Closing the Fuel Cycle
Prof. Myung Seung Yang, Institute of Energy and Environment Youngsan University, Republic of Korea

Berta Oates
We're just getting set up for the next webinar for the Gen IV International Forum or GIF webinars. We welcome everyone. Thank you for joining us today. Doing today's introduction, Patricia Paviet. Dr. Paviet is the Chair of GIF Education and Training Task Force, responsible for bringing you these webinars. She is also the Director within Department of Energy, Nuclear Engineering Office of Materials and Chemical Technologies. Without any further ado, I'll turn the time over to Patricia Paviet.

Patricia Paviet
Thank you so much Berta. It's really a great pleasure to have Professor Yang today giving a webinar on 'Closing the Nuclear Fuel Cycle.' Professor Yang graduated from the Seoul National University with a Bachelor of Science in Metallurgical Engineering in 1973, and from Northwestern University with a Ph.D. in Material Science and Engineering in 1984. He has been working at the Korean Atomic Energy Research Institute for 30 years on the research and development of PWR/CANDU fuel fabrication, quality control of fuel, DUPIC cycle, and the pyroprocessing. He gained his experience in nonproliferation while participating to the GIF Proliferation Risk and Physical Protection activity as well as the International Project on Innovative Nuclear Reactors and Fuel Cycles activities.

He served as the President of KAERI from 2007 to 2010 and he is a member of the National Academy of Engineering of Korea. He is a Professor at the Institute of Energy and Environment at Youngsan University of Republic of Korea since 2015. He received a decoration 'Woong-Bee Order' from the Korean government in 2011, and a World Nuclear Association in 2009 for his contribution to the peaceful use of nuclear energy.

Without any delay, I give you the floor Professor Yang. I really thank you for volunteering to give this GIF webinar and I'm ready to listen to you. Thank you, Professor Yang.

Myung Seung Yang
Okay. Thank you, Patricia, for the nice introduction. And hello, everyone. And I am Myung Seung Yang and it is my great pleasure to have an opportunity to participate in this webinar. The topic I am going to talk about today is Closing Nuclear Fuel Cycle. Closing the nuclear fuel cycle means the use of spent fuel to make the recycling of spent fuel many,

many times possible. So, I am going to use the word used fuel instead of spent fuel because it can be reused, not just discarding as always.

The outline of my talk is I will explain the concept of nuclear fuel cycle first. Then I will explain the characteristics of the spent fuel and how they will affect the management of the spent fuel. Then I will explain briefly the nuclear fuel cycle technology. Since there are so many spent fuel reuse technology, I will just explain the basic concept of the most representative reuse process, the PUREX process for wet processing and the pyroprocess for the dry processing. And then I'll talk about the additional important area to be considered, that is international nonproliferation and the safeguard activity.

Since we are talking about nuclear fuel, we have to look at the nuclear reactor system first because there are different types of nuclear fuel depending on various types of a nuclear reactors. This slide show schematically the nuclear power reactor system of PWR, pressurized water reactor. PWR is the most popular power reactor system in the world. It consists of the pressure vessel where the nuclear fuel is located and the pressurizer to pressurize the cooling water and reactor coolant pump to circulate the coolant and the steam generator.

This red colored system is called a primary loop cooling system and the heat of the primary loop will be transferred to the secondary loop, secondary loop cooling system as the steam generator. So, water in the secondary loop are converted to the steam in the steam generator and that steam is supplied to the turbine to generate electricity. The secondary loop cooling system is colored as green. And after that, the steam is cooled down a condenser by the still [ph] water and it is recirculated to the steam generator and this is called a tertiary low cooling system, which is colored blue.

The nuclear reactor can be classified based on the level of neutron energy; level of neutron is used for the fission. For example, it is using thermal neutrons, that is energy of neutron is less than 0.1 electron volts, then that is thermal reactor. And if it is using high energy fast neutrons, then it is called fast reactor. Also, the reactor can be classified by what kind of moderator is used. If it is using normal water, then it is called a light water reactor like a PWR and the BWR reactor. And if it is using heavy water reactor, then it is called heavy water reactor like CANDU reactor. And if it is using graphite, then it is called the graphite reactor. Also it can be classified by the coolant. If it is using light water, then it is the light water reactor; if it is using heavy water, then it is heavy water reactor. And if it is using liquid sodium or lead, then it is called the liquid metal reactor. And if it is using helium gas, then it is called the gas cooled reactor.

Depending on what kind of moderator and coolant are used, the type of nuclear fuel is determined. For example, for the light water reactor, the fuels are based of enriched uranium oxide, the content of uranium-235 in the fuel is about 5%. And for the pressurized heavy-water reactor like CANDU reactor, the fuels are based of natural uranium oxide. That means, the content of uranium-235 is just 0.7%. And in case of liquid metal reactor like sodium-cooled fast reactor, the fuel can be made of mixed oxide uranium and plutonium, which is called the MOX fuel. And moreover, the fuel for SFR also can be made of metallic [ph] form which is based of metallic alloys of uranium, plutonium and other transuranic elements.

This slide shows the concept of nuclear fuel cycle. In this slide, the nuclear fuel cycle for PWR is shown as an example. The fuel cycle start from the uranium mining and after the uranium ores are mined, the impurities are removed at the milling and refining process and then the pure uranium nitrate called yellow cake and uranium oxide are supplied to the conversion plant. And at the conversion process, the uranium oxide is converted to the uranium fluoride form. Then at enrichment stage, the uranium fluoride is changing to the gaseous form by heating. Then by using this uranium fluoride gas, the isotopic content of uranium-235 can be created up to 5% to be used for the nuclear fuel. The enriched uranium fluoride is reconverted to enriched uranium oxide at the reconversion plant. Then the enriched uranium oxide is fabricated at the nuclear fuel assembly by using powder metallurgy technique, co-nuclear [Unclear] and with other structural tests.

Then nuclear fuel assembly are loaded to the nuclear reactor and burned at Reactor IV for around 3 years to generate electricity. And the process test from uranium mining to fuel fabrication before loading to the nuclear reactor is called front end fuel cycle. And after 3 years of burning in reactor, the fuels are discharged from the reactor as a spent fuel. The fuel content is called as used fuel. And the process test from the discharge of the fuel from reactor and the following processes are called as the back end fuel cycle. In the back end fuel cycle, there are various ways to treat the spent fuel.

The simplest one is the spend fuel is stored at the interim storage facility for a period of time, then the spent fuel is buried under the ground at the high-level waste disposal site. And this type of fuel cycle is called once-through fuel cycle or open fuel cycle. And the other way is the spent fuel from the interim storage is moved to the reprocessing facility.

And at the processing, the remained uranium and the newly produced plutonium are recovered from the spent fuel and then the plutonium is fabricated as the plutonium building mixed oxide fuel or TRU fuel, and which will be given at the reactor. And after the plutonium building fuel is re-burned at reactor, the spent MOX or TRU fuel will be again reprocessed to remove the impurity and to recover the uranium and plutonium and which will be again re-fabricated as a fuel. So theoretically, this type of the recycling is possible for the several times. So, this type of fuel cycle is closed fuel cycle.

This slide shows schematically several examples of the possible fuel cycle alternatives. Regarding back end fuel cycle, theoretically, many, many fuel cycle alternatives are possible. They say more than 60 fuel cycle alternatives are possible. But there are two main routes, one is dry process route and the other one is wet route. And first one is, the spent fuel will be treated by the wet process called PUREX process to recover the remaining uranium and plutonium. Then the recovered plutonium is fabricated as a MOX fuel. And also for the recovered uranium, it will be converted to the fluoride form and it needs to be to be used as uranium fuel for the PWR reactor.

The second one is the spent fuel will be treated by the dry process called the pyroprocessing to retrieve the remained uranium and plutonium with other TRU material. And then the uranium and the TRU materials will be fabricated as fuel for the fast reactor like sodium-cooled fast reactor. And the other possible way is PWR fuel is directly re-fabricated for the fuel of heavy-water reactor like CANDU. The content of the fissile material in the spent PWR fuel is large enough to be used in CANDU reactor, whose fuel is based natural uranium and this process is called the DUPIC process.

The other option is the spent fuel is treated by dry process to recover the transuranic material with fission product like iodine and technetium and then the material is fabricated as a target for the accelerator-driven system. At the accelerator-driven system, the long-lived fission product will be translated to the short-lived element. So, this will be beneficial for the management of hazardous long-lived fission product. So, this is called HYPER system. HYPER stand for Hybrid Power Extraction Reactor.

When we are dealing with the nuclear fuel cycle, one important issue is nuclear nonproliferation. So, for the enrichment process in the front-end fuel cycle, since the highly enriched uranium can be used for the nuclear weapon material, the enrichment process is the internationally sensitive area. And for the reprocess of test, in the back end fuel cycle, the pure plutonium can be used for the nuclear weapon material. So the reprocessing process, especially which can produce the pure plutonium is also internationally sensitive area.

This slide shows the typical example of the composition of the spent fuel. Surely, the spent fuel has various compositions depending on the initial enrichment level and the born history at reactor. In case of 4.5% U-235 enriched fuel which is burned up to 55 gigawatt, then the composition of spent fuel will roughly look like this.

So, fresh nuclear fuel is made of 100% pure uranium. But in the spent fuel, 94% of spent fuel is composed of the remained uranium. So, it means only about 6% of uranium is burned in the reactor. And during the burning, the uranium is converted to the plutonium and the amount of plutonium is about 1% and 0.2% of spent fuel is the minor actinide elements such as neptunium, americium, curium and so on. And the plutonium and the minor actinides element are called TRU elements. That means transuranic elements.

During fission, various fission products are produced. And among them several elements need special attention. Iodine and technetium has the long half-life. They are long lived fission products which need long period of special care for the permanent disposal. And the amount of these long lived fissions products are about 0.2%. And some fission products like cesium and strontium has the high decay heat which also need special care for the permanent disposal. And the amount of high decay heat elements are about 0.5%. And the remaining fission product has a short half-life of less than 300 years and it amount is about 4%. So, therefore, for the best management of spent fuel, we need to close the fuel cycle. That means, reusing the remaining fissile material in the spent fuel and that means the 94% of remained uranium and 1.3% of TRU material will be recovered and recycled in the reactor.

About 5% fission product will be separated and especially treated and disposed permanently at the depository site.

This slide shows the amount of decay heat generated which decreased as time passed by. When nuclear fuel is irradiated in reactor, the elements become unstable. So, they tend to be changed to the stable state by emitting heat. And we call this as decay heat. And the amount of decay heat and it's change of time is very important factor for the permanent disposal of spent fuel. The decay heat is the catalyst of spent fuel; that is, even though nuclear fuel is discharged from reactor, the spent fuel will generate decay heat. So, spent fuel should be cooled down for a period of time. For example, in case of uranium, the amount of decay heat is 0.1 watt. It's quite small. But it doesn't change much with the time.

But in case of praseodymium [ph], the decay heat is about the 5000 watt. It is quite large, but it is decreasing quite fast. So, it will be almost zero in 20 years. And in case of plutonium, the decay heat is around 200 watt and it is relatively large and it lasts a very, very long time. So, it is needs almost 1 million year to be cooled down.

Collectively, the change of decay heat from all the fission products are shown in this red curve. It shows that the decay heat from the fission product will be cooled down in about 300 years. And the change of decay heat from all the actinides including plutonium and americium et cetera are shown in this blue curve. The initial decay heat is large, about 1000 watt and it lasts about 1 million year to be cooled down.

So, the change of the grand total value of decay heat are shown in the black curve. The initial value is large and also it also lasts very, very long mainly because of TRU elements. So, therefore, this fact is the region why we need to reprocess the spent fuel; that is, the actinide elements are separated from the spent fuel and they will be burned at the fast reactor. And if the TRU elements are removed from the spent fuel, then it will only need about 300 years to cool down the decay heat.

This slide shows the comparison of the radiotoxicity with that of natural uranium. For the spent fuel, which contains the plutonium, minor actinides and all the fission products, the value of radiotoxicity is about 1000 times larger than that of natural uranium and it takes about 300,000 years to decrease to that of natural uranium level. And for the materials which contains minor actinide and fission product without plutonium, it takes about 15,000 years to become natural uranium level. And for the materials which contains only fission products without plutonium and the minor actinides, it will take about 300 years. So, this time to decrease the radiotoxicity to the natural level is the time period for which we need to manage the permanent waste disposal site. So, if spent fuel is not treated at all and directly disposed, then waste disposal time needed to be managed over 300,000 years. But if all the TRU materials are partitioned, then we need about 300 years for the disposal site management. And this is why we are developing the advanced fuel cycle to remove the TRU elements and to use them by burning a fast reactor. So, that is to close the fuel cycle.

Regarding the interim storage of the spent fuel, when the spent fuel that discharged from reactor, they are normally stored under the water for about 10 years to cool down the decay heat. Then after 10 years of wet storage, they can be moved to the dry storage canister to store them more economically.

Eventually, the spent fuel and high-level waste will be moved to the repository for the permanent disposal. And this slide shows the typical example of permanent disposal site. On surface, there are encapsulation and the bentonite plant to seal the radioactive waste, and the other service facility. And under the ground, there are vertical shaft for service activity and the ventilation and there are horizontal tunnels to store the intermediate [ph] waste safely for long periods of time.

When we select the permanent disposal site like this, there are some special consideration needed. They are, how will the prolonged exposure to heat and radiation from the waste affect the surrounding rock. So that is, the long-term integrity of the engineering and the natural barriers on the high radiation and heat environment is important. So, we should consider radiation shielding of the canister and the maximum allowable thermal loading of the disposal package.

The second point is, how soon will the repository be filled with groundwater; that is, the prevention of groundwater intrusion. So, this requires the selection of buffer and backfill material with low permeability. And third thing is, how fast will the disposal canister corrode? So, this requires that the canister is based on high-corrosion resistant material like copper, titanium, stainless steel, etcetera.

The fourth point is, how fast will the various radionuclides dissolve and how will the dissolved substance travel through the rock. So, the groundwater movement in the rock is an important factor. So, considering the long-term integrity and the safety of the disposal, it is not easy to select the proper waste disposal site in terms of engineering viewpoint. Moreover, it is also not easy to get the public consent and acceptance. So currently, many countries, including South Korea have such a challenge to select the waste disposal site.

So, this is another reason why we need to develop the advanced fuel cycle technology to close nuclear fuel cycle in purpose of to reduce the amount of radioactive waste and to reduce necessary area for the permanent disposal of the spent fuel, and to decrease the time period needed to manage the final disposal site.

In the first half of 2000, there are some international efforts to develop innovative nuclear energy systems. The main activities are led by the GIF and IAEA. The objective of this effort for innovative nuclear systems are to improve the sustainability and for the optimal waste management and environmental effect and improving the economics and also enhancing the proliferation resistance.

This slide shows the basic requirement of the advanced fuel cycle. For the environmental aspect, we need to reduce the environmental burden by reducing the radiotoxicity of spent fuel. So, the target is the decay time of spent fuel to the toxicity level to natural uranium should be less than 300 years. And for the waste aspect, it will minimize the required repository footprint. That is, by reducing the heat load of waste by 100, the necessary repository footprint also can be reduced by 100.

And for the proliferation risk aspect, the proliferation resistance can be enhanced by recycling all the TRU material together based on the concept of so-called dirty fuel-clean waste. And for the economic aspect, the new technology should be economically compatible with the current technical options.

Even though a lot of technology alternatives are proposed for the treatment of spent fuel, it can be classified roughly by two methods. They are wet processing routes like to PUREX and dry processing routes like pyroprocessing. And I'm going to explain this process in more detail in the following slides. The product from the PUREX process can be used for the PWR and the Gen IV reactor as a MOX fuel and product from the pyroprocessing can be used for the fuel of Gen IV reactor as a metallic fuel.

One of the interesting concept is DUPIC. So where the spent PWR fuel will be directly re-fabricated as a fuel for the CANDU type reactor. So, this is a typical example of the concept so-called the dirty fuel-clean waste. So, in past we tried to make a nuclear fuel with high purity material in order to attain high burnup and for ease of fuel management. But this produced hazardous radioactive waste. So recently, we tried to make a fuel with uranium and TRU element and they will be burned at the reactor. So in this way, we can make easy to manage the clean radioactive waste. So, this slide show the process flows of each reusing process.

This slide show the overall process flow of wet reprocessing like PUREX process. So it composes of six areas. So, first is receiving the spent fuel cask and they will be stored under the water. And second is disassembling, chopping, and dissolving area. So here, the fuel assembly is chopped to the small piece and they will be dissolved in the nitric acid. In this process uranium, plutonium and some fission products are dissolved in the nitric acid, but metallic parts like cladding tubes are not dissolved. So, this kind of solid metallic part can be separated from nitric acid through a solution. And those are called head end process.

Third area is the separation area. So, here it will separate uranium and plutonium solution from the fission product by using solvent extraction. Then by using the uranium and plutonium mixtures, which are free from fission product, plutonium can again be separated from uranium by solvent extraction.

And the fourth area is the purification area, so it is to purify separated uranium and plutonium from remaining impurity by using solvent extraction. And fifth area is denitration area. So, it is to denitrate the uranium and plutonium nitrate to produce pure uranium and plutonium material. Then uranium and plutonium is converted to oxide for storage.

So, this slide shows the main equipment and its function in the PUREX process for the disassembly and the chopping of the fuel mechanical and laser method can be used. And dissolving is to dissolve the fuel material in nitric acid. And here the fuel material can be separated from the structural path. And during this process, radioactive gases will be released from the fuel. So, this off-gas treatment by adsorption columns and HEPA filter is also important area. And uranium-plutonium extraction and purification can be performed by solvent extraction method by using equipment like mixer-settler and pulsed column. Then sure uranium and plutonium material can be produced by the denitration using evaporator. And along with these processes, the radioactive process waste treatment is also very important. So, the waste is the volume reduced by evaporator and the compacter and then it will be solidified by the cementation and vitrification.

This slide shows the basic concept of solvent extraction, which is commonly used in the originally chemical plant. So, that is, solvent and fuel solution with the fission product will be mixed together. Then undissolved fission product will be settled town to the bottom part. And the uranium and plutonium, which are dissolved in the solvent will be located at the upper part. In this way they can be separated from each other. So, in this process, the most popular process equipment used is mixer-settler or pulsed column.

And this type of mixer-settler can be arranged in series to repeat the mixing and the settling process to achieve higher purity. The pulsed column has very similar function regarding the mixing and settling by pulsing.

So, nowadays PUREX processes is well developed and commercialized by the five weapon states, Japan, and India. By using PUREX process, uranium and plutonium oxide mixed fuel called MOX fuel can be fabricated and it can be used at current light water reactor and this is called pu-thermal recycling. However, nowadays more advanced wet reprocessing is under development to improve the economistic proliferation resistance and the volume reduction of the high-level waste. That is, by producing the uranium and the plutonium with the other long-lived nuclides together and by burning them in fast reactor, they can be transmitted to the short-lived element for the environmentally friendly recycling.

Also, by recovering uranium and fissile element like plutonium in the spent fuel and burning them, we can improve the uranium utilization by completely closing the nuclear fuel cycle. Moreover, by partitioning the long-lived nuclide and the highly heat-generating element from the waste, we can improve the efficiency of permanent waste disposal by reducing the volume of high-level waste and by shortening the management period of permanent disposal time.

Several advanced wet process are under development, such as co-decontamination and actinide-lanthanide separation process to separate uranium-plutonium and the TRU together in the USA. And NEXT process development to separate uranium-plutonium-neptunium in Japan. And COEX process development to separate uranium-plutonium together in France.

So mainly, the objective of these technology developments are to improve the recovery of TRU, cesium, strontium, which are high decay heat element and also long-lived fission element, and to reduce secondary process waste amount and to co-separate uranium, plutonium, minor actinide, and actinide-lanthanide partition, and to use the eco-friendly salt-free solvent. So, these researches are nowadays performed under the GIF program.

This slide shows the one example of nuclear fuel cycle strategy, which can be used for some countries with heavy-water reactor like CANDU and the fast reactor like sodium-cooled fast reactor. So, the spent PWR fuel can be directly fabricated as a DUPIC fuel to be used as a CANDU reactor. And also spent PWR can be treated by the dry pyroprocessing to produce the metallic fuel based of uranium and TRU element and zirconium. Then they will be used as a fuel for the sodium-cooled fast reactor. And in this way, we can save the permanent disposal space of the waste and it can improve the uranium utilization. And also this dry process has intrinsic proliferation resistance.

This slide show schematically the process flow of the DUPIC fuel fabrication. So the spent PWR fuel is disassembled and cut to small pieces and they are decladded by mechanical and formal method. Then the spent fuel materials are treated by a series of oxidation and reduction to make the fuel powder soft and porous and resinterable. And once the resinterable powder is prepared, then the remaining fabrication process is same as a typical standard fuel fabrication. So, this contest has improved at the level [Unclear] scale and the performance was evaluated by the evaluation at the research reactor in cooperation with South Korea, Canada and the USA. But it has not been commercialized.

This slide shows the case studies of the dry processing method. So, there are several dry processing technologies. So, the pyro-metallurgical process is developed for the metallic fuel fabrication at the EBR-II program in the USA in early 1950s. And the pyro-chemical process are under development in South Korea, USA, China, India, Russia, etcetera. And flouride volatility process are mainly for treating the research fuel. So, the dry process has high proliferation resistance because it does not separate plutonium. And fuel with mixture of uranium, plutonium and the minor actinides can be fabricated and to be used as the Gen IV type reactor.

This slide shows the closed fuel cycle for the pyroprocessing linked to the sodium fast reactor. So, at first, the PWR spent fuel is disassembled, then the spent material will be located at the cathode basket. And anode is made of platinum. Then electrolytic reduction will take place in the molten salt. And uranium and TRU oxide will be reduced to the metallic form here. So, next stage is electro-refining process. Here the metallide uranium, plutonium, and the minor actinides and the fission products are placed at the anode. And the here uranium will be recovered at the solid cathode and the TRU and the fission product and residual uranium will be dissolved in the salt. And next process is electrowinning process. So, by using the liquid cadmium as the cathode, uranium and TRU material in the salt can be recovered at the cathode. Then cadmium will be distillated, then recovered uranium and TRU material can be used for the sodium-fast reactor fuel fabrication. So, by using the spent fuel in this way, the uranium utilization can be increased by a factor of 100 and also the volume of the high-level waste can be reduced. And moreover, as the sodium fast reactor can burn the long-lived TRUs, it can reduce the radiotoxicity with decreasing time. And this means, we can shorten the management period of the geological repository to a few hundred years. In this pyroprocessing, there are no stream of pure plutonium separation and the product is mixture of uranium and TRU material. So, this process can be considered as the highly proliferation resistance.

This slide shows the material flow in the pyroprocessing. So, the spent fuel is disassembled and those elements are cut to smaller pieces, then the last cut are decladded by mechanical and the thermal method. And then recovered fuel materials are subject to the high temperature treatment to get rid of off-gas like iodine, krypton, and xenon. Then the oxide material composed of uranium, TRU and the fission product reduced to the metallic form at the electro reduction process. Then the metallic uranium, TRU, noble metal and rare-earth elements are treated by the electrowinning to recover uranium. And they are treated by the uranium refining to recover the uranium and treated by the electrowinning to recover the TRU material. Then the uranium and TRU material will be used for the sodium fast reactor fuel fabrication. And then the spent SFR fuel will again be recycled in this way to close the fuel cycle.

This slide shows one example of chemical reaction in the electrolyte reduction. So, the reaction occurs at the cathode. It’s for the reduction and the reaction at the anode is for the oxidation. After this electro-reduction process, the uranium and TRU elements like plutonium, americium, curium, neptunium, and noble metal like zirconium and palladium will be reduced to the metallic form.

But rare-earth elements like Yttrium are not reduced and the alkaline materials and alkaline-earth material cesium and strontium will be remained in the salt.

This slide shows contextual comparison of this wet and dry recycling. So, regarding the complexity of process, that means the compactness of the process, pyroprocessing is rather compact. And for the cooling time needed for the spent fuel to be processed, PUREX process requires more than 5 years cooling to be treated, but pyroprocessing can process spent fuel that is just cooled in about 1 year. And regarding the criticality hazard, the PUREX process has high criticality because you use the wet process. And PUREX process can separate the pure plutonium. But in case of pyroprocessing, the separation of pure plutonium is rather difficult. However, the pyroprocessing is just under development in the laboratory scale and while the PUREX is already commercialized in the world. Moreover, the pyroprocessing is producing more process waste and it is basically wet type process. So, it needs more development for the large scale production. So, currently, there are R&D efforts to improve the pyroprocessing. The research objectives are, for the process development, it is to develop high throughput process and to develop corrosion resistance material. Second is, for the process waste minimization by recycling the used salt. Third is to improve the safeguardability by developing near real-time accounting technique and design improvement of the facility design stage. And to improve the economic feasibility by the process modeling and to have the integrated engineering-scale demonstration.

When we are dealing with nuclear fuel cycle, one important issue is nuclear nonproliferation. So, from the beginning of IAEA, the international efforts were made to encourage peaceful use of nuclear energy while ensuring prevention or diversion of nuclear technology. So, nuclear nonproliferation regime means the system to prevent the divergence of peaceful use technology for military use and to prevent the nuclear weapon test to improve it. So, the latter is called vertical proliferation and former is called horizontal proliferation; that means, increasing the number of countries using nuclear weapons.

So, for the prevention of the horizontal proliferation, there are various preventive measures like safeguard, and export control and physical protection. And among them, safeguard measures play most important role.

The safeguard can be defined as all the activity that impede the diversion of undeclared production of nuclear material. So, it’s composed of material control and accounting and containment and surveillance. And IAEA inspection including recording, reporting, and verification is also important activity. Moreover, when we develop new fuel cycle technology, we have to better consider the safeguardability of the process in advance to make the process easy to be safeguarded. The safeguardability is defined as the degree of ease with which IAEA technical objective can be met in cost effectiveness and to establish facility whose process design layout supports the effective and efficient implementation of IAEA safeguard.

The pyroprocess has rather a lower proliferation potential compared with other fuel cycle technology because it has limited capability in separating pure plutonium. And also it has less flexibility in changing the product purity and throughput and the high dose of uranium and TRU product requires additional radiation shielding, so it makes the diversion very difficult. However, it needs more development to solve safeguard challenges for the pyroprocessing. So, the first is there are less experience for the safeguard practice because there are no commercial scale pyroprocessing facility yet. And second is there are larger measurement uncertainty of feed, product, waste and process materials. And third is, sampling procedures including destructive analysis and the non-destructive analysis and the process parameter are not well established yet. And moreover, current signature and indicator of IAEA physical model are needed to be updated for the pyroprocessing application.

So therefore, in parallel to the process technology development, the safeguard R&D has better be performed simultaneously. So, the R&D area for the safeguard of the pyroprocessing are to develop the nuclear material accounting and surveillance technology and to design the safeguard system based on the concept, so-called, Safeguards-by-Design. And to investigate the safeguardability of pyroprocessing facility.

This slide shows some examples of safeguard R&D. So, safeguard neutron counter is to measure with the amount of sensitive material in non-destructive method. And this is passive neutron coincidence counter with a full remote maintenance capabilities. And another one is containment and surveillance system development. This containment and surveillance monitoring data is transmitted to the regulatory body and the IAEA through virtual private network.

Another example is to develop laser induced breakdown spectroscopy monitoring system. So, this is to determine the elemental composition of samples through real-time analysis. And by using this system, the *in-situ* measurement and multi-element analysis will be possible.

Before making a decision to invest or deposit, we need to perform the economical analysis of the fuel cycle. So, dynamic behavior of nuclear energy system economics was performed by comparing the total system cost for the once-through fuel cycle with those for the closed fuel cycle associated with pyroprocessing and SFR. So, the tentative study results shows that, for example, regarding the total system costs, the closed nuclear energy system is a little bit more expensive than that of once-through system. But regarding the fuel cycle costs only, the once-through fuel cycle is expected to increase the cost of electricity by about 7% compared to that of the closed fuel cycle. However, the levelized cost distributions of the two nuclear systems is very similar because of large cost uncertainties involved with all the system steps. So it requires further technology development and the demonstration on the engineering-commercial scale basis in order to prove the cost saving for the closed system.

This slide shows some representative comparison of nuclear fuel cycle policy of the major countries in the world. For example, in Korea, the fuel cycle policy will be determined later, so-called we are in the wait and see stage. So that means it will be decided later considering the result of current ongoing pyroprocessing research. Then, the demonstration research will be completed by the end of the 2020 and recycling would propose this combining the pyroprocessing and the sodium-cooled fast reactor with metallic fuel. For Japan, they are using the wet processing with sodium fast reactor with oxide fuel. So, for the other countries policy, the details are shown in this slide.

In summary, the closing fuel cycle has many benefits like sustainability by reusing remaining fissile materials and benefit for high-level waste management by reducing the volume and the radiotoxicity and the benefit of environmental protection. It also helps to cope with the challenges to find the permanent disposal site by reducing its required repository footprint and the management period. And along with commercialized wet processing route, the advanced wet process and dry pyroprocess technologies are under development to recover uranium and the TRU elements together and to reuse them in advanced Gen IV fast reactor.

And safeguards technology development is also important for the closing fuel cycle because closing fuel cycle deals with active nuclear material. National policy for the fuel cycle and spent fuel management will be decided based on the progress of current R&D effort. So thank you for the attention. This slide shows the upcoming webinars. So, thank you.

Berta Oates
Thank you Professor Yang. The upcoming webinars. In November we have an Introduction to Nuclear Reactor Design by Dr. Claude Renault from France, in December a Sodium-Cooled Fast Reactors presentation by Dr. Robert Hill in the USA. And in January a Very High Temperature Reactors presentation by Dr. Carl Sink also from the USA.

If you have questions for Dr. Yang, please go ahead and type those into the chat pod now and we will take as many of those as we have time for. Professor Yang, do you see the first question, I see is.

Myung Seung Yang
Yes. The first question is, are there currently any plans to use MOX fuel in commercial reactors in the USA? So, I think we have better answer that question.

Berta Oates
I am sorry.

Myung Seung Yang
So, the first question is from Dr. Litman, but I think that question is, are there any currently plans to use MOX fuel in the USA? So, I think you have the better answer that question for me.

Patricia Paviet
Yeah. Okay. So, this is Patricia Paviet from DOE and now for the moment there is no plan to use mix oxide fuel in the US.

Berta Oates
Dr. Litman also has a question about cesium-137, strontium-90, americium-241.

Myung Seung Yang
Yes, I think that question is better answered by Patricia. Right.

Patricia Paviet
Okay and I don't see the question Berta. Okay, I see it now. Cesium, strontium, americium are radionuclide waste from the fuel cycle that have many beneficial uses. Are there any current or planned program to attend the recovery? Okay, in the United States until 2008, we developed the UX process where there was a plan to extract cesium and strontium. But unfortunately, when you go from R&D to engineering scale and then industrial scale, you realize that you are generating a lot of streams and some of the streams are not compatible. So, which means that you increase the waste. So, right now we have stopped any research on extracting cesium and strontium. We are pursuing more a robust and simplified flow sheet. Basically you would dissolve the spent fuel in nitric acid and then we have two paths, either a heterogeneous recycling or a homogeneous recycling. Homogeneous, we will try to extract all of the actinide of importance, basically uranium, plutonium, neptunium, americium. And for the heterogenous we will start with a modified PUREX process, uranium, plutonium, neptunium, followed by the ALSEP process which stands for actinide-lanthanide separation process where you would separate the trivalent actinide americium and curium from the trivalent

lanthanides using acidic extractant combined with the neutral extractants. So yes, for the americium, we have a lot of research going on. We are also investigating the oxidation of americium 3 to americium 6.

Myung Seung Yang
Right. The other question is also regarding the sodium fuel molten salt reactor and also I see I need some advice from Patricia.

Patricia Paviet
Okay. Let's see. I do not see the question right now. So, problem with safeguards in countries currently without nuclear capability is that there is a certain reliability in the world community on honesty, project participation in truthful inspections. Would we all be better served by putting more effort in the…

Berta Oates
…into the development of thorium MSRs.

Patricia Paviet
Okay, for the moment the United States are not focusing on the sodium fuel cycle at all, we are focusing on uranium fuel cycle.

Myung Seung Yang
And also the question from Mr. Farrar is, for radiotoxicity with spent nuclear fuel treatment. Actually, you are right. There is radiotoxicity, it's based on the external exposure and intake of the radionuclides together. So, for the details, I do not have the material right now, but radiotoxicity is kind of collective content.

The other question is, is there a minimum of nuclear power plant or annual spent nuclear fuel generation for establishing closing the fuel cycle? Yeah, surely, that is a very good question. And when we perform the economical analysis of the fuel cycle, we have to assume some minimum amount of spent fuel. And also that is depending on what kind of nuclear fuel technology we are going to use. So in case of pyroprocessing, that is mainly based on the batch type process, so more amount of spent nuclear fuel can be treated. But in case of wet process, since that is a continuous process, they need a large amount of spent fuel. So surely, they will use a minimum of nuclear power plant and spent fuel generation for closing the fuel cycle. But surely the minimum amount is depending on what kind of fuel cycle technology we are going to use.

The other question is what are the issues that need to be resolved before pyroprocessing become commercialized? Yeah, that is also very challenging question. Nowadays, the feasibility of pyroprocessing is proved just at the laboratory level. So, in order for the pyroprocess to become commercialized, sure you have many technology obstacles.

Surely, to find the optimum process parameter could be one challenge, but big challenge is mainly pyroprocessing is the batch type process. So, to be commercialized or to have a large scale processing of the pyrotechnology will be challenging one. So, that is why we are performing that kind of researches. So in coming five years, the feasibility of pyroprocessing will be evaluated in terms of technical feasibility and the safeguardability and also in terms of economics. So maybe I can answer more clearly in coming 5 years, about 5 years later.

Berta Oates
Great. The next question deals with research by the AEC in the 1960s.

Myung Seung Yang
Let me see.

Berta Oates
I know there was research by the AEC in the 1960s into the SFRs in the USA. What is the current direction towards the use of this type in the USA?

Myung Seung Yang
I need advice from Patricia.

Patricia Paviet
Yeah, right. We are going to have actually a presentation and I refer Tim Welty who asked, I know there was research by the AEC in the 60s into sodium fast reactors in the USA. What's the current direction towards the use of this type in the USA? Bob Hill from Argonne National Laboratory, he is our National Technical Director and I really invite you to listen to his webinar in 2 months on the 15th of December and I guess he will answer your questions. Yes, we are pursuing research on sodium fast reactors and other types of reactors.

Myung Seung Yang
So, I think no more questions. Thank you very much for your attention. My presentation is bit long.

Patricia Paviet
Yeah, thank you so much Professor Yang. That was a very comprehensive presentation. And as we always said, these webinars are archived. That's the beauty of them. So, you feel free to send to your colleagues the link on Gen IV, gen-4.org and they will be posted very soon. We thank you very much for your attention. I give the floor to Berta.

Berta Oates

Thank you, Patricia. Thank you, Professor Yang. Lisa, thank you as always for running behind the scenes there and thanks to everyone who took time out of their day to join us. In the USA, these presentations are early and we appreciate people getting up to join us for learning more about nuclear energy. I think with that we will adjourn and look forward to reconvening on the 22nd of November for an introduction to nuclear reactor design.

Patricia Paviet
Thank you Berta. Thank you, Professor Yang, thanks Lisa.

Myung Seung Yang
Thank you very much.

Patricia Paviet
Bye-bye.

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