Metal Fuel for Prototype Gen-IV Sodium Cooled Fast Reactor (PGSFR)
Dr. Chan Bock Lee, KAERI, Korea

Bertha
Welcome everyone to the Next GEN IV International Forum webinar presentation. Today's presentation on Metal Fuel for Prototype Generation-IV SFR: Design, Fabrication and Qualification will be presented by Dr. Chan Bock Lee. At this time, it's my pleasure to introduce Dr. Patricia Paviet. Patricia is the group leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She is also the chair of the GEN IV International Forum Education and Training Working Group. Patricia?

Patricia Paviet
Thank you so much, Bertha, for the introduction. Good morning, good evening everyone. It's a pleasure to have Dr. Chan Bock Lee with us today. He has been working at the Korea Atomic Energy Research Institute since 1989. He worked on the design, fabrication, and post-irradiation examination of uranium dioxide fuel for the commercial PWRs in Korea. After that, he worked on the development of diverse fuel for PWR, research reactor, and very high temperature gas-cooled reactor. Since 2007, he has worked on metal fuel developments for sodium fast reactor. He received his bachelor and master in nuclear engineering from Seoul National University in South Korea and his Ph.D. in nuclear engineering from MIT in the United States. He served as Division Director of Fuel Development at KAERI, Chair of Nuclear Fuel and Materials Division in Korea Nuclear Society, and Co-Chair of OECD/NEA Nuclear Innovation-2050 Fuel and Fuel Cycle Subgroup.

Without any delay, I am going to give the floor to Dr. Lee. Thank you again, Dr. Lee, for volunteering to give this webinar, but before I do that again for the people who wants to have access to the slide you have a box, it's called 'hands out' and in this box you will find the webinar and the flyer. So, Dr. Lee, you have the floor now. Thank you again.

Dr. Chan Bock Lee
Thank you very much Dr. Patricia Paviet for kind introduction and giving me opportunity to present this webinar. I also would like to thank Ms. Bertha [Unclear] for organizing this webinar. Hello, it is my great pleasure to introduce our work on the metal fuel development for PGSFR in this webinar. This work is actually the result of the many people, over 100 people in our institute KAERI for almost 15 years. Today, my presentation covered, first introductions. I'll briefly explain the background of this project. Then, I will explain our fuel development work from fuel design, fuel fabrication, and fuel qualification for licensing application. Then, finally, I will summarize and explain our future plan.

In Korea, also in our institute KAERI, we have [Unclear] pyro-electrochemical fuel recycling in SFR. From the spent fuel or light water reactor fuel, pyro-electrochemical processing recovers uranium and TRU element together to fabricate the fuel for SFR. In this SFR, the transmutation of minor actinides can reduce the environmental burden and repository space and also can enhance the utilization of uranium resource.

For the fuel, we selected metallic form [ph] of the fuels for this SFR. As you know, the metal fuel has high semi-conductivity. It can keep the fuel temperature low. Based on that low temperature, the inherent passive reactor safety can be achieved through these characteristics. Also, the metallic fuel can accommodate more minor charge, so it can transmute more efficiently through minor charge. By recovering the TRU plutonium and minor charge [ph] together through this pyro processing, so that is more proliferation resistance. These are characteristics we can meet target of our generation IV, for example, sustainability, safety, economy, and proliferation resistance.

I have to mention this metallic fuel in SFR is based on the much experience accumulated in the United States as you know [Unclear] and experience irradiation and design work of the IFR [ph] and [Unclear]. So, during this work, we have very good collaboration with research organization in the United States like Idaho National Laboratory and Argonne National Laboratory.

This table shows the design characteristics of the PGSFR. Also, this channel purpose is demonstration of the TRU transmutations coupled with pyro-processing. So, initial fuel, driving fuel is uranium-zirconium [ph] fuel which was much verified [ph] in the United States. And if we qualify the TRU fuel later and TRU fuel will be the main fuel in the later stage. The electric capacity is about 150 megawatt electrics and core outlet temperature is 545 centigrade. For safety, because of the metallic fuels, high thermal conductivity and low temperature the core damage frequency of 10 to the minus 6 can be easily achieved and also as a part-time hypothetical extent of the station blackout that can be maintained safe [ph] more than 3 days. Depending on the design it can go much longer than this time.

This shows the core design of the reactors. Thermal power is about 392 and the inner temperature is about 390 or so. The fuel is used earlier [ph] fuels about 19.2. It can reach the cycle length about 290 and cladding is the ferritic–martensitic steel, which has very low swelling rate. Core height is about 90 centimeters and fuel diameter is about 7.4 millimeters and the average burnup is about 66 kilowatt per metric tons.

This shows the fuel characteristics, fuel design. For this fuel design, we collaborated with our national lab. They have much experience. Here, fuel length is about 90 centimeters and there are bigger length of the gas plenum because about over 80% of the fission gas generated in the fuel are released to the plenum, so there is large column [ph] of the plenum length.

Here you can see the fuel assembly. Its length is about 4.55 meters even though the fuel rod length is about half of the size. Between bottom and top of the fuel rod there is reflector. This reflector protects lower and upper structure of the core from the fast neutron coming from the fuel. Here is the handling socket and nose piece. The sodium coolant is going here and flow [ph]. For this reflector design, we adopt a block-type reflector. It’s simple to fabricate and maybe possibly it can be reused after discharge to other fuels. The main reason to this one is to fabricate, that is the main reason to adopt this block-type reflector.

I explained our fuel design. As you know in fuel design, there are some parameters to be considered. Discharge burnups, peak fuel power and peak fuel temperature and peak cladding fast neutron fluence. These are related about fuel burnup, so it is better to achieve higher burnup and higher temperature to get fuel economy. Taking into account those parameters, fuel design basis set. Basic requirement is to maintain the fuel integrity during the operations. Fuel temperature, fuel melting need to be prevented and eutectic melting need to be controlled during the operation. For cladding, there are some cladding behaviors during irradiations; creep, swelling, and cumulative damage fraction and strain. Those criteria needs to be checked and verified to maintain – to verify the fuel integrity. Considering all those parameters, we finally set fuel design. It includes fuel dimensions, fuel shapes, and arrangement and configuration of the fuel assembly. Also, the selection of the right materials of fuel components need to be done.

This shows the typical irradiation performance of metallic fuel. In the fuel, fission is occurring. Fission gas generator released to the [Unclear] and you can see here as a burnup, active burnup about 6, almost 70 fission gas release. Fission gas are released to the gas plenum and the metal fuel swelling and axial growth occurs. This shows the microstructure with the fuels. There are core holes filled with the fission gas and some fission gas are released to the outside of this fuel slug through these open channels. Here you can see – this is before the irradiation, there are lots of [ph] sodium space and after irradiation it swelled and it contact with claddings. Also during the irradiations, fuel element migrate by diffusions because of this behavior this fuel element can migrate inside or outside depending on each element. There is thermodynamics. For cladding – on the cladding, there is always the tensile stress. Because of that cladding is cleared out and also high [Unclear] neutron plugs, the irradiation swelling occurs on the cladding. Because of these two behavior of cladding ductility is also reduced. This shows cladding swelling. This is the HT9 data. HT9 has the body centered cubic rated structure, so it showed low swelling rate. This one is the [Unclear] claddings of face-centered cubic, [Unclear] and it has a higher swelling rate. Also the fuel and cladding are both metals. There are some – they can occur some chemical, fuel cladding chemical interaction like eutectic melting or cladding wastage. Also because of some of tensile stress and also to fuel swelling there are some fuel cladding mechanical interactions can occur.

This showed design analysis result of our fuel design in this PGSFR as I explained. Fuel design – for fuel rod, the design criteria for normal operation and operational transients. Fuel integrity should be maintained. We need to check fuel temperature, cladding strain, and cladding CDF and fuel cladding chemical interaction. Considering all the uncertainties like rate operation uncertainties also fuel fabrication tolerance, we analyzed the fuel level conservativity and even though with those conservation maximum fuel temperature is about – maximum cladding mid-wall temperature is about 652 and cladding strain is 0.54. The criteria is 1% and CDF is 0.05 and it is satisfied and also the maximum fuel centerline temperature is about 715. It's much lower than melting temperature. We confirm the fuel rod integrity is maintained. Also for fuel assembly design criteria is more than the fuel rod. The integrity of the fuel assembly needs to be maintained in normal operation also for design base accident because to keep the fuel core structure, fuel assembly needs to be intact even under the design base accident.

This showed fuel fabrication. This one is the fuel slug and this one is the fuel cladding and fuel rod and fuel rod wire and the reflector, tunnel pattern, and nose piece and handling socket. This is hexagonal fuel assembly duct and this showed fuel size fuel assembly fabrication. Inside the fuel assembly you can see the array of the fuel rod here. I explained how we pivoted all those fuel compound.

First, fuel slug casting. Initially, we made a lab scale [ph] about batch size is about 2.5 and we tested different composition of the fuel slug to find optimum condition of the fuel testing like temperature, pressure, heating rate, and duration and time. Then, we make engineering scale about 20 kilogram per batch here and made fuel slug. Check fuel slug whether to meet fuel specification like dimensions and content homogeneity [ph] in the fuel and impurity level in the fuel slug was checked to meet to the specifications.

Next, this showed general steps for fuel cladding tube. Here from the ingot melting, forging, and machining, hot extrusion, drawing, and pilgering and heat treatment and final cladding tubes. To fabricate the cladding tube, we are collaborating with steel company in Korea to fabricate cladding tube.

From about 1 ton size of the ingot melting, forging, and through these steps hot extrusions, drawings, and pilgering. After pilgering, we fabricate the cladding tubes. Final size about 3 meters of these dimensions. We fabricated this cladding. First HT9 cladding tube and also we fabricated some advanced cladding. We call it FC92. We fabricated two separate cladding tubes in cooperation with this company.

HT9 is very good cladding and for irradiation database is a lot. To achieve more higher plenum [ph] or to reach the higher core on the temperature, we try to develop the advanced claddings which has a better performance especially in high temperature. We tested about 38 alloys and by changing the alloy composition and heat treatment we developed one alloy. We called FC92 and we fabricated and by the test it showed about at this high temperature 650 because creep rupture strength was improved more than 30%. We fabricated the cladding tube of this FC92 also.

This showed our work on the fuel rod fabrications. Inside the fuel rod there is sodium bonding. Sodium is very good semiconductor. This was to lower the fuel slug temperature. There is the sodium bonding between fuel and cladding. From the cladding and solid sodium is loaded into the cladding at room temperature. Then the fuel slug inserted at the time of the sodium and the end-cap [ph] is welding and sodium bonding is done. Through at this time [Unclear] through the X-ray [ph] is mentioned, so we can check how the sodium bonding is good or there are some poor [Unclear] or so we can check and it works well. Through this process, we fabricated the 12 fuel rodlet to irradiate in our HANARO research reactors.

This then showed fuel rod wire and fuel assembly duct. It's made from HT9. For wire, about 1 ton's ingots or through the rolling and drawing this wire was fabricated. For the duct, it's tough work to fabricate long hexagonal duct. From 3 tons of ingot through this process; hot forging, piercing, throwing, and heat treatment we finally succeeded to fabricate this duct length of 4 meters, thickness of 3 millimeters, 2 meters [Unclear] specification or specific uniform thickness and straightness of this duct.

As I said because the metal fuel and metal cladding the chemical interaction can occur. We investigated the barriers to prevent this chemical reaction, barrier or function as the fission barrier of the element. We tried the diverse barrier candidate and a good behavior was found for this barrier, chromium [ph], vanadium, and chromium oxide. These are the chromium candidate, electroplated on the inside surface of the cladding and chromium oxide can be formed by oxidation of inside cladding. Other nitrification and liner also we did the studies. Also we studied not on the cladding inner surface, also the surface oxidation of fuel slug [Unclear]. It's easy to make [Unclear] because this uranium [ph] fuel slug [Unclear] is easy to oxidize. We can form the very same thickness of the oxide here and we tested chemical interaction between cladding and fuel slug and it works well. Based on this result and for practical reasons, we chose the electroplating of the chromium with the main failure candidate.

This is chrome electroplating. This is the apparatus for electroplating of chromium on the inner surface of claddings. About 20 micrometer thickness of the layer was plated on the inner surface. We did out-of-pile test and also then make cladding and make fuel rod and we did irradiation test in HANARO. I will show later it works well to prevent inter-diffusion between fuel and cladding.

This showed result of our irradiation test in HANARO including the cladding. We did 12 rodlets for difference, 12 composition and with chrome barrier at 5.5 millimeters. First one achieved about 3% of burnup for this 182 days and PIE was done. After that we fabricated 12 fuel rodlets of similar. First one is we are very careful, so this one was irradiated low burnup, also at low temperature. It's about maximum cladding temperature is about 550. It's good. There was no fuel failure in this first one. Second one we fabricated and this one was designed to reach about higher temperature of the cladding in the cladding temperature to achieve higher burnup. But even though we complete fabrication, we are still waiting to be irradiated for some operation problem in the HANARO reactors. This showed PIE result of the HANARO before irradiation and after irradiation about 3% burnup and this red point showed fission gas release rate. It's low burnups, so there are some scattering, this measure data. This showed chromium barriers and it works well. The barrier was intact and the thickness was there in the [Unclear]. They found some crack here for cladding. Later we worked to prevent this cracking. We worked on to improve the electroplating process of the chromium by forming the small grain sized of the chrome multigrain on the chromium films.

Also we did irradiation testing, the fast research reactor, BOR-60 measure. For that we fabricated also about 12 kilowatt, fabricated in our institute and then we transported this fuel rod to the BOR-60 for irradiation test. During the irradiation, the peak linear power is changing about 364 to 319 depending on the late operation condition, also depending on the fuel rod positions. Peak cladding temperature is about 650 to 617 centigrade. During this irradiation test reached in May 2020, about 7% or 10% and there are some interim nondestructive examination of this rod. This showed that nondestructive examinations like appearance, gamma scanning, and cladding profilometry to measure the cladding diameters. We have plan to extend this irradiation up to 10. We are waiting for our permanent approval for this extension.

At separate we did also test cladding samples in this BOR-60 to check cladding properties. We used two material test rig post FC92 and HT9. We tested these two cladding materials at the same condition to compare the behavior of this cladding. Two material tests of different temperature and different irradiations. The irradiation dose achieved in August 2020 is about this one 46 and 77.5 dpa. Interim inspection was done to measure the cladding diameters and cladding testing to derive the cladding creep and cladding swelling. This shows the picture of the interim inspection and also the test rig and irradiation specimen for the creep and swelling. Microstructure also and also for the tensile test purpose.

For those cladding, FC92 and HT9. HT9 has about 12 chromium content and FC92 has 9 chromium contents. To check whether the [Unclear] in the chemical interesting behavior, we did some comparison test with the fuels and we found there was no specific difference between this cladding. Also by using the irradiated fuel, irradiated HANARO about 3% [Unclear] we did the median test [ph] in half cells [ph] to check the FCCI behavior and to show that this is the [Unclear] test, the [Unclear] inside half cells and this showed actual test result of this irradiated fuels. It found about 800 from the semi-eutectic [ph] reaction was found. This test we make some database to confirm our fuel behavior and to be used for our licensing purpose later.

For the fabrication test of our full-size fuel assembly, we did hydraulic test of the fuel assembly. We constructed test facility for hydraulic test on the fuel assembly. This is operation condition. This has similar Reynold number of sodium. This assembly is used in the sodium cooled reactor. At similar condition of using the water we did test here. For example, pressure test of fuel assembly and hydraulic lift-off and hold-down test by changing the flow rate of the water and also checked fuel induced hydrogen test using this facility.

This is for the mechanical test of fuel assembly. We used existing facility, which was used for the light water reactor fuel assembly mechanical test. We make some slight change to accommodate our SFR fuel assembly here by installing some sensors. We did measure the fuel assembly structure response like vibration characteristics, lateral bending, and axial impact. Through this test, fuel assembly structural integrity was verified in these tests. Also stress and strain was measured under maximum withdrawal force to simulate condition in SFR in-vessel transport machines.

So, far I explained our work on the uranium-zirconium fuels. The fabrication and [Unclear] for licensing of this fuel for our PGSFR. Next, I explained our research on the TRU fuels, which will be used at later stage of this PGSFR. Anyhow, we need to show the technical feasibility of this TRU fuel recycling. We did work on this TRU fuels. As I said, go through the pyro-electrochemical processing of the spent light water reactor fuel. TRU extracted and fuel fabricated, and then it will be inserted in the SFR. Fuel design is exactly same, only the fuel composition of the fuel slug are different from uranium-zirconium to uranium-TRU-zirconium fuel.

In this TRU ingot there are some impurities of layers [ph], of various elements. It's typical composition ratio, and this layer has similar electrochemical characteristics to the minor actinide. They come together with minor actinide. We need to take care of these layers during the fabrications and also irradiation behaviors.

Next [Unclear]. You may know well this TRU fuels, there are highly radioactive element like curiums, americiums, because of that this fuel should be handled in shielded environment like hot cells. Fuel need to be fabricated in hot cell remotely, and so that is the challenge for the fuel calculations. Also, the americium is volatile, so during the melting of the fuel ingots at high temperature, americium can be evaporated. Those evaporations need to be controlled, and also the layers element, impurities, they are very chemically active. Those need to be taken care for fuel fabrication. Therefore, fuel fabrication, those are the challenges and also the irradiation performance of this TRU fuels with some RE-Zr impurities and also minor actinide those need to be checked and because of this advance of the barrier technology more [Unclear] for TRU fuels to prevent. Those are about irradiation performance side of the TRU fuel. Because of that advanced cladding to achieve higher burnup and higher temperature is desirable to enhance the economy. Those are the three technical challenge for the TRU fuels.

We worked on this one. This showed typical completion of the PWR spent fuels about 1 ton, almost two fuel assemblies after cooling for 40 years. There are mainly the uranium left and there are some plutonium, this amount, and minor actinide and fission products. In this fission products, there are some lanthanides. [Unclear] is included in this lanthanide element. From this spent fuel, pyro processing straight to TRU element through the two-steps. First stage to convert this uranium oxide to the metal reductions process and second stage is from the metal to TRU is extracted through the electrochemical process.

For the remote fabrication technology studies, we installed local remote facilities here and we through many development work, we finally make engineering scale of the fuel slug casting. With that casting apparatus first we used copper like slug and copper and nickel. Finally, we make uranium and zirconium through using this mockup facilities like remote operations. Still there is long way to go, but we just show that it can be fabricated remotely. We need to work more to fabricate this fuel slug, more automatic operations and more reliable operations.

We did study also some innovative design of the fuel specifically [ph] the TRU fuels applications. This one showed particulate fuel. By this atomization process this is the martingale this is high speed rotating plate. Then, the spherical particle can be fabricated by this atomization [Unclear]. This is well-established in our institute KAERI to actually to – this technique is used to fabricate research reactor fuels in our HANARO reactor. By using this [Unclear] we fabricated particles – particulate fuel, so uranium-10 zirconiums. We can make particle size by changing the rotating conditions and we fabricate particle and we consolidate by the sintering process like this size. Then, this fuel can be inserted and cladding. Advantage of this particulate fuel is because fuel particle can directly contact with the cladding from the start, so sodium bond can be removed on this design and also by using this process compared with casting. In the casting, we need mold and we need crucible. Those are mold and crucible is not needed here. This waste generation especially for TRU fuel casting, waste generation can be reduced. That is the advantage of these particulate fuels. We can fabricate this one, but it's still unknown how it will behave during the irradiation. Irradiation test needs to be done to verify the irradiation behavior of this particulate fuel. How it will behave during the irradiations, we need to do this test.

Also we are working on the annular fuel slug. Annular has also advantage if we can also remove the sodium by making this annular fuel slug direct contact with cladding. First [Unclear], by using the copper by extrusions we made this annular fuel and this is – this one is the extrusion of copper. We cut it out to check microstructures. Copper is the current stage of this work.

For barrier, for more stronger barrier we worked on the liner cladding. Electroplating of the chromium, this one is another thing to solve the barrier like the liner [Unclear] or titanium about this thickness 50 micron is thickness liner was fabricated by the cold drawing and pilgering steps. We calculated this liner cladding about the length of 1 meter with two different liners. We are working on this process also.

Those are the work for the TRU fuel behavior and fabrications. In summary I explained also for initial fuels, so uranium and zirconium fuels, we fabricated the fuels in collaboration with the Korean state company and by fabricating the fuel size fuel assembly and we did test of hydraulic [ph] and test for licensing of this dry fuels. Also, we have been working on the TRU fuels recycling to show the technical feasibility of the TRU fuel from the pyro-electrochemical processing of the light water spent fuel. Today, I didn't cover our collaboration work with Idaho National Laboratory. We collate joint fuel cycle study. We have been working together for last 10 years for pyro processing, also the TRU fuel. From the spent oxide fuel, TRU element extracted by the pyro-processing and this TRU material was used to fabricate the fuel enhancer, and it was irradiated in the ATL [ph] in Idaho National Laboratory. Irradiation was done [Unclear] about 0.5% burnup and we did some PIE and there was no specific – no anomaly. This behaved as expected. It showed good behavior. It showed some feasibility we can say that it's recycling of TRU through the pyro processing. We hope to continue this work after approval from the government.

Now, in Korea, we finished those work and we generated data polarization for the PGSFR with uranium 10 [ph]-zirconium. We finished the basic design, and so we can stay to start preliminary safety analysis if the government decides to construct later, but we are still waiting this year for final decision of the Korean Government.

I personally think there was some positive signal because of our research result to show some promising results. Even though the schedule maybe the construction of the facilities and reactor maybe proceed in long-term schedule, but I personally expect it is continuous also.

Also, as you know, this net zero in the world to reduce the carbon dioxide released into the hemisphere. There are some more interesting nuclear powerplant constructions. In later stage, like 2040 or 2050, this past reactor had more – again have a more interest. Also as you know well in the United States there are some good projects going on like neutron reactors and also [Unclear] construction. Those are all based on the metallic fuels and SFRs. I hope this project is going well. Maybe, it will also help our project in Korea. Thank you very much for long time. It's all my presentation. Thank you.

Bertha
Thank you, Dr. Lee. If we have questions, please go ahead and type those in to questions pane. While questions are coming in, we will take a quick look at the upcoming webinar presentations that we have planned. In November, geometry design and transition simulation of heat pipe micro-reactor. In December, Development of an Austenitic/Martensitic Gradient Steel by Additive Manufacturing. In January, ESFR SMART European Sodium Fast Reactor Concept including the European Feedback Experience and the New Safety Commitments following Fukushima Accident. We have questions. Bear with me, just 1 minute please. So, Dr. Lee, there is a question. Dr. Lee, has there been any consideration for using of fuel without sodium bonding in case the pyro-process is unavailable and the fuel needs direct disposal?

Dr. Chan Bock Lee
TRU fuel without sodium bonding?

Bertha
Correct. Considering using of fuel without sodium bonding in case the pyro-process is unavailable and the fuel needs direct disposal?

Dr. Chan Bock Lee
It's possible but it's long way to go. It may be possible but I can say it's not our prime candidate for our fuels. For example, the particulate fuel design, this works well. Then later, this sodium bonding can be omitted in

this fuel design. It has some possibility to remove the sodium bonding, but it's in the later stage, I can see.

Bertha
Thank you. Was the swelling of this metal directly depended on anyway or did it uniformly swell from irradiation?

Dr. Chan Bock Lee
Yes, quite uniformly the swelling occurs. Even though locally there are some swelling is small, but still sodium is there. There is no problem for the heat transfer from tertiary [ph] levels to the cladding. Sodium is very good medium to accommodate any discontinuity of fuel slug and cladding. But after about some burnup like 3% or 4%, normally the fuel slug and swelling, and it fully contact with cladding.

Bertha
Thank you. Why is the criteria of CDF so small, approximately 0.05?

Dr. Chan Bock Lee
It's a good question. This CDF is a separate concept of the design parameter. It's only used on this SFR fuel. It's not used in the light water reactor fuels. In the light water reactor, it's always outside pressure about 150 ton higher than the inside the fuel. In this SFR, outside pressure must be like 1 ton, but inside is high temperature. Because of that, during the irradiation there is always tensile stress from inside to outside. This stress changes with the time depending on the temperature and the power and inside pressure. To consider those time change in the tensile stress, the concept of CDF is coming. Locally, the cladding – there are some non-uniformity of the cladding like local thinning and other barriers and considering those local variations, I think that's why the [Unclear] theoretically 1.0 should be the limit, but to be consulted, [Unclear] it was set at 0.05 to consider all those uncertainties in the criteria.

Bertha
Thank you. On slide 21, you identified a crack into the chromium coating, was this the only one crack or the whole world [Unclear] or were there multiple cracks seen?

Dr. Chan Bock Lee
Actually for irradiation test, we didn't check all the fuel rod. So, for HANARO test, we found those cracks. Then after that we worked hard to prevent those cracks occurring during the irradiations and by forming this smaller multigrain in the chromium matrix [ph]. Unfortunately, we didn't do the second irradiation. Second irradiation will tell us how it will behave. Also, we did test in the high ATL [ph] in the Idaho National Lab with our chrome plated cladding tube and [Unclear] also showed how it will behave.

Bertha
Thank you. Has there been any consideration of also using a high-entropy alloy mix for the fuel?

Dr. Chan Bock Lee
What composition you're mentioning about there?

Bertha
Dr. Hayes [ph], will you give some more information on your question? It best reads, any consideration of also using a high-entropy alloy mix for the fuel? We will see if Dr. Hayes will provide some clarification in follow-up. In the meantime, can your test results be used for US licensing, what are the QA protocols that you used?

Dr. Chan Bock Lee
QA protocols, we did for HANARO irradiation test, we did requirement for qualifications, so we have our qualification. I think is quite strict. It can be – I don't remember the exact name, but QA was applied per our HANARO evaluation test.

Bertha
Thank you. How much is the weight ratio of REMA in the fresh metal fuel?

Dr. Chan Bock Lee
Fresh metal fuel. For HANARO irradiation test…? For HANARO, this test we did like [Unclear] local with 5% of [Unclear] content to check how it will behave. We found because it's low temperature and low burnup, we couldn't find any significant difference compared to the uranium 10, just uranium 10 zirconium fuels. We didn't find any migration of [Unclear] to the cladding.

Bertha
Thank you. Given all of your challenges with casting and cladding, would you comment on using molten salt technology instead?

Dr. Chan Bock Lee
It's done with the molten salt reactors, I am not sure. But where is the molten salt used. As a coolant, instead of sodium or just molten salt reactor or purely [ph] dissolved in the molten salt. Is that the question?

Bertha
Yes, I am not sure. So, Mr. Steve, if you add some additional clarification to your question. Then in the meantime, for someone not familiar with SFR fuel cladding concepts, can you discuss the relative merits of chromium, electroplated cladded fuel versus sodium bonded fuel?

Dr. Chan Bock Lee

Even though with chromium plated there should be sodium bonding for this design. This chromium barrier is good to prevent chemical interaction between fuel slug and cladding, but even though with the chromium barrier, there needs to be the sodium bonding for heat transplant. Chromium barrier is to help to prevent chemical interaction to reach the higher burnup. Also in [Unclear] fuel, if there are some high content of the chemically active layers, the barrier can help to prevent any adverse effect coming from the layers. That is the reason, we are working on the barrier development.

Bertha
Thank you. Dr. Lee on slides 25 and 26, you mentioned hydraulic and mechanical testing facilities. Are these designed to test spent fuel or just fresh fuel?

Dr. Chan Bock Lee
Just the fresh fuel. We cannot use spent fuel, it's radioactive, so it's fresh fuel and polarization purpose, only the test of the fresh fuel is necessary. We don't need to test with the spent fuel.

Bertha
Thank you. Do we use quartz glass for injection casting? If so, how do you treat the used quartz glass waste?

Dr. Chan Bock Lee
That's a good question. We didn't actually work more about this waste of quartz glass. There are some studies I think in Idaho National Laboratory. It can be reused or it can be used as our other waste treatment purpose. For that purpose, we didn't much work on this quartz waste.

Bertha
Thank you. Are fuel radiations still being conducted in the BOR-60? When will they be completed and when were they completed?

Dr. Chan Bock Lee
It's reached about 7%. As I said in the final slide, we are waiting for our government's decision this year. We hope the government will allow us to continue for the irradiation in the BOR-60. We are waiting for government's decision.

Bertha
Thank you. We have some follow-up on those previous questions which were confusing to us. Is it the intention mix of five or more metals with some in low proportion to force chaos and arrangement processing changes to crystal and grain formation?

Dr. Chan Bock Lee

Excuse me. Please explain it again.

Bertha
Sorry about that. It is the intentional mix of five or more metals with some in low proportion to force chaos in the arrangement causing changes to crystal entity and grain formation, etcetera?

Dr. Chan Bock Lee
I am sorry. It's about question on the fuel composition or…?

Bertha
Yes, the previous question… Let me see if I can… I think it was the swollen… I think it was… You know it may be best if… Dr. Hayes, if you email, we can take it offline that might be our best solution to this topic. Dr. Lee's email is on that link for presenter slide or if you send it to me I will make sure that he gets it and we will get you the answer to the question that you are trying to ask.

Dr. Chan Bock Lee
Yes, I can…

Bertha
Do you have a plan for an irradiation of an annular fuel slug?

Dr. Chan Bock Lee
Yes, we are working on – as I said, we are now at a stage of the annular [Unclear] of copper. I should say it's long term because if we have some fund I would like to make annular fuel and to irradiate in our HANARO reactors. As I said in second irradiation, we are still waiting. Then, about in third [ph] campaign we can do this annular and also the particulate fuels. We hope to make the fuel and irradiate in the HANARO in third campaigns.

Bertha
Thank you. Dr. Lee, what advantages do you foresee using metal fuel over a MOX fuel on a fast reactor considering the extensive experience in fast reactors for MOX fuel compared with the limited experience of metal fuels in fast reactors? If the pursuit of metal fuel primarily tied to the use of a pyro process?

Dr. Chan Bock Lee
As I said metallic fuel has higher thermal conductivity than oxide fuels. I think regardless of the pyro-processing metal fuel itself has very good irradiation behavior in SFR. I think the metal fuel is better for the reactor safety than the oxide fuel. Oxide fuel has some potential to reactor with [Unclear] and there may be some concern about [Unclear] fuel swelling which may result in the reduction of the flow. Probably, reactor safety point of view, I think metal fuel is much better than the oxide fuel. That's why

even though one through cycle SFR fast reactor. The metal fuel is the candidate and those reactor developments were done in the United States. I think there are some several designs just for metal fuels in SFR advanced fuel. So, yes, that's my opinion.

Bertha
Thank you. Then RE is difficult to remove from MA by the pyro-process. How much do you expect the RE-MA ratio in the actual fresh fuel?

Dr. Chan Bock Lee
This one depends purely on the pyro-processing itself. I am not much familiar with pyro-processing, but they said to us it depends on the economy. During the many steps of the chemical processing, the content of layers can be decreased, but it is also related about cost of the processing. We are in conversation with the processing how much can be allowed in the fuels. For example, 5% of [Unclear] it can be allowed in the fuel fabrication and irradiation performance or it can be lower than 5 or for example 3% of levels can be acceptable. We are in discussion with the processing, pyro processing people. I think it's optimization considering the economy.

Bertha
Thank you. Dr. Hayes, I appreciate your effort to keep asking your question. It's not – it's because your facilitator doesn't enough technology to formulate other than read the question on the screen. With that caveat, the question reads – I have not always been the best communicator. A high-entropy alloy is one where you take an alloy and then intentionally put another metals of low proportion to change the properties in many ways which can increase strength and power. The impurity metals increase chaos and arrangements and are called high-entropy alloys.

Dr. Chan Bock Lee
Actually, I am not much familiar with high-entropy, but I will answer. If you send me the email I can answer, but inside the fuel there is lot of increase – there are lots of fission products accumulated in the fuel. In this fuel slug, there are large different fission products are mixed together in the fuel slug. Also the [Unclear] migrating inside or outside. In the fuel slug itself inside during irradiation there are many elements working together to react. I am not sure how your idea of the mixing of different alloy – element will affect fuel behavior. It needs to be considered there are accumulation of the many different element of the fission product inside the fuel slug.

Bertha
Thank you. We have some great feedback. Dr. Lee, thank you for great presentation. Korea has an impressive and comprehensive programs to develop and assess lot of fuel designs with [Unclear] further results. What

welding process was used on the cladding that [Unclear]? What welding process was used?

Dr. Chan Bock Lee
We used TIG welding.

Bertha
Thank you. In general is transmutation in a fast reactor more efficient and effective using metal or oxide fuel?

Dr. Chan Bock Lee
I think metal fuel as I said before metal fuel can accumulate many different element. The microstructure is more like alloy can more easily accommodate different alloy. For oxide there are some limitation for the sintering. If you insert many different elements, it may make more difficult to like sintering initially. In this sense, the metal fuel can accommodate more minor actinide and that means transmutation of minor actinide can be more efficient in metal fuel than oxide. Also the energy spectrum of the metal fuel design is more hardened that means the high energy neutron is more available. It's also more efficient to transmit [ph] minor actinide in metal case compared with oxide fuel. Those are what I studied from the [Unclear] design papers. Thank you.

Bertha
Thank you. I think we have time for maybe just one last question. Do you have any information about the situation of the Pride facility now?

Dr. Chan Bock Lee
Pride is the pyro-processing research facilities. It's next to our building and it's ready. Same is our case. We are waiting the government decision this year. We hope we have some positive signal to continue to work on this pyro-processing also to our fuel research. It's same as us. It's still there, and we hope it will continue.

Bertha
Thank you Dr. Lee for sharing your time and your expertise with us. It was a great presentation. We can always get an indication of the engagement by the number of questions, and I think we had 35 minutes of questions which is so fantastic. Thank you to the audience for being so engaged and then bringing you enthusiasm to the topic. With that, I think we will conclude today's presentation. Patricia, did you have any last thoughts?

Patricia Paviet
No, but like I said, you know, these webinars are very different because we have all these Q&A sessions at the end; very technical and extremely interesting question and answer. Again, thank you so much Dr. Lee for all

the knowledge you have and you were willing to share with us. Thank you so much.

Bertha
Thank you.

Dr. Chan Bock Lee
Thank you very much, Dr. Patricia and Betha.

Bertha
Thank you, Dr. Lee. Have a good day, everyone. Bye-bye.

Patricia Paviet
Bye-bye.

Dr. Chan Bock Lee
Bye.

END