including their construction and component manufacturing costs. All three, along with solar power and biomass, are well below coal, oil, and natural gas (60–460 gCeq/kWh) even when accounting for carbon dioxide capture and storage (Refer to Fig. 2).



Source: Weisser 2007

Fig 2. CO_2 Emission Rates

Globally, nuclear power currently saves approximately 600 million tons of carbon (MtC) emissions annually (8% of the current global carbon emissions), which is about the same as that saved by hydropower. In the OECD countries, nuclear power has, for the last 35 years, accounted for most of the reduction in the carbon intensity per unit of delivered energy. Moreover, nuclear power can act as a low-cost CO_2 mitigation option for the electricity generation sector (Refer to Fig. 3).



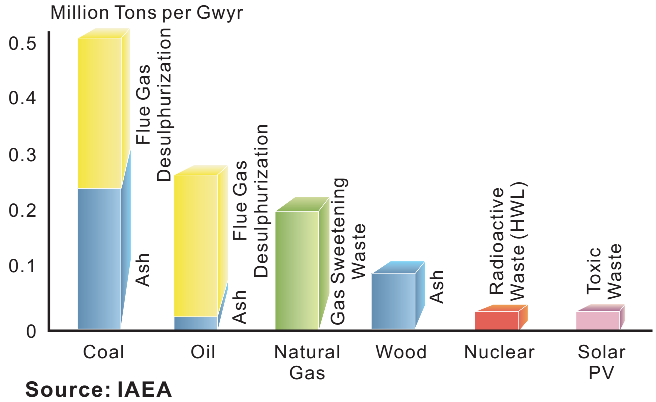
Source: World Bank

Fig 3. Illustrative CO_2 Mitigation Costs

Nuclear power reactors emit virtually none of the traditional air pollutants associated with fossil fuel combustion: principally, sulfur dioxide (SO_2), nitrogen oxides (NO_x), and suspended particulate matter (SPM). Nor do they emit trace heavy metals such as arsenic and mercury, which are associated with coal combustion. SO_2 and NO_x contribute to human morbidity and mortality, reduce crop yields, and are the principal causes of acid rain. In turn, acid rain damages crops, forests, ecosystems, and even building materials.

Nuclear Waste

Waste minimization is the central tenet of sustainable development. Waste disposal is one area in which nuclear power generally surpasses its alternatives. Nuclear waste is small in volume, well confined, and highly monitored, which is unlike the solid and toxic wastes produced by other fuel chains (Refer to Fig. 4). The spent fuel produced by all the world's operating reactors in one year would only cover one soccer field to a depth of about 1.5 m. Moreover, in most countries, the cost of containing, storing, and disposing of nuclear waste is included in the price of the electricity generated.

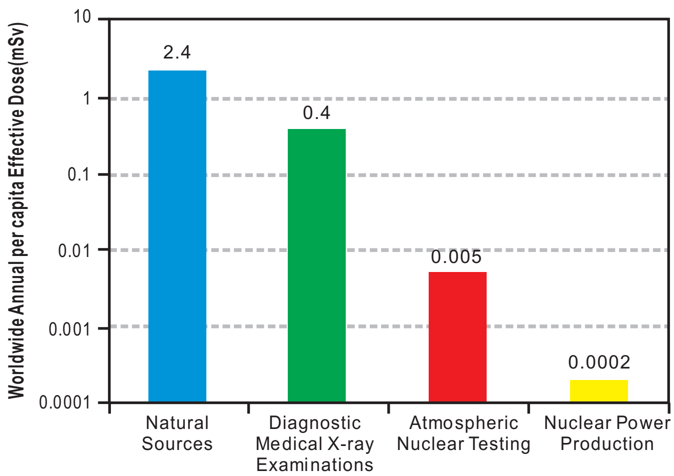


Source: IAEA

Fig 4. Waste Generated in Fuel Preparation and Plant Operation

Social Aspects

As estimated by the US Environmental Protection Agency (EPA), people living within 50 miles of a NPP receive only 0.09 μSv—this is more than one thousand times less than the average dose received by people in the United States from X-rays and other medical procedures, and more than ten thousand times less than their average dose from natural background radiation (Refer to Fig. 5).



Source: UNSCEAR 2000

Fig 5. Worldwide Annual per capita Dose from Natural and Anthropogenic Radiation

Significant health impacts from NPPs thus arise only from major accidents that release radiation, of which there has been one—the 1986 Chernobyl accident. Caused by serious design flaws coupled with major operator errors, Chernobyl was a catastrophic accident that cost many lives and caused widespread suffering. On the other hand, it has also brought about major changes, including the founding of a safety culture around nuclear energy that includes constant improvement, thorough post-incident analysis, and sharing of recommended best practices.

Thus, today, the broad dissemination of the lessons learned is an essential part of maintaining and strengthening the safe operation of NPPs; there is strong empirical evidence to show that learning from NPP operating experiences has led, and continues to lead, to improvements in plant safety. This safety culture has been demonstrating its effectiveness for over two decades and provides the basis for countries now considering the construction of new NPPs.

Nonproliferation of Nuclear Material

Nuclear weapons preceded civilian nuclear power. Hence, in 1953, US President Eisenhower proposed the establishment of an international agency and international assistance to promote the peaceful applications of nuclear energy so that countries wishing to acquire nuclear expertise for peaceful purposes did not feel compelled to follow the "weapons-first" path of the nuclear pioneers. Three years later, the International Atomic Energy Agency (IAEA) was founded "to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world." The IAEA's Statute also authorizes it to establish safeguards to ensure that the materials provided by nuclear power countries are not used for military purposes.

Effective safeguards against nuclear weapons proliferation and terrorism are required as long as nuclear technologies can be used to generate weapons-grade fissile material, irrespective of whether the material is used for NPPs or for medical, agricultural, and other peaceful applications. The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) is at the center of the international nonproliferation regime. Other components of the regime are the Convention on the Physical Protection of Nuclear Material and nuclear weapon-free zones in different parts of the world. Moreover, the growing adherence to the Additional Protocols of the NPT and other safeguard agreements further strengthen this regime. Such agreements are critical irrespective of the future of civilian nuclear power, and efforts to strengthen them will advance the cause of nonproliferation much further than restrictions on nuclear power.

The NPT and the IAEA's safeguard system has thus far been remarkably successful in limiting the spread of nuclear weapons and remains at the center of the current global nonproliferation regime.

Security of Nuclear Material

The September 2001 attacks in the United States and subsequent attacks elsewhere have driven a dramatic reevaluation of the terrorist threat to all sensitive locations—urban centers, industrial complexes, harbors, oil refineries, air and rail travel, and also nuclear facilities. However, at the same time, they have brought added attention to nuclear security—the ability to control and protect nuclear and other radioactive material, nuclear installations, and material transportation from terrorist and other illegal activities.

The assessments of plant security note that plants and other fuel cycle facilities are designed to withstand natural disasters such as earthquakes, floods, tornadoes, and hurricanes. However, terrorist attacks involving explosives and fire would be analogous to such external events with regard to their capability for damage and release of radioactivity; the containment building and other plant buildings are, by design, large, hardened structures that would be particularly resistant to an attack. An evaluation of an aircraft crash into a NPP by the Electric Power Research Institute in the United States concluded in 2002 that the containments would not be breached by such an attack. Switzerland's Nuclear Safety Inspectorate studied a similar scenario and reported in 2003 that the danger of any radiation release would be low for older plants and extremely low for newer ones.

Conclusion

This article attempts to put nuclear power into perspective for sustainable development. The quasi-comparative assessment of nuclear power presented in this article suggests the following:

Nuclear power

- can be a cost-effective electricity supply technology, especially at current fossil fuel price levels;
- surpasses other options in internalizing its externalities;
- is a cost-effective way to reduce carbon emissions from an electricity generation (any internalization of greenhouse gas emissions further improves its competitively);
- manages its waste safely;
- has an incomparable industrial safety record with a philosophy of continual improvement; and
- is not a principal contributor to proliferation risks, and that halting or reversing the expansion of nuclear power would not appreciably reduce such a risk.

The choice of technologies to advance sustainable development is a sovereign choice, and each country will require a mix of technologies that are suited to its individual situation and requirements. However, given the advantages of nuclear power in contributing to the sustainable development objectives, it can be an important part of the energy mix in many countries.

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In response to this, many countries, both developing and industrialized, are considering which sources of energy will best suit their future energy needs. Some countries lack indigenous energy resources, while others want to reduce their dependency on imported energy or are anxious to increase the diversity of their energy resources; and many are committed to reducing their emissions of greenhouse gases, particularly carbon dioxide, in an attempt to reduce global warming and climate change.

Governments are reassessing their nuclear policies.

A number of governments are currently actively reassessing their civil nuclear policies. With the prospect of a nuclear renaissance in mind, the nuclear industry is proclaiming the virtues of nuclear power as a large-scale source of reliable, zero-carbon electricity at an affordable price, while dismissing alternatives such as wind and solar power as inadequate to support the demands of industrialized economies.

On the other hand, the critics of nuclear power point out that it is by no means a low-carbon source of electricity; extracting, processing, and transporting uranium all use energy that produces greenhouse gases, as does the construction of nuclear power plants, the storage of radioactive wastes, and the decommissioning of nuclear facilities. Thus, as more high-quality uranium ore is consumed, nuclear power will produce even more carbon dioxide.

Currently, approximately 42 gigatons (GT) of carbon dioxide equivalent are emitted annually. If these emissions are capped at this level, then atmospheric greenhouse gas concentrations will reach 550 parts per million by 2050—up from today's approximately 370 parts per million.

According to a scientific consensus, to maintain climate changes to within manageable limits and to prevent the risk of unmanageable changes, it is essential that the average global temperatures do not rise by more than approximately 2 °C. This implies maintaining the concentration of atmospheric greenhouse gases to no more than 550 parts per million.

This threshold may be reached by about 2035 unless urgent action is taken. Thus, if nuclear power is to play a significant role in attaining this target, it does not have long to do so. Furthermore, if nuclear power is to play more than a marginal role in combating global warming, then nuclear power reactors will have to be operated in many developing countries.

Can enough new nuclear power reactors be built fast enough to make a significant dent in global warming?

Currently, the world's nuclear power reactors generate a total of 372 gigawatts (GW) of electricity. This represents about 6% of the world's total power production of 15,000 GW and 16% of the world's total electricity generated.

In order to make a significant dent in global cumulative carbon emissions, by say 2075, assuming that countries generate one kilowatt (KW) of electricity per capita (probably an underestimation) and that they generate half of their electricity by nuclear power, the world would need to generate 3,000 GW of electricity by nuclear power—about eight times the current amount.

Today, nuclear power is found in but a few industrialized countries. Of the world's 372 GW of nuclear power generation capacity, less than 10 GW is in developing countries. Hence, it must be emphasized that if nuclear power is to play a substantial role in the world's energy economy and have an impact on global warming, much of it will have to be produced in developing countries.

Thus, the crucial question is whether such countries can obtain the capital and technical expertise needed to operate and safely maintain nuclear power reactors, and also dispose of the high-level radioactive produced.

There are now 28 new nuclear power reactors under construction—each with an average generating capacity of 0.8 GW. In addition, some countries have announced plans to build another 76 reactors with an average capacity of 1 GW. Furthermore, there are 162 proposed new reactors. If these are all built, the number of countries operating nuclear power reactors will increase from today's number of 31 to 38.

Some of the future reactors will generate more electricity than those used today. The new reactor under construction in Finland, for example, will have a generating capacity of 1.6 GW. However, smaller nuclear power reactors are better suited to supplying the electricity needs of some countries. For example, the reactors that South Africa proposes to construct will have an average generating capacity of less than 0.2 GW.

How do these nuclear plans tie in with the future global demand for energy? Future energy demands will depend on the country's population size. For example, it is probable that by 2075 the population of China will reach approximately 1,600 million; that of India, 1,800 million; and that of Indonesia, 375 million.

Assuming that these countries generate one kilowatt of electricity per capita and that they generate a third of their electricity by nuclear power (twice today's world share), China would require approximately 530 GW of nuclear power; India, 600 GW; and Indonesia, 125 GW.

Bangladesh, Brazil, Congo, Ethiopia, Nigeria, and Pakistan would each need more than 65 GW. Among these, Bangladesh, Congo, Ethiopia, Indonesia, and Nigeria currently have no nuclear power reactors. For a comparison, the population of the United States is likely to be approximately 445 million by 2075, requiring approximately 146 GW, assuming one kilowatt of electricity per capita and a third of the electricity being generated by nuclear power.

To suggest that these huge amounts of nuclear electricity could be generated is unrealistic—a pipe dream.

Is there enough uranium to fuel a large increase in the number of power reactors?

According to the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development (OECD), the known recoverable uranium resources are 4.7 teragrams (Tg). This figure includes uranium ores that are of a relatively low ore grade, occur at greater depths, require long transport distances, and are harder to mine. At the current consumption rate of 68,000 megagrams (Mg) a year, these uranium resources will last for 69 years.

As the richest ores are depleted first, the net energy extracted from the current uranium ore resources will decrease; the richest ores will be depleted within a decade and the average grade will fall to below 0.1%. At this rate, and with lesser grades of uranium ore, the net energy generation rate from uranium will be significantly lesser.

Assuming that the world's nuclear capacity remains constant at 370 GW, the net energy generation rate from uranium will fall to zero by around 2070. From another perspective, assuming that the world's nuclear share remains constant at 2.2% of the world's energy supply, the net energy generation rate from uranium will fall to zero by as early as around 2050.

The shortage of uranium ore rich enough to provide a positive net energy generation rate will lead to the use of fast breeder reactors, which use fuel containing mainly plutonium and require only a small input of uranium. If the nuclear industry gets its way, fast breeder reactors will see commercial use after around 2030.

If we move to a plutonium economy, can the risk of nuclear weapons proliferation and nuclear terrorism be controlled?

Any country operating a breeder reactor will have relatively easy access to usable weapons-grade plutonium for effective nuclear weapons, and will have competent nuclear physicists and engineers who could design and fabricate them. Because they could produce a nuclear force in a short time—months rather than years—these countries will be latent nuclear weapons powers. Further, it must be expected that some of them will make the irrevocable political decision to become actual nuclear weapons powers.

If the world is using 3,000 GW of nuclear electricity in 2075, and if this is based on a once-through nuclear cycle using light-water reactors, it will be generating approximately 600 tons of plutonium annually (and would require roughly 500,000 tons of uranium). However, if this nuclear capacity were based on fast breeder reactors as the nuclear industry predicts, more than 4,000 tons of plutonium will have to be fabricated into fresh reactor fuel each year.

A significant use of breeder reactors will carry with it the real risk that nuclear terrorist groups will eventually acquire some plutonium, fabricate primitive nuclear weapons, and then use them in terrorist attacks.

Conclusion

Some very respected advocates of nuclear power do not dispute that a significant increase in the use of new nuclear power reactors would increase the risk of nuclear weapons proliferation and nuclear terrorism, but they nevertheless argue in favor of a nuclear renaissance. They argue that the risks to national and global security of a failure to reduce the greenhouse gas emissions of outweigh the risks of nuclear war and nuclear terrorism.

The alternative argument is that low-carbon energy sources such as solar, wind, tidal, and other renewable energy sources are available and could be installed faster, more cheaply, and with less risk to national and global security than nuclear power.

In the end, society has to judge whether or not the risks of nuclear weapons proliferation and nuclear terrorism are acceptable in a world with many nuclear power reactors. In my opinion, this is definitely not acceptable.

Research Notes

KAERI Pursues an SFR Fuel Cycle with Pyroprocessing

As of the end of 2006, approximately 9,000 tons of spent fuel have been generated in Korea, with an additional 700 tons (approx.) being generated every year. Further, this rate of spent-fuel generation will inevitably increase in the future considering the currently planned nuclear power program of Korea. At present, these materials are largely stored in temporary storage pools at plant sites, while a portion of the CANDU spent fuel is dry-stored in concrete canisters.

Thus, to realize the more efficient and effective management of spent fuel, the Korea Atomic Energy Research Institute (KAERI) has been developing a strategy for implementing an SFR fuel cycle that includes pyroprocessing, whereby spent PWR fuel can be converted into a metal fuel and recycled back into the SFRs, while the uranium removed from the spent PWR fuel can be easily disposed of as low- and intermediate-level radioactive wastes. In this cycle, the spent SFR fuel is pyroprocessed and recycled once again into the SFRs, while the Cs- and Sr-containing high-level radioactive wastes (HLW) are managed separately.

If the SFR fuel cycle with pyroprocessing is adopted successfully, Korea is expected to be able to significantly reduce its accumulated amount of spent fuel, and thus reduce the number and size of the required repositories. Moreover, large reductions can be realized in the amounts of long-lived transuranic isotopes that remain in nuclear waste, thereby reducing the time necessary for radioactive decay to more acceptable levels. This directly implies that the time frame for human responsibility in nuclear waste management could be reduced to several centuries, rather than the several hundreds of thousands of years required at present.

Other advantages include the effective utilization of uranium resources as well as enhanced proliferation-resistance for the fuel cycle as a whole.

In order to complete the SFR fuel cycle with pyroprocessing in Korea, KAERI is devoting its research efforts to developing technologies in three main areas: pyroprocessing, SFRs, and HLW disposal. The first issue of *The Advanced Fuel Cycle System in Korea* introduces these research activities that are currently underway at KAERI.

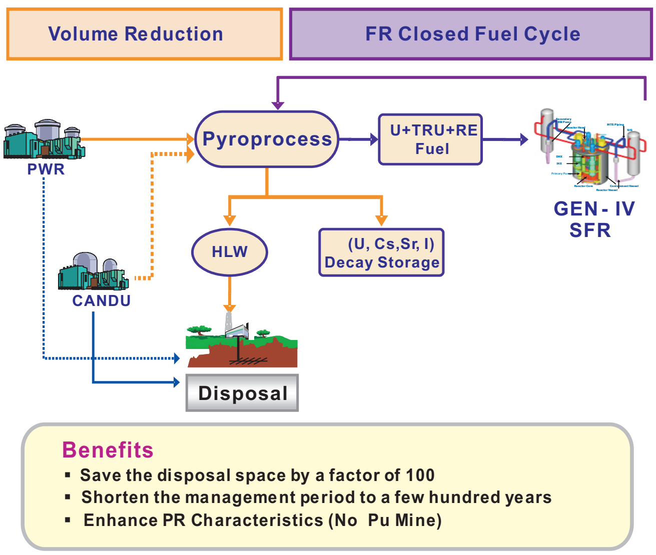


Fig 1. SFR Fuel Cycle with Pyroprocessing

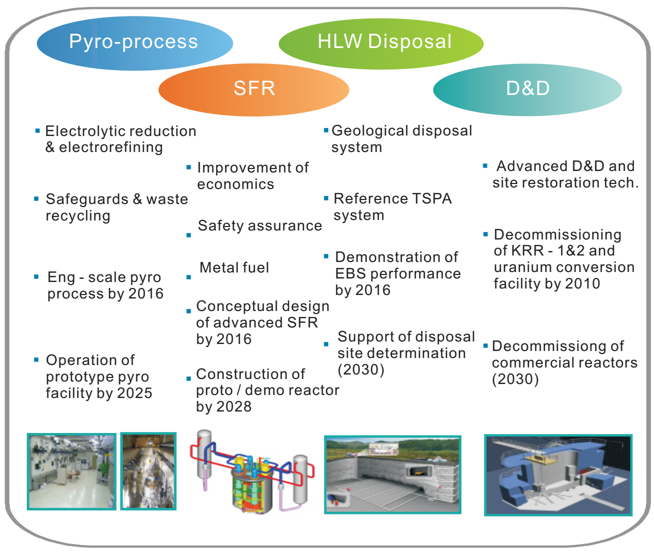


Fig 2. Major R&D Projects of KAERI

KAERI DEVELOPS A HIGH-THROUGHPUT ELECTROREFINER

Written by Jong-hyeon Lee and Han-soo Lee

1. Introduction

Pyroprocessing—a process by which actinides can be recovered from spent fuel for recycling—comprises several steps, including chopping, decladding, voloxidation, oxide reduction, and electrorefining. Among these, the electrorefining step is the most critical, since it is at this point that the uranium and transuranic elements are recovered and separated from the other materials in the spent fuel. However, for pyroprocessing to be commercialized, the electrorefining process should be scaled up to realize cost-effective production. In other words, the electrorefiner—the main device used in this process—should be suitable for mass production.

The currently available electrorefiners have several drawbacks in this regard.

A conventional electrorefiner comprises an anode basket that contains segments of a metal fuel and an iron-based cathode at which pure uranium is to be deposited. When applying the current, the uranium ion in the uranium chloride in the molten salt is reduced to uranium, which is deposited at the cathode, and the chlorine ion dissolves the metal uranium and other actinides at the anode. Thus, pure uranium can be obtained at the cathode, while the actinides remain in the molten salt and consequently enable the separation of uranium from the composite metal.

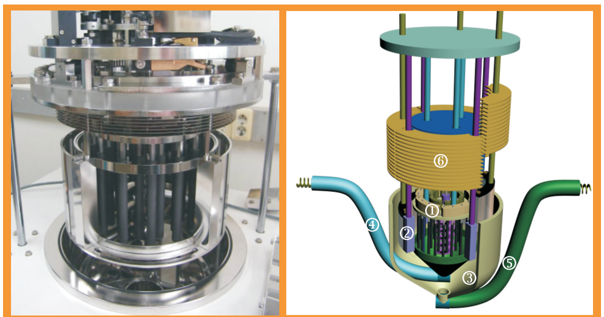
As for the product transportation after the reaction is completed, the cathode is taken away from the reactor. The deposited uranium is scraped and then transported to the next process. This procedure obstructs continuous process operation. If the product is moved away as soon as it is generated without jamming at a certain step, the throughput of the process is increased. Another point that should be noted is the treatment of transition element particles that remain in the metal fuel and finally settle to the bottom of the reactor after consuming feed material. Without any treatment of these transition element particles, they will be accumulated at the bottom of the reactor.

2. Characteristics of KAERI's High-throughput Electrorefiner

There are several different designs for electrorefiners that are currently in use: all these devices use an iron-based cathode, and thus require a mechanical scraping process and/or stripping process to collect the electrolytically deposited uranium at the cathode into a collecting basket. Such a requirement makes it impossible for these electrorefiners to provide a continuous operation, and thus they cannot produce large quantities of products in a limited amount of time.

In order to overcome the abovementioned drawbacks of the existing devices, the Korea Atomic Energy Research Institute (KAERI) has been developing a new electrorefiner concept; it is designed to provide the continuous electrolytic refining of uranium metal, allowing the collection of high-purity uranium deposits and transition element particles generated during the electrolysis process without having to stop the process.

In order to achieve the above technical objective, the KAERI electrorefiner (1) uses graphite cathodes instead of iron-based ones, (2) employs screw-type conveyors to extract the uranium electrodeposit from the high-temperature molten salt, and (3) possesses two separate collecting basins each for the uranium electrodeposit and undissolved transition element particles (Refer to Fig. 1).



① Graphite Cathodes
② Anode Basket ③ Electrolytic Cell
④ Screw-type Conveyor for Uranium Collection
⑤ Screw-type Conveyor for Transition-element Collection
⑥ Heat Shield Plates

Fig 1. Continuous Electrorefiner Equipped with Graphite Cathodes

First, by employing graphite cathodes, the KAERI electrorefiner realizes a self-scraping mechanism. As a result, the efficiency of the electrorefining process is improved remarkably. The self-scraping of the graphite cathode occurs as uranium–graphite intercalation compounds are formed on the surface of the cathode. When the gravitational force on the deposited uranium dendrites exceeds the bonding strength with the outermost layer of the elongated graphite, the self-scraping mechanism is realized.

Due to this self-scraping mechanism, the KAERI electrorefiner does not require a mechanical scraping process. In addition, a stripping process is also unnecessary because there would be no residuals stuck to the surface of the cathode after the uranium metal has been separated. As a result, the electrodeposition process can be continued for as long as the raw material is supplied to the anode basket.

Without the scraping and stripping processes, the KAERI electrorefiner is simplified, and thus a high current efficiency can be achieved by broadening the electrodes. In order to maximize the electrode area, the device also incorporates multiple graphite cathodes installed in the form of concentric circles, as shown in Fig. 1. As a result, the device supplies a high electric current, which is the key factor deciding the process throughput.

The second feature of the KAERI electrorefiner is that it employs two screw-type conveyors to withdraw the uranium electrodeposit from the high-temperature molten salt with a minimum number of rotary motions. As they are of screw form without a central axis, and by controlling their speed of revolution, the uranium electrodeposit and molten salt can be made to separate spontaneously at the free surface of the molten salt. As a result, the amount of molten salt mixed with the electrodeposit can be minimized, thereby reducing the process time required for salt distillation. Fig. 2 shows the result of a simulation using Ansys CFX with a revolution speed of 5 rpm. The simulation result shows that the molten salt remains below at a certain liquid level.

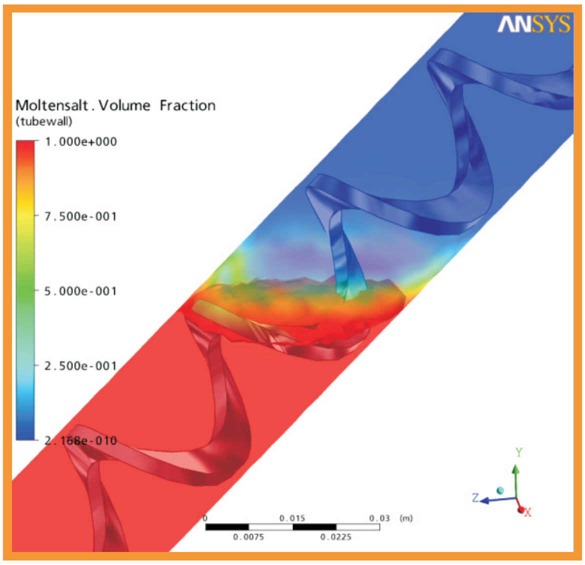


Fig 2. Screw-type Conveyor Simulation with a Revolution Speed of 5 rpm

Another feature of the KAERI electrorefiner is that, unlike other existing electrorefining devices in which the uranium electrodeposit and undissolved transition element particles are mixed in a collecting basket, it has two separate collecting basins for each product: a uranium collection basin for collecting the uranium metal deposited on to and detached from the graphite cathode at the bottom of the cathode section within the electrolytic cell and another for withdrawing the collected uranium metal from the electrolytic cell; and a transition element collecting basin coupled to the bottom of the electrolytic cell to withdraw the transition metal element particles released from the anode section and those collected at the bottom of the electrolytic cell. With this arrangement, it is possible for the KAERI electrorefiner to produce high-purity uranium by preventing the transition element particles from mixing with the uranium in the collecting basin.

3. Conclusion

By using a graphite cathode and thereby eliminating the scraping and stripping processes, the KAERI electrorefiner realizes a continuous electrorefining process. The KAERI electrorefiner also adopts a cylindrical anode basket formed by the combination of four arc-shaped baskets of quadrants; these can be individually replaced, and thus allowing the electrorefining process to run continuously without withdrawing the entire anode section from the electrolytic cell.

In addition, using screw-type conveyors and two separate collecting basins, transition element particles are prevented from mixing with the uranium electrodeposit, thereby affording high-purity uranium throughout the entire process. As a result, the efficiency of the process is remarkably improved; it is estimated that the speed of the process is 15 times greater than that of the Mark V electrorefiner.

KAERI is planning to complete a laboratory-scale electrorefining system by 2008 based on this concept, subsequently expand it to an engineering-scale system, and construct a mock-up facility by 2016 (Refer to Fig. 3).

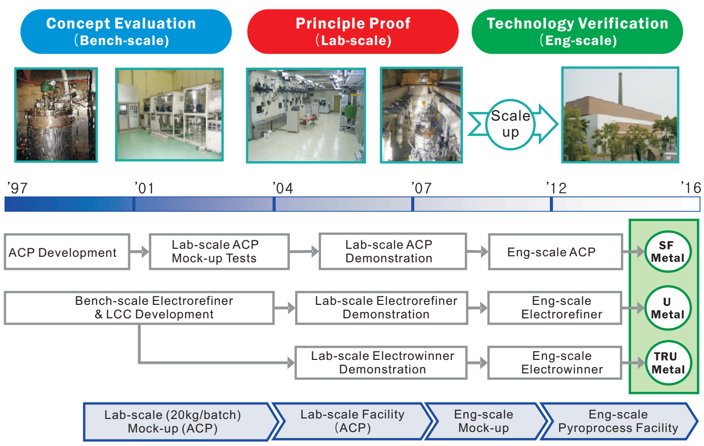


Fig 3. Milestones of Pyroprocessing R&D

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KALIMER-600: A FAST REACTOR UNDER DEVELOPMENT AT KAERI

Written by Yeong-il Kim and Do-hee Hahn

1. Introduction

As compared to PWRs and PHWRs, a sodium-cooled fast reactor (SFR) uses higher-energy fast neutrons that in turn produce a greater number of neutrons per fission. Accordingly, it can be designed as a breeder—a reactor that creates more fissile material than it consumes—and thus provide an increasing energy resource that does not require a continual supply of fissile material.

In addition, these high-energy fast neutrons are more likely to fission transuranics; long-lived transuranic radionuclides can be transmuted to stable elements or those that are less radiotoxic. Accordingly, if SFRs are used, the available uranium resources can be utilized much more efficiently—more than 100 times that with a PWR—and the radiotoxicity of the spent fuel is greatly reduced—it is less than 100 times that of a PWR*.

* The radiotoxicity of spent fuel from an SFR becomes lesser than that of uranium ore after several hundred years, while that of conventional spent fuel does so after approximately 300,000 years.

With the recognition of such advantages, SFR technology development efforts commenced at the Korea Atomic Energy Research Institute (KAERI) in 1997 as a national mid- and long-term nuclear R&D program. This led to the development of an advanced SFR concept called KALIMER (Korea Advanced Liquid Metal Reactor)-150 in 2001. Based on the KALIMER-150 design, KAERI completed the conceptual design of KALIMER-600 in February 2007.

2. General Features of KALIMER-600

KALIMER-600 is a sodium-cooled, metallic-fuel, pool-type fast reactor with an electrical power generation capacity of 600 MW. Fig. 1 shows a schematic of the configuration of KALIMER-600, while Table 1 summarizes its key design parameters.

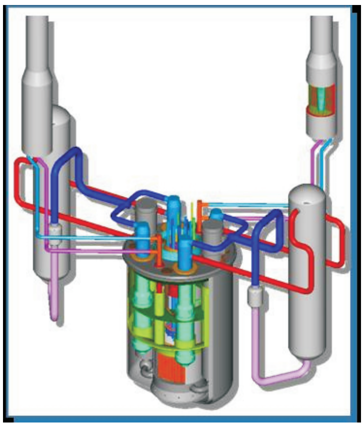

Fig 1. System Configuration of KALIMER-600

OVERALL		PHTS	
Net Plant Power, MWe	600	Reactor Core I/O Temp., °C	390.0/545.0
Core Power, MWt	1523.4	Total PHTS Flow Rate, kg/s	7731.3
Gross Plant Efficiency, %	41.9	Primary Pump Type	Centrifugal
Net Plant Efficiency, %	39.4	Number of Primary Pumps	2
Reactor Type	Pool Type	**IHTS**	
Number of IHTS Loops	2	IHX I/O Temp., °C	320.7/526.0
Safety Decay Heat Removal	PDRC	IHTS Total Flow Rate, kg/s	5800.7
Seismic Design	Seismic Isolation Bearing	IHTS Pump Type	Electromagnetic
CORE		Total Number of IHXs	4
Core Configuration	Radially Homogeneous	**SGS**	
Core Height, mm	940	Steam Flow Rate, kg/s	663.25
Maximum Core Diameter, mm	5209	Steam Temperature., °C	503.1
Metal Alloy Fuel Form	U-TRU-10% Zr	Steam Pressure, MPa	16.5
Cycle Length (EFPM)	18	Number of SGs	2

Table 1. Key Design Parameters of KALIMER-600

The foremost feature of KALIMER-600 is that strong emphasis has been placed on proliferation-resistance within its core design. By eliminating blanket assemblies, KALIMER-600 does not produce high-quality plutonium in its core, and thus substantially improves its proliferation-resistance.

Another feature of KALIMER-600 relates to its pool-type design. By adopting such a design, KALIMER-600 eliminates the possibility of coolant loss by pipe breakage in the primary system, and provides large thermal damping to the system. Accordingly, it yields a slower transient, a longer grace time in the event of an accident, and eventually increases overall plant safety.

In addition, the Passive Decay Heat Removal Circuit (PDRC), the design concept of the decay heat removal system of KALIMER-600, is extensively based on inherently passive features without any provision for active components. As a result, it provides a highly reliable heat removal capability.

The safety-grade PDRC system comprises two independent intermediate sodium loops. Each loop is equipped with a single sodium–sodium decay heat exchanger (DHX), a single sodium–air heat exchanger (AHX), the main sodium pipes that connect the DHX with the AHX, and other related instruments. The intermediate sodium pipe, designed to ensure a natural circulation of sodium and air, plays an important role in transporting the heat from the reactor pool to the AHX and in discharging the same into the atmosphere.

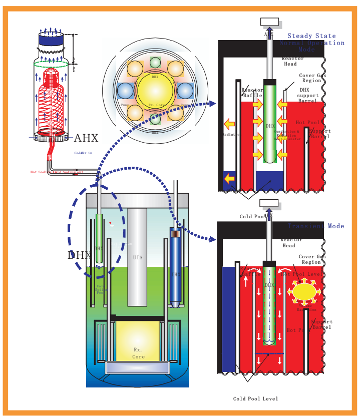

Fig 2. Decay Heat Removal Process of PDRC

PDRC is a closed loop filled with sodium; it rejects the core decay heat through the DHX and AHX. The DHX, a shell-and-tube-type counter-current flow heat exchanger, is placed at a position higher than the cold-pool free surface during normal plant operation, and thus does not directly come into contact with the hot sodium. However, when the primary pump shuts down following a reactor trip, the cold-pool level rises up to the hot-pool level, as shown in Fig. 2, and then the hot-pool sodium expands due to the accumulation of the core decay heat. The expanded hot sodium consequently overflows into the cold pool through the shell-side DHX, and comes into direct contact with the DHX.

From these passive and inherent safety design features, together with inherent reactivity feedback mechanisms, the safety of KALIMER-600 has been significantly improved, thus ensuring benign performance during anticipated transients without scram (ATWS) events without any reactor control or protection system intervention.

3. Conclusion

It has been recognized throughout the world that a fast reactor is one of the most promising nuclear options for electricity generation, affording the efficient utilization of the available uranium resources and a reduction in the amount of radioactive wastes produced by nuclear power plants. With this in mind, KAERI has developed an advanced SFR concept, KALIMER-600, which has significantly improved inherent safety features.

KALIMER-600, whose conceptual design was completed in February 2007, is expected to serve as a reference design for the future GEN-IV SFR system, which KAERI envisions to be commercialized in Korea by around 2040 (Refer to Fig. 3).

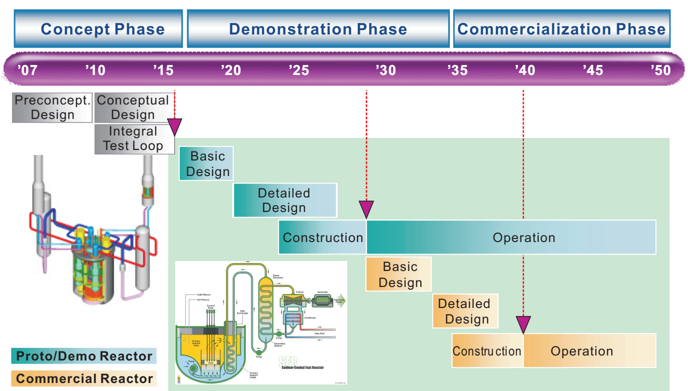

Fig 3. Milestones of SFR Development

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KAERI'S UNDERGROUND RESEARCH TUNNEL (KURT)

Written by Heui-joo Choi and Jong-won Choi

1. Introduction

The benefits offered by an SFR fuel cycle with pyroprocessing are clear; it reduces the amount of spent fuel to be disposed of, and thus reduces the number and size of the required repositories. It also reduces the amounts of long-lived transuranic isotopes remaining in spent fuel, and thus reduces the time necessary for radioactive decay.

Nevertheless, the fuel cycle does not eliminate the need for geological repositories; all countries with an active nuclear power program require a geological disposal facility. In view of this requirement, over the last 10 years, the Korea Atomic Energy Research Institute (KAERI) has been carrying out vigorous research activities on high-level radioactive waste (HLW) disposal, with the ultimate goal of developing a Korean Reference Disposal System (KRS) for HLWs.

In developing such a system, it is required to validate and demonstrate, with various in situ experiments, the safety and feasibility of the proposed disposal system. Accordingly, in 2003, KAERI began a project to construct an underground research laboratory suitable for such activities; in November 2006, KAERI's Underground Research Tunnel (KURT) was successfully completed.

2. KAERI's Underground Research Tunnel (KURT)

Located in a mountainous area inside the KAERI territory in Yuseong-gu, Daejeon, South Korea, KURT comprises a 180-m long access tunnel and two research modules with a total length of 75 m and reaching a depth of 90 m (Refer to Fig. 1). Such a depth could be obtained by locating KURT at the peak of a mountain with a steep slope and by constructing the access tunnel with a slope of –10%. In order to realize natural drainage, each of the research modules was built with a slope of +2%.

Situated in granite rock, the tunnel system, on the whole, is in the form of a horseshoe, 6 m wide and 6 m high.

Table 1. Key Design Parameters of KURT

Tunnel Geometry	Access Tunnel	Research Module
. Horseshoe Shape . 6 m Wide x 6 m High	. Length: 180 m . Slope: -10%	. Length (Left): 30 m . Length (Right): 45 m . Slope: +2% . Maximum Depth: 90 m

Fig 1. Entrance to KURT and the Two Research Modules

The geological characteristics of the site were investigated from borehole drillings and in situ tests carried out prior to the construction of KURT; these are described as follows: Underneath the 2-m thick weathered soil, a 2.2-m thick layer of weathered rock was laid. Subsequently, sequential layers of weak rock, normal rock, and hard rock were distributed. Biotite granite and schistose granite were the major rock types, while andesite dikes were encountered in some locations. The borehole drillings showed that the rock conditions improved with depth.

KAERI completed the construction of KURT in November 2006, and since then, has been vigorously carrying out research activities in this facility. The activities include studies of the following:

- Thermal Behavior of Rock
- THM Behavior of Engineered Barrier System
- Characteristics and Mechanical Stability of EDZ
- Solute Migration through Fractured Rock
- Hydrogeological and Geochemical Baseline Data

3. Conclusion

In order to safely dispose high-level radioactive wastes (HLW) in geological formations, it is necessary to assess the feasibility, safety, appropriateness, and stability of the disposal concept in an underground research laboratory with the same geological characteristics as the proposed host rock. For this reason, many countries that are considering the geological disposal of HLWs have constructed their own underground research laboratories where they can perform various in situ experiments.

KURT at KAERI, although currently operating on a small scale, will be the core infrastructure for the future R&D activities related to the HLW disposal program in Korea. As policies on spent fuel and HLW management are established and the HLW disposal program is expanded in Korea, the experience gained from operating KURT will be a great asset.

Heui-joo Choi is a principal researcher in High Level Waste Management Research Center. Email. hjchoi@kaeri.re.kr.

Calendar

2007

NOV 19~20

4th KAERI-JAEA Workshop on Safety Assessment of Radwaste Disposal
Organized by Nuclear Fuel Cycle Strategy Research Lab.
Contact : Sung-ho Lee
Tel. +82-42-868-2382
Fax. +82-42-868-2035
Email. shlee10@kaeri.re.kr

NOV 27~20

GIF SFR Advanced Fuel PMB Meeting
Organized by Fast Reactor and Fuel Development Division
Contact : Yong-bum Lee
Tel. +82-42-868-8724
Fax. +82-42-868-2075
Email. yblee@kaeri.re.kr

DEC 10~13

KAERI-CEA Workshop on Nuclear R&D
Organized by Advanced Fuel Cycle System Engineering Group
Contact : Won-il Ko
Tel. +82-42-868-2040
Fax. +82-42-868-8679
Email. nwiko@kaeri.re.kr

DEC 10~14

6th KAERI-CEA Technology Information Exchange Meeting on Decommissioning
Organized by Decommissioning Technology Development Center
Contact : Jei-kwon Moon
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Fax. +82-42-868-4797
Email. njkmoon@kaeri.re.kr

DEC 29~30

4th International Workshop on the Nuclear Material Thermo-physical Properties
Sokcho, South Korea
Organized by Fast Reactor Fuel Development Group
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Fax. +82-42-868-2403
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KAERI in Brief

KAERI and CEA Hold the 1st Joint Workshop on Nuclear R&D in Korea

The Korea Atomic Energy Research Institute (KAERI) and the French Atomic Energy Commission (CEA) held the 1st Joint Workshop on Nuclear Research and Development in Daejeon, South Korea, on December 10–13, 2007, with the objective of strengthening their bilateral and cooperative ties for nuclear R&D activities. 27 French representatives led by Y. Kaluzny, the Managing Director for International Affairs and Cooperation, visited Daejeon, while more than 70 KAERI experts attended the workshop. The topics that were covered in the workshop included PWR safety, Sodium Fast Reactor, Pyrochemistry, Material for Gas Cooled Reactors, Hydrogen Production, Decommissioning & Decontainment, and Research Reactors and Fuel.

After the plenary session, in which 14 papers were presented, the experts gathered in seven field groups for more detailed technical discussions. Potential collaborations between the two institutions were also discussed in the framework of the Specific Topical Collaboration (STC).

The two institutions agreed to hold the 2nd Joint Workshop in France in October, 2009, in parallel with the 19th ROK–France Joint Coordinating Committee on Nuclear Energy (JCCNE). Meanwhile, the field coordinators will commit themselves to assure active work in their fields by organizing appropriate technical meetings and discussions.

KAERI and CRIEPI Seek to Jointly Perform In-situ Migration Tests in KURT

The Korea Atomic Energy Research Institute (KAERI) invited 3 researchers, K. Kiho, K. Suzuki, and Y. Tanaka, from the Central Research Institute of Electric Power Industry (CRIEPI) to the 1st KAERI-CRIEPI Workshop on In-situ Migration Experiments in the Underground Research Laboratory (URL), held on September 18–19, 2007 in Daejeon, South Korea.

During this two-day workshop, the participants introduced the R&D activities carried out by their respective institutes and had technical discussions. The topics covered in these presentations included:

- Introduction of the two institutes and their nuclear R&D activities;
- KAERI Underground Research Tunnel (KURT);
- Studies of radionuclide migration, heated-rock behavior, and interaction between minerals and microorganisms;
- Results of the tracer tests performed by CRIEPI; and
- Geophysical investigation methods for the characterization of rock fractures.

The participants also discussed the future collaboration between the two institutes including co-participation in the international research program of the Grimsel Test Site (GTS) of the National Co-operative for the Disposal of Radioactive Waste (NAGRA) in Switzerland, which is regarded as one of the leading URL sites in the world. In particular, the two institutes agreed to demonstrate the acoustic tomography technology developed by CRIEPI at KURT.

KAERI Hosts a Workshop on Nonproliferation

The Korea Atomic Energy Research Institute (KAERI) and the Sandia National Laboratory (SNL) co-hosted the 3rd East Asian Nuclear Nonproliferation Workshop held on August 13–15, 2007 in Daejeon, South Korea. More than 50 nuclear and nonproliferation experts from China, Indonesia, Japan, Korea, Russia, the United States, and Vietnam gathered together and exchanged their views.

With opening addresses by Seong-won Park, Vice-President of KAERI, and Arian Pregenzer, Senior Scientist of SNL, the workshop covered topics such as initiatives to provide international nuclear fuel cycle services, the current nuclear power programs and nonproliferation policies of each country, and the technologies being developed to increase transparency and support nonproliferation efforts. Several activities were also proposed on the last day of the workshop for increased regional cooperation for enhancing nuclear safety and security. As most of the participants recognized the importance of joint efforts in this area, it was agreed that the annual East Asian Nuclear Nonproliferation Workshop would provide a significant opportunity to experts in the region for networking and exchanging views.

During this workshop, KAERI invited all the participants to visit the Advance Conditioning Process Facility (ACPF) at KAERI and, to enhance its own level of transparency, introduced them all to its various activities.

** KAERI and SNL signed an MOU in October 2006, agreeing to work together to enhance nuclear transparency in the East Asian region through regional cooperation.

Twelve US Representatives Attend the 3rd ROK-US Advanced Fuel Cycle R&D Forum

Twelve US representatives, including Alex Burkart (DOS) and Buzz Savage (DOE), arrived at the Korea Atomic Energy Research Institute (KAERI) to attend the 3rd ROK-US Advanced Fuel Cycle R&D Forum held on October 17–19, 2007 in Daejeon, South Korea. 20 representatives from Korea, including Young-shik Kim (Director General, MOST) and Seong-won Park (Vice-President, KAERI), who also participated in the meeting, exchanged information on their recent achievements in advanced nuclear fuel cycle R&D with the representatives from the US. The ongoing collaborative research projects between the two countries, such as I-NERI and KAERI-10, were also discussed at this meeting.

On October 16, the day prior to the forum, a pre-meeting was held during which all the participants were introduced to the research activities currently underway at KAERI on advanced fuels for next-generation reactors; discussions were held on the development of various fuels such as high burn-up PWR fuels, metallic fuels for SFRs and the HANARO reactor, and DUPIC, TRISO, and SMART fuels.

The ROK-US Advanced Fuel Cycle R&D Forum, held twice a year, is a venue through which the two countries exchange information and coordinate their R&D activities on the development of an advanced fuel cycle.

Delegates from KAERI Participated in the 21st Policy Group Meeting of GIF

The delegates from KAERI, led by Youn-ho Jung, participated in the 21st policy group meeting of the Generation IV International Forum (GIF) held on November 29–30, 2007 at the Hilton Hotel in Gyeongju, South Korea.

GIF was chartered in July 2001 with 9 founding members including Argentina, Brazil, Canada, France, Japan, Korea, South Africa, the United Kingdom, and the United States to develop, through collaboration, next generation nuclear energy systems to satisfy the world's future energy requirements. The 9 GIF founding members were later joined by Switzerland in 2002, Euratom in 2003, and most recently by China and Russia at the end of 2006.

The policy group, which acts as a decision-making body, meets two or three times a year to review past activities, provides guidance to the Experts Group and Systems Steering Committees, and determines future program direction.

Around 50 delegates from the 13 member countries participated in this meeting.

New President of KAERI

Myung-seung Yang was elected as the 17th President of the Korea Atomic Energy Research Institute (KAERI) on November 27, 2007.

Yang received his Ph. D. from the Department of Materials Science and Engineering at Northwestern University, U.S.A. in 1983. He received his BS and MS from Seoul National University in 1973 and the Korea Advanced Institute of Science in 1975, respectively. Since joining KAERI in 1984, he has served as the Director of the Nuclear Fuel Development Division and has led the DUPIC fuel development project.

Yang will serve his presidential term of 3 years until November 2010.

Recently Published

- Dong-keun Cho, "Characteristics of a Geological Disposal System for the Increasing Burnup of the Spent Nuclear Fuel in Korea," *Journal of Nuclear Science and Technology*, **44**, 10, 2007.
- Seok-ki Choi, "Evaluation of Turbulence Models for Thermal Striping in a Triple Jet," *Journal of Pressure Vessel Technology*, **129**, 2007.
- Jae-hyuk Eoh, "Feasibility Study of a Passive DHR System with Heat Transfer Enhancement Mechanism in a Lead-cooled Fast Reactor," *Nuclear Technology*, **160**, 2007.
- Hee-chul Eun, "Separation of Pure LiCl-KCl Eutectic Salt from a Mixture of LiCl-KCl Eutectic Salt and Rare-Earth Precipitates by a Vacuum Distillation," *Journal of Nuclear Science and Technology*, **44**, 10, 2007.
- Hee-chul Eun, "Study on the Oxidizing Reaction of Rare-Earth Chlorides ($CeCl_3$ and $PrCl_3$) in LiCl-KCl Eutectic Salt by O_2 Injection," *Journal of Radioanalytical and Nuclear Chemistry*, **274**, 3, 2007.
- Kweon-ho Kang, "Thermal Conductivity of a Simulated Fuel with Dissolved Fission Products," *International Journal of Thermophysics*, **28**, 5, 2007.
- Seung-soo Kim, "Estimation of the Corrosion Thickness of a Disposal Container for High-Level Radioactive Wastes in a Wet Bentoniite," *Journal of Industry and Engineering Chemistry*, **13**, 6, 2007.
- Sung-ki Kim, "Cost Estimation of the Canisters for an HLW Repository in Korea," *Progress in Nuclear Energy*, **49**, 7, 2007.
- Seung-woo Paek, "The Performance of a Trickle-Bed Reactor Packed with a Pt/SDBC Catalyst Mixture for the CECE Process," *Fusion Engineering and Design*, **82**, 2007.
- Tae-hoon Lee, "Preliminary Calibration of the ACP Safeguards Neutron Counter," *Nuclear Instruments & Methods in Physics Research Section A*, **580**, 2007.
- Yoon-sub Sim, "Development of a New Decay Heat Removal System for a High Temperature Gas Cooled Reactor," *Annals of Nuclear Energy*, **34**, 2007.
- Hee-chul Yang, "Kinetic Study of a Thermal Dechlorination and Oxidation of Neodymium Oxychloride," *Thermochimica Acta*, **460**, 2007.

Welcome to our Newsletter
The Advanced Nuclear Fuel Cycle System in Korea

A Message from Seong-won Park, Chief Editor

The nuclear energy program in Korea has steadily grown since the first commercial operation of Kori 1 in 1978. As of December 2007, a total of 20 nuclear power plants are in operation. Their generating capacity is about 18,000 MWe in total, which accounts for about 40% of the total electricity production in Korea. According to the Korean government, 8 new nuclear power plants will be constructed by 2020, bringing the total to 28. The total generating capacity will then increase to 27,300 MWe, which will account for about 44% of the total electricity production in the country.

In order to continue to benefit from nuclear energy, however, it is necessary for Korea to establish itself in the international community as a responsible and peaceful nuclear nation. Such confidence-building could start with, among other things, sharing information with other interested parties.

Toward this end, Sustainable Nuclear System Development, a department of the Korea Atomic Energy Research Institute (KAERI), has begun to issue a newsletter to provide information on its research activities to experts, decision makers, and the general public. In doing so, *The Advanced Nuclear Fuel Cycle System in Korea* would like to be of service to our country in maintaining its principle of nuclear transparency, even if it is only in this small way.

It is our hope that *The Advanced Nuclear Fuel Cycle System in Korea* will provide you with timely and useful information on our research activities, which are aimed at expanding the role of nuclear energy in our future.

Welcome to our newsletter, *The Advanced Nuclear Fuel Cycle System in Korea*; please enjoy.

The Advanced Nuclear Fuel Cycle System in Korea is published by the Korea Atomic Energy Research Institute (KAERI), 1045 Daedeok-daero Yuseong-gu, Daejeon 305-353 SOUTH KOREA.

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The Advanced Nuclear Fuel Cycle System in Korea, published quarterly by Sustainable Nuclear System Development, a department of the Korea Atomic Energy Research Institute (KAERI), is devoted to providing information on its research activities to experts, decision makers, and the general public. It is distributed without charge to readers who prefer a hardcopy; written requests should be addressed to newsletter@kaeri.re.kr.

Inside this Issue