Sodium Integral Effect Test Loop for Safety Simulation and Assessment (STELLA)
Dr. Jewhan Lee, KAERI, Korea

Berta Oates
Welcome everyone to the next Gen IV International Forum webinar presentation. Today's presentation on Sodium Integral Effect Test Loop for Safety Simulation and Assessment will be presented by Dr. Lee shortly.

Doing the introduction today is Dr. Patricia Paviet. Dr. Paviet is the Group Leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She's also the National Technical Director of the Molten Salt Reactor Program, and she's the chair of the Gen IV International Forum Education Training and Working Group. Patricia.

Patricia Paviet
Thank you very much Berta. Good morning. Good evening everyone. It's a pleasure to have Dr. Jewhan Lee with us today. He's currently the project manager of STELLA program. He's the team leader of the sodium experiment team in the Korea Atomic Energy Research Institute. He earned his Ph.D. in nuclear engineering and established his career as a sodium experiment professional. He has supported the Technical Director of the expert group, and now he's a member of Gen IV International Forum Sodium Fast Reactor-System Steering Committee Safety and Operation Project Management Board.

His expertise is in the sodium heat transfer of both analytical and experimental works. He has experience on the handling and managing the alchemy metal and evaluating the performance of various heat transfer systems using various analysis tools. He has a deep understanding of the liquid metal system from component level to system level. His recent interest expands to the innovative instrumentation for high temperature liquid metal as well as various liquid metal applications such as thermal energy storage system. So, without any delay, I give you the floor, Dr. Lee. I really thank you again for volunteering to give this presentation. Thank you.

Jewhan Lee
Thank you. Thank you for the warm welcome and introduction. Good morning, afternoon, and evening. I'm pleased to give a seminar on STELLA program here in Gen IV. My name is Jewhan Lee again, and I work for KAERI. Currently, I'm in charge of all the sodium experiment activities in KAERI including STELLA facility. I started my career with the STELLA facility after Ph.D., and now I'm in charge of it. I'm very lucky to have this opportunity.

I'm going to talk about STELLA program, which is divided into two phases. STELLA-1 is, what we call it, a Separate Effect Test. STELLA-2 is an Integral Effect Test. More detail, STELLA-1 is a component test facility whereas STELLA-2 is a system test facility. I will briefly tell you about how these facilities work or how it is doing and after that I will share the future plan.

This is a summarized overview of STELLA and actually it contains all the key information. STELLA program was first launched in 2009. Of course, the discussion and debate was there before this time, but it started its first footstep with the funding in 2009. It is a large scale sodium test program that Korea never had experienced.

As a first step, STELLA-1 facility to test key component was designed, constructed, and operated. During this period, the reference reactors was changed from KALIMER-600 to PGSFR. We added extra tests for new components to be consistent with PGSFR which is SELFA. This is actually an extension of STELLA-1. The reason we have different name is that the facility is physically separate from STELLA-1, although it shares the same purpose to support PGSFR.

In the year 2012, STELLA-1 finished its construction and accomplished this primary objective in 2014. And then, it was modified to test the extended range until 2017. In case of SELFA, it finished its construction in 2016, and the experiment was done at the end of 2017. In this phase one, the focus of experiment was to test the thermal hydraulic performance of key heat exchangers. At the same time, there were many implicit activities that must be accompanied by. Dealing with such a large amount of sodium was a whole new experience for us. With the data here, we were able to validate the thermal sizing and design codes.

In parallel to STELLA-1, STELLA-2 was also ongoing. Design started in 2014 but the concept and higher level decision making was far earlier. The construction was finished in 2020. Since then, it is actively in operation. The focus of phase two is to observe and investigate the system dynamic behavior. It's rather a comprehensive evaluation test of the system. Contrary to the phase one, the result of this will be used to validate the system codes.

Let me talk about the reference vector first. As I told you earlier, the reference vector was KALIMER-600 at the beginning of the program but the reactor design was changed to PGSFR and the STELLA facilities are designed to support it.

In this slide, some of the main design features are listed. On the right side picture, there are more details. But I won't go into details because I'm sure that you have enough understanding as long as you are in this Gen IV international forum.

Before I move on, just one thing that I have done is highlighted in blue here. In PGSFR, there are four independent Decay Heat Removal System. Two are passively working and two are actively working. This is to satisfy the diversity and redundancy concept of safety.

These are some illustrations of PGSFR. If you need more information about PGSFR, there are plenty open sources or you can email me. So, I'll just move on to the main ones.

Separate Effect Test. That's it for the appetizer. We move on to the main dish. As I said before, STELLA-1 is to pass the heat exchanger. They are DHX and AHX. DHX is a straight tube type sodium-to-sodium heat exchanger located inside the sodium pool. On the other end, AHX is a helical-tube type sodium-to-air heat exchanger. These two components are the key for the Safe Decay Heat Removal. Using almost 18 tons of sodium and about 2.5 megawatt power, these two components were tested.

You can see there is another item here. Since we have a large amount of sodium and facility, we also wanted to test the mechanical pump performance under sodium environment. We designed the pump. We tested in water. And finally, we tested in sodium to compare the result. Some of the details for STELLA-1 is in this table; 18 tons of sodium, 600 degree C, and 10 bars are the design values, and 2.5 megawatt in total power. The flow rate is max 25 kilogram per second. It is not shown here but the max flow rate to test the mechanical pump is 125 kilogram per second.

This is SELFA, an extension of STELLA-1. Again, it is to test another key heat exchanger called FHX. FHX is a finned-tube type sodium-to-air heat exchanger. As I told you before, there was the only DHX and AHX in KALIMER-600. The reactor changed to PGSFR and the safety feature was enhanced with diversity mean. So, actively working heat exchanger was added.

There were some people asking why we built a separate facility for this instead of just adding to STELLA-1? Well, at that time, we had the opportunity to reuse the existing structure and recycle some of the equipment. And so, we saved the money, simple reason. It took less budget to go this way.

Some of the details for SELFA is in this table just like the one you saw in previous slide. Comparably, the sodium amount is small and the power is small, but it just fits the purpose of this test.

The Model Heat Exchanger for test was designed based on three requirements. We adopted volume scaling. The length scale is one to one. We conserved the tube size, pitch and heat transfer coefficient and the Delta T. As you can see in the table for DHX and AHX in STELLA-1, the area ratio is 2/5 and for FHX in SELFA, it's 1/8.

There are three in-house codes for thermal sizing of heat exchangers. The name is SHXSA, AHXSA, and FHXSA. They use control volume approach solving the basic three equations. You can see on the right side the mass balance, momentum and energy balance.

This is summarized table for each code description. There are information of the most important part, the correlations for pressure drop and heat transfer. If it's too small to read, please refer to many open sources that we have published.

Here are the summarized result of STELLA-1. Basically, we set the inlet temperature of each heat exchanger for tube-side and shell-side, and we measure the outlet temperature. And, we can analyze the temperature as well as the heat transfer capacity. Since this data was used for licensing, all the experiments were under thorough QA procedure and the evaluation was done with ASME Uncertainty Analysis Guidance.

Let's look at one by one. For sodium-to-sodium test, we were surprised of the excellence in the deviation of experiment data from code calculation. As you can see here with numbers, this was really, really good. And for sodium-to-air test for helical tube, the sodium side was still very good while the air side was comparably moderate. But in general, 10% is still a good result if you think of other air experiments. For sodium-to-air test for finned-tube, discrepancy was in similar range with a helical type experiment. Again, for more information, please refer to the published papers with these things.

Lastly with STELLA-1, we were able to test the natural circulation flow development. Because it is a three-loop system, we can set the condition for natural circulation to occur in the sodium loop. There is one sodium loop for heater and DHX shell-side. And there is another sodium loop for DHX tube-side and AHX tube-side. And there is one air loop for AHX shell-side that makes two closed loops and one open loop.

With this experiment, we were able to validate the in-house code named FLOWTRAN. The trend prediction was in good agreement, but the calculated flow rate was somewhat lower than the experiment. Because of a complicated condition and environment, it was not easy to evaluate the reason for this. We were working on STELLA-2, which is more dedicated facility for natural circulation, so we didn't go into further with this.

Now it’s the main of the main dish. Thank you. In fact, the name of STELLA is for this activity and facility. I should say STELLA-1 is a prequel of STELLA. As I mentioned before, it is aimed for comprehensive review so that the safety analysis code can be validated. Distinctive feature of this facility is that it is almost like a reactor. So, it can simulate the transient responses. Also, the dynamic behaviors can be observed for off-normal conditions, but it is not a reactor with a nuclear fuel. So, the power level is at the decay heat level.

When we were thinking about the concept of the experiment, we started with identifying what will be tested. The very first step was to look over the safety event categorization of the reference reactor. From there, we were able to determine the scope of tests which includes most of the DBAs plus total loss of DHRS.

Then we started designing. With considerable discussion, the reduced height scaling was decided. This slide you can find some basic information and comparison of different scaling methodologies. The key factor was the cost. To minimize this, the power level and physical space were mainly considered. In conclusion, the three level scaling law was selected. And it is suitable for natural circulation phenomena at STELLA-2 we’ll be looking at. Before I move on, just one thing to note is that in reduced height scale, the time and velocity scale is not one to one, as you can see on the right bottom side with the red dotted box.

Here is a simplified version of how we scale. First, we do the global scaling that it considers geometry, time, and other thermo-hydraulic parameters. Second is the inventory scaling where mass and energy inventory is evaluated. Lastly, local phenomenon scaling is done to assure the proper heat transfer flow and energy mixing, heat loss and so on. On the right top side, the six important non-dimensional numbers are shown.

The result of scaling is the requirement for the facility. Considering the most important factor of course, the height scale was decided to be 1/5 and eventually the volume scale is 1/125. The sodium will be used as same as reactor and pressure and temperature condition will be same. General arrangement of reactor internals and components were kept the same. The facility simulates the decay heat generation. It simulates primary transfer system pump close down. It simulates pump pipe break event, and it simulates reactor vessel cooling system heat removal.

So, what to be seen? The focus of this facility is as written in this slide. The short and long term cooling capability will be examined. And also, symmetric decay heat removal operation will be tested. Flow and heat transfer characteristic will be seen and also flow distribution and mixing in pool will be seen.

Okay, here are some main design features of the facility. It has one vessel, eight loops, and five different types of heat exchangers. The vessel size is about 2.2 meter in diameter and 3.7 meter in height. Sodium amount is about 15 tons, and the core power is about 500 kilowatts. Comparably, total system power is about three megawatts. You can see the layouts spinning around on the right side.

STELLA-2 resembles the reactor, but there are three differences. Can you just click it three times to show the red circles? Thank you. Yeah, thank you. Core, of course, is replaced by electric heater. Another difference is that steam generator is replaced by sodium-to-air heat exchanger. Lastly, the mechanical pump is replaced by pump simulation loop. Let me go into one by one.

Let me start with the core first. It is obvious using electric heater instead of actual reactive nuclear material. Instead of just block heater which also works, we designed to have same geometry. There is rods, wire wraps, and hexagonal assembly with wrapping duct. Each assembly has one dummy rod for instrumentation at the center. So, it is quite complex system rather than just the heater. Many details are in this slide.

Next slide please. Designing the primary side is the most important part. Vessel, redan, separation plate, reactor head, inlet plenum for the core, pump pipe, Upper Internal Structure, etcetera. To keep the similarity, the inventory was conserved and the relative elevation of components was also conserved, and we did the design.

The replacement of mechanical pump was suggested to measure the primary site flow rate. We have taken out the loop and installed flow meter with electromagnetic pumps outside. With this feature, we can exactly measure the primary flow rate, whether it's a forced flow or natural circulation flow. This loop simulates the coastdown curve of the mechanical pump by controlling the power of electromagnetic pump. And to keep the similarity, the pressure drop, of course, was conserved. And at the same time, the inlet and outlet position of the pump was conserved.

Our sodium loop design, intermediate and Decay Heat Removal loops were designed to conserve the relative elevation of the heat exchangers. This is very important because the loop is working with natural circulation. Also, the sodium inventory was conserved inside the loop.

Finally, the art of designing lies on here for the five different types of heat exchangers; IHX, DHX, AHX, FHX, UHX were designed to keep the similarity. Basically, the conserved parameters are total heat transfer coefficient and the temperature difference.

Of course, before the construction, there should be valuation using one of the system code as you may all know MARS-LMR. We conducted scoping analysis to compare the transient between reactor and STELLA-2. Also, as you can see here, we did a lot of CFD analysis to verify the design. Especially for the core inlet orifice design, we did water mock up tests.

These are what STELLA-2 makes special and unique. It is capable of simulating the pipe break inside the pool and simulating the ex-vessel cooling. To do this, we have installed specially designed three-way bell which has universal joint long-reach arm and very short actuation time. And we have reactor vessel cooling system with the airflow jacket, and there's a blower outside, and the flow rate is controlled with the flow meters.

What's going on and what will be done?

Here are some pictures of when we were constructing and installing. We have built dedicate building for this STELLA-2 facility, and you are seeing some of these structures here.

Also, these are some of the past pictures. On the left top side, there are electric heaters cores. In the middle that's the redan, IHX, DHX and so on. On the right side is above the reactor head. Those rusty thing is the IHX. In the middle, there are FHX, AHX. Also, there are cold trap. And at the bottom, there are certain [ph] storage tank and gas supply systems and so on.

Now it is actively operating to get as many as data possible. The task matrix includes enormous cases, and we are vigorously working on it. This is what will come out.

With the preliminary experiment data, we try to compare with the calculation result of system code. This is just an example of loss of flow event with one AHX, one FHX failure. I said it's preliminary. The detailed analysis will be done in the future.

For the future, now, we are very into the experiment. But at the same time, we are looking for the opportunity in future. Of course, within Gen IV framework, the benchmark calculation activity has been proposed. Within IAEA framework, we will prepare a proposal for CRP, the Coordinate Research Project. But other than this, we are looking for the mutual collaboration with various research groups like IDAO [ph], Argonne, France, Japan and anywhere else. And, of course, the industry is very tempted to what we have. They are reaching out to contact us.

It's a summary.

STELLA program was launched to support the development of first SFR in Korea. It will serve as a strong supporter of PGSFR license in future. It is a basic infrastructure for sodium system. STELLA-1 accomplished this mission successfully. Key components, the heat exchangers for safety of SFR was tested. Code verification and validation completed to assure the calculation results. STELLA-2 is ready to achieve valuable data. Potentially be used for licensing and various activities and works planned under international collaboration framework. Thank you. Thank you very much for listening. If you have any question, please feel free to ask. Thank you.

Berta Oates
Thank you Dr. Lee. Well, questions are coming in. We'll just take a quick look at the upcoming webinar presentations on our schedule. In November, Geospatial Analytics for Energy and Resilience Analysis. In December, the Mechanisms Engineering Test Loop Facility at Argonne National Laboratory, and in January the Molten Salt Reactors Taxonomy and Fuel Cycle Performance. Dr. Lee, how big is your team? How many people do you have working under you or with you?

Jewhan Lee
Well, the people involved in the STELLA-2 facility is about 12 to 14. It's all variety of technicians and researchers and someone in the middle. We should say 12 colleagues.

Berta Oates
Do you sponsor internships? Are you working with your local universities, for people to work on their Ph.D.'s or is this something that?

Jewhan Lee
Yes, we do. We do. We have several undergraduate interns. We were trying to have some of the postdocs, but we haven't got any postdocs yet. But we are still open to accept all those interns and postdocs and so on.

Berta Oates
If you have any questions for Dr. Lee, please go ahead and type those into the Q&A chat pod. I don't see questions coming in at this point. People do have your email, they can reach out to you, I presume offline, if they have questions that come up. If you have a couple of minutes, we'll just hang tight and see if maybe people are having difficulty with the dialog box.

Jewhan Lee
Sure. Yes. Thank you.

Berta Oates
Are there measurements inside the AHX and the CFD grade?

Jewhan Lee
E-grade? Well, we have measurement. You mean the instrumentation? Yes, of course, we have temperature for the air side and get the exact meaning of CFD grade.

Berta Oates
She means, I mean local values.

Jewhan Lee
Local values? Well, yeah, it is. We are measuring inside the AHX, the sodium side as well as the air side. Yeah. We measure the temperature, and we measure the flow rates. That's what we do in the experiment.

Berta Oates
Thank you.

Jewhan Lee
Does that CFD grade means how fine, I mean, the resolution? If it’s that what it means, well for STELLA-1, we didn't have that many instrumentation, many thesis [ph] in the head section. For the STELLA-2, we have put a lot of instrumentations.

For example, we have about more than 3000 temperature points. And we have about 500 pressure points and several more. In total, the IO points we call it, the In and Out points, it's about 5000. That's all dedicated for this measurement.

Berta Oates
Thank you. We have a quiet group today. Thank you. Under what conditions the experimental data could be shared with other institutions interested in CFD code validation?

Jewhan Lee
Well, it's a very good question. Because me, and my manager and boss are just thinking of how we can share this data. Because we started to open our data in Gen IV and IAEA frameworks, but we cannot go on with this because this international framework is not enough. If we make a mutual collaboration, there will be some ways we can make up kind of a contract or any projects so that we can share our data. Maybe, we can do some experiments of the request from the other organizations or other institutes. But we're still looking at the ways how we can share the data.

Berta Oates
Thank you. Can you talk about the design cycle for STELLA-2? When did the design process begin and when did construction begin?

Jewhan Lee
Okay. I think I had a slide for that. Well, I talked about the STELLA program. This whole STELLA program was for STELLA-2. But we started with STELLA-1 because we had no experience with this large facility. And also, we needed to test the heat exchanger first with a limited budget. So we went on with STELLA-1 first. But as I told you before, STELLA program itself was for STELLA-2. The very, very beginning of STELLA-2 is same as the start of the STELLA program. It's about year 2009.

But the design started from then, and we had a lot of repetitions, and we finished the basic design in year 2014. I think I've written that in the slides. I mean, in year 2015, we started the specific design. What it means is that we are thinking of the fabrications and installations, structures and where to build it, and the buildings and these kind of things. We finished the design in year 2019, and we finished the construction in year 2020. It was early 2020 we finished the construction and since then we are actively working on it. Thank you.

Berta Oates
Thank you. Certainly, you're welcome to move the slides back, Dr. Lee, to emphasize some of your answers.

Jewhan Lee
Okay.

Berta Oates
I don't see any more questions coming in. Patricia, did you have any last minute thoughts?

Patricia Paviet
What did you say Berta?

Berta Oates
Do you have any last minute thoughts that you'd like to share? I don't see any more questions.

Patricia Paviet
Okay, very good. I don't see the questions. No, I don't have anything to say besides, again to thank Dr. Lee for his time and for his excellent presentation. Again, thank you very much Dr. Lee.

Jewhan Lee
Thank you.

Berta Oates
Dr. Lee where are the publicly available papers on the CFD analysis that you performed?

Jewhan Lee
Well, most of the papers include the word STELLA. I just suggest you to type STELLA, but put the keyword STELLA because it must have this term. And regarding the CFD analysis, we have several papers, and I'm preparing the CFD analysis for the heat exchangers. So, try to look for it in the internet. And if you cannot do it just send me an email. I'll send it to you.

Berta Oates
Thank you. Thanks to the participants who joined with us today and for engaging in an enlightening conversation. We appreciate your feedback and your participation. With that, I think we will conclude today's presentation. Thank you very much again, Dr. Lee.

Jewhan Lee
Thank you.

Berta Oates
Bye-bye.

Jewhan Lee

Bye.

Patricia Paviet
Goodbye everyone.

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