Geometry Design and Transient Simulation of a Heat Pipe Micro Reactor

Dr. Jun Wang, University of Wisconsin, USA

Bertha

Doing today's introduction is Dr. Patricia Paviet. Dr. Paviet is the group leader of the radiological materials group at Pacific Northwest National Laboratory. She's also the chairperson of the GEN IV International Forum Education and Training Working Group. Patricia.

Patricia Paviet

Thank you so much, Bertha. Good morning, good evening, everyone. We have with us today Dr. Jun Wang. He's an Associate Scientist of Nuclear Engineering and Engineering Physics at the University of Wisconsin-Madison. His research interests include the advanced numerical analysis of nuclear safety and reliability for various reactor designs. He's leading a few projects on the heat pipe micro reactor, high temperature gas cooled reactor transient analysis, and uncertainty quantification by artificial intelligence. He is also serving on the ANS thermal hydraulics committee, and the journal Progress in Nuclear Energy, Annals of Energy Research as editorial board. Dr. Wang earned his Ph.D. from Xi'an Jiaotong University. Without any further delay, I give you the floor, Dr. Wang, thank you so much again for volunteering to give this webinar.

Dr. Jun Wang

Okay, good morning and good afternoon and good evening everyone, and thanks a lot for the introduction. I appreciate the opportunity to speak at the Generation IV International Forum here, and thanks a lot for all audience who came to listen to me, sharing my recent research on heat pipe micro reactor. First of all, I would like to go through the development of micro reactor history and introduce some basic concept of how heat pipe works.

Micro reactor is becoming more popular and attracting more interest due to its flexible and its reliable power supply, and it's small enough to be transported and provide on-site installation. It has been applied or could be applied in multi-application situation. For example, the explanation of deep space, the government's off-grid energy supply, and also energy supply for some remote communities. Currently, the most popular designs include the heat pipe cooled micro reactor, and also the gas cooled micro reactor. However, last year, a lot of concepts and technologies are not tested and not proven. We still have to conduct the research to demonstrate whether the designs are safe and efficient enough.

Efforts developing micro reactor technologies could start from 1960s along with the using of nuclear energy and a bunch of projects like KRUSTY, HOMER, and a lot of others are already being conducted, started from 1960s, and this figure shows an example of engineers from NASA and National Nuclear Security who are working on a Kilo power reactor system. The efforts are still going on, so at least some of like calendar efforts from the United States Industry, so for example, the Westinghouse is working on eVinci, and Oklo from California is working on Aurora, and both of them consider uranium as a fuel. The Westinghouse also considered TRISO fuel. The reactor power is between 1 to 5 Megawatts, and we also have other efforts from gas-cooled micro reactor. The companies like HolosGen, USNC, and X-Energy are working on it. Most of the power are below 15 megawatts.

A bunch of flow details of the heat pipe micro reactor design. Westinghouse eVinci design uses mature heat pipe technology from Los Alamos National Lab. It's considered a solid block with three different types of channels, including fuel rods, moderators, and heat pipes. Oklo's Aurora Powerhouse is inspired by the NASA's Kilopower Reactor. It also uses solid block with uranium fuel and heat piping technology.

Another background I would like to share is how the heat pipe works, so as you see in this figure from internal to outside, the heat pipe could be separated into three parts, the coolant, the wicker, and the wall. From the left part to the right part, your heat pipe also includes three parts, evaporator, adiabatic and the condenser. Firstly, it is liquid sodium here as the coolant channel of the left side, and here, the liquid solid where we heat it into vapor solid and goes through adiabatic and go into the condenser.

Here, we cool it down into liquid sodium again, and flow back through the wicker. Through this process, the energy will be transferred from heat source to heat sink and proceeds down to actual energy supply, and the energy transfer cum efficiency is high. That is why heat pipe is still popular and it is considered to be a pride in micro reactor technologies and also a bunch of multi-industry engineering application.

In the first chapter, we introduced some background of the micro reactor development history, and then we introduced how the heat pipe works. Then after that, I would like to introduce the numerical tool we are using and the benchmark comparison between our results and other national labs' results as part of verification and validation. In numerical tool, we are using, it's called SAM and MOOSE, and then we also use Trelis and Cubit to build a geometry and creating a niche for us.

MOOSE is multi-physics platform, origin from Idaho National Lab. It can provide definition of key physical process, material properties, and post processing. Trelis and Cubit is a software from Sandia National Lab. It can provide the building of CFD geometry and also meshing, so MOOSE can be the 3D geometry from Trelis and Cubit.

SAM is a software prepared for otherwise the reactor and its origin is from Argonne National Lab, and SAM also has the 2D heat pipe model, which can calculate the fluid flow and heat transfer behavior in the heat pipe. The whole process could be summarized as 3D heat conduction, liquid flow, heat transfer in a SAM's model and interfacial mass, momentum, and energy transfer in a heat pipe model instead. The following figure explains how those softwares are working together.

Here is a benchmark example problem provided by Argonne National Lab. At this moment, since we don't have any published experimental data, we have to do a code to code benchmark comparison to check our calculation result. As we can see from the left figure, so our red block is the monolith and internal [Unclear] is the fuel rod, there are six heat pipes inserted into the monolith. The right figure is a cross section from top view, fuel, heat pipes, [Unclear] 2D heat pipes and monoliths. The fuel rod and monolith length are 2 meters as an assumption here, and the heat pipe length is 3 meters, while the evaporator is also 2 meters. It is totally inserted into the monolith.

We also have adiabatic and condenser, that is 0.5 meters each. We have some other details, parameters already done. First of all, we keep our time step for both calculations. Initial temperature for a system is 875 Kelvin, and the solid monolith boundary condition is adiabatic, and heat pipe condenser temperature is 750 Kelvin. The system energy source is related to the heater, and the energy sink is the heat pipe. In this table, we list a bunch of some properties, including the density, specific heat and thermal conductivity for three parts of a system monolith, fuel rods, the three components of the heat pipe, including the coolant, the wick and the wall.

We come to our results. Left figure shows the maximum temperature comparison and the right figure shows the heat transfer comparison. We can see the results of the UW and Argonne National Lab match each other very well. [Unclear] very small difference between these two models, it's mesh nodes. We are using different software to be able to do the geometry, and the number of nodes are a little different listed here. We assume natural reasons for a small difference at 10,000 seconds, and also at least 10 points is a transfer from temperature increasing, heat transfer increasing comes to a steady state. We on stability, like our calculation results that matches to Argonne National Lab's results were, and there are codes to code benchmark comparison and code support our future numerical analysis for safety transient check for a heat pipe micro reactor.

After the introduction, background information of the numerical tool and their benchmark verification and validation, we start with steady state calculation and based on this steady state calculation, we selected a few creative parameters to check sensitivity analysis, check how these created parameters affect the results. The research target we selected is called MAGNET. The full name of MAGNET is micro reactor agile non-nuclear experimental test-bed, and it's a facility at Idaho National Lab, and this facility is a test-bed and it's open for different micro reactor design. Emission design is the heat pipe cooled configuration and the details of the design are shown on the right figure.

We have 54 fuels, it is the blue circle, and the bright circle is the heat pipes and the number is 37. Left part is the figure for test-bed. It has MPD internal, and when we have the experimental facility already, we can start it into the test-bed, and a bunch of more details of like experimental design. The total value of the channels is 91, and on the energy source, the system is heated by electrical heater, and the monolith block and heater are made up of stainless steel.

We know in reality, this design could be some material difference, like monoliths could be graphite and fuel rods could be uranium or TRISO fuel rod. For experimental design, we use stainless steel here, and for the power distribution at our initial power calculation, we can see all the power in different fuel rods, SAM. That means, in other words, we didn't consider in which one [Unclear] fewer, but in the future, we can consider the industry suggestion and maybe we reduce the power at the side and increase the power in the center of the monolith.

Each of the fuel, we assume a cosine power shape which is closer to actual power profile. Important note is like recalculate the 3D monolith and the electrical heater, and recalculate the 2D heat pipe, layered calculation in the same time and same system, but in two different parts of the software. Okay, so here comes our model of the MAGNET facility. This is a 3D model including the monolith and fuel rods and heat pipe inserted, so it is very similar to our first example, but it's more concrete, and the right figure shows a cross section from the top view.

Here, we also have heat pipes and fuel rods in different level [Ph], so this could help us explain our calculation results much better in the following results. Here are some more details of experimental facility. Three most important parts, monolith, electrical heater and heat pipe. Monolith height is 1 meter, diameter is 0.244 meters. Material is stainless steel; boundary condition is adiabatic. Electrical heater, number is 54, diameter is 0.014 meters, stainless steel and power is 75 kilowatts. This power is connected to a number of heat pipes. We assume each heat pipe could remove the power of 2 kilowatts, and we have 37 heat pipes and that is why we define the power for power of 75 kilowatts here.

The diameter of heat pipe is 0.0156, materials including sodium, wick was stainless steel, and the radius is inclusive from [Unclear] to wick and to wall. Length is 2 meters total, 1 meter is evaporator, SAM to monolith and electrical heater, and 0.2 meter is adiabatic and 0.8 meters of condenser. Heat transfer coefficient between the monolith and electrical heat pipe is 10 to the power 5 watts per meter square per kilo. The condenser wall temperature is 755 Kelvin.

These are the details of the MAGNET facility. Once we put all these information into our numerical modeling, we can get results, and the most significant results we can get is the 2D temperature distribution, and we use a software called panel view to deal with those. This is the result of your best steady state result. We can find the list in a cross section from top view and cross section from side view, and the temperature here, there are some significant heat pipe in the location for fuel, and the monoliths between each fuel rod is also hot and will leave [Unclear] for the 2D heat pipe.

Besides the 2D temperature distribution graph, we can also use graphite to test our results. For example, so you can see, we selected a line on the surface of a cross section of the monolith, fuel, and a heat pipe system, and we can show a temperature history, temperature distribution along with this line at X-axis. The peak points are the location of the electrical heater, and there are no points in the location of heat pipe, and the temperature between them is [Unclear], and when we connect all the temperatures together, we can find it's a constant line. We also can draw a figure from Y axis and which all of these graphs are trying to help us find a location of hot pipe in the system.

After the steady state, we did a bunch of other different change of parameters to compare sensitivity analysis. In first group, we changed the mesh type, initial mesh, we are using is HEX20 and we can change it to HEX8 and HEX27. Another parameter we change is the heating power, increase it from 75 to 100, and then the third sensitivity parameter is the heat transfer coefficient. We transfer it from 10 to the power of 3 to 10 to the power 7 and the first one is the condenser temperature from heat pipe, and we changed it from 750 Kelvin to 730 Kelvin. Some of the background information of what's the mesh type, so HEX8 is 8 nodes. When we want to describe a volume, we use eight nodes to describe it, and the HEX20 and 27 is 20 nodes and 27 nodes.

In CRA, when we are using higher number of nodes, the calculation result, the prediction is more accuracy. However, since we are using more source to moderate, the calculations will be delayed, so we have to balance the demand on the prediction accuracy and the preparation state. We come to the result. The first one is comparison of different mesh types. We can notice line HEX20 is the line here. If we reduce the nodes number, the result is changed, and we may have much less point in the lines. Of course, the accuracy is lower.

If we increase the nodes number from 20 to 27, the result is not changing too much, which means HEX27 is our best option. We don't want to reduce it to reduce the prediction accuracy. We also don't want to increase it to reduce the calculation speed. We also check some other parameters like heating power, and we can find with two different heating power, heat pipe still works very good, it transfers energy out very efficient and the monolith’s temperature are not changed too much. We also change the heat transfer coefficient in the left figure, and also the conventional temperature of heat pipe as in the right figure. All of them, the monolith and fuel temperatures are not affected too much, which means all these parameters are under the limit value of low sensitivity test.

In section three, we introduce our work on steady state and also a test of sensitivity for different numbers of parameters. After that, we start to think about what we can do for some change in the safety case, what we are having is different numbers of heat pipe flares or heat pipe flares at different time, so we want to check and to greatly offer heat pipe micro reactor in some transient case.

The first group of transient is listed in this figure. Case 1 is the base case. No heat pipe flares, and in Case 2 as we discussed before, so we have four rings of heat pipe. In Case 2, first ring of heat pipe flares, Case 3, first two rings of heat pipe flares, three ring heat pipe flares and four rings of heat pipe flares. That is the difference between Case 1 to Case 5 in the transient safety calculation.

Then we come to the calculation results. First result we want to check is the maximum and average fuel temperature. We can see here, the pink line with [Unclear] flares, the temperature increasing to super higher, which is about 1400 Kelvin, almost to 1500 Kelvin. It's much higher comparing with maximum temperature of stainless steel, and of course, it's greater than the integrity of heat pipe micro reactor system. At the same time, we can compare the other calculation results, and we have the lines, when more heat pipe flares, the temperature increasing could be much higher.

Speeding could be much higher, and our final temperature is also higher. The same situation is observed in the field of average fuel temperature. We also checked the peak and average monolith temperature, and in these two figures, we get rid of crazy pink line, and here we can find like again, the temperature when more heat pipe flares, the increasing of the temperature is much higher and also the final temperature could be higher comparing with different other cases. The tendency is then in different parameters, no matter it's maximum or average monolith temperature.

Another parameters we can compare is the temperature distribution and this line on the surface of a cross section from top view. We can clearly find the comparison from Case 1 to Case 4. The peak point is the location of fuel and the lower point is location of heat pipe, and then the connection is the monolith, and we can still clearly see like multi-pipe flares, higher temperature [Unclear], at least it is three link flares, two link flares, one link flare, and bright line is in a steady state.

We selected the two case examples to show the temperature to the temperature cloud. These three figures are heat pipe, monolith from side view, monolith from top view. For heat pipe, we can find the real pipe in the bottom, so where the heat pipe is inserted from the monolith, our center temperature is much higher and the cloud view from side could be something like this, and the temperature distribution is similar to a cosine distribution, which might adjust the definition of the fuel power, initial condition, and also we observe the similar thing on the 2D heat pipe distribution here.

We can also check values of the heat pipe. We already discussed like the heat pipe in ring one and heat pipe in ring two flares, if we all go like heat pipe one, heat pipe three, ring one and ring two, that we are first to the bottom, same through the condensing temperature of 750 Kelvin, and heat pipe 15 is from ring three, and that is why it is still working. When some other heat pipe flares, the burden of heat pipe obviously increases, which transfers more energy from the system, more energy transfer from heat pipes, it might be just consideration will be observed for the temperature.

Another case is case file. In this case, all heat pipe flares and the [Unclear] the 2D heat pipe situation, temperature here doesn’t make any change. Also we check the monolith temperature from third view, from top view, and we can observe light. If we compare a cutter, it's over 400 Kelvin, below 1500 Kevin, its super higher, higher than the melting temperature of less than it is there.

Also for the situation of heat pipe, every single first time of heat pipe failures and there is not any heat energy transfer from a system from all the heat pipe, no matter it is from ring one or ring two or ring three.

Let's look at first group of our calculation and we compared different numbers of heat pipe flares and we checked our results. After that, we considered what will happen if things have, if the same heat pipe number of flares, but it happens at different times. Here we keep the case one, steady state, and we use Case 3 as the base case. Here two heat pipe flares at 0 seconds and from Case 6 to Case 7, all of them are two rings of heat pipe flares, but it happened at different time, 500 seconds, 2000 seconds, and 10,000 seconds, and then we check what will happen.

Here are the results. First result I showed here, it's the maximum and average fuel temperature, and we confirmed like case one is the stage state and fully other case, they have the same tendency, but at some point, the temperatures were increasing because two rings of heat pipe flares and the monolith and the heat pipe are suffering at higher energy input. At some point, where it comes to a stable state and the peak temperature will stay here. The tendency for all of these case are same, but it's [Unclear] delayed due to difference on failure time of heat pipe, and also the situation is similar for average fuel temperature.

Then we also check the situation for the maximum and average monolith temperature, same conclusion here. All the cases are canceled delayed, depends on the different failure time of the heat pipe. Now we compare the 2D cloud temperature of cases 3, 6, 7, 8 at 5000 seconds. At this point, Case 3 and Case 6, so Case 3, heat pipe fails at 0 second, Case 6, it fails at 5000 seconds. For both of them, at 5000 seconds, and the temperature really reaches the steady state at a peak point. In Case 7, the temperature is still increasing. In Case 8, nothing has happened yet at 5000 seconds and that is why we have the different temperature in different case.

Another temperature comparison at 20,000 seconds actually end of the calculation. We have observed 10 CR single SAM for this plan at X axis, and the peak point is fuel and the low point is heat pipe, and at the end of calculation, all of the case reaches to its peak temperature, so no matter how long you hold the failure of heat pipe, finally, it will come to the case of heat pipe. The only bright line here is at a steady state and full of comparison.

Here we selected one case, Case 8 as an example to share a distribution. Here is the heat pipe, monolith from side view, monolith from top view, and if you still remember what I showed for Case 3, so I had 20,000 seconds, the temperature distribution is 10 from Case 3.

We can also check the situation of heat pipe. We can select new one and neutral flares at 2000 seconds and ring 3 and other rings are taking higher height and higher burden, and the situation is same for any heat transfer system. In this second group of our calculation, we check heat pipe, two rings of heat pipe fails at different time, and we get to the conclusion like the delay of heat pipe failure once change of tendency of the change in the case, but it will be delayed due to different delay of heat pipe failure time.

Finally, based on all this calculation, no minor steady state or transient safety calculation, so we can safely come to our conclusion. We successfully developed our 3D and 2D SAM and most covering system and the prior to the heat pipe micro reactor, and we checked that energy can be safely removed from the primary system to secondary system via the heat pipe technologies. We did a steady state calculation and checked some critical parameters for sensitivity analysis. Also, we checked some transient safety case to check different numbers of heat pipe failure and heat pipe failures at different time, and we can come to a conclusion like in some case of transient case, can [Unclear] the integrity of the heat pipe micro reactor system.

In the future, we are working on foreign projects. First is, we will do the more detailed heat pipe model based on average design and we will work on these by covering with Westinghouse, and at the same time, we will develop the heat exchange technology. We might use super CO2 to transfer energy from a condenser heat pipe part to that in the secondary side, and always work on cooperating with Westinghouse eVinci Group.

Analysis that we can do is consider enrichment of the fuel in the micro heat pipe micro reactor system coupling to neutronics and thermal hydraulics and set the fuel into different ignition power in the calculation. Actually, at the end of the presentation, I would like to thank for the financial support from United States Department of Energy, NEUP Program, and I would also like to thank for the support from the MAGNET Manager, Dr. Morton from Idaho National Lab, and also to Dr. Hu from Argonne National Lab, the developer group of the SAM software. Thank you very much for your support. I also would like to thank all audience for their patience and their time to listen to my presentation. Please let me know if you have any questions. I will be more than happy to be here to discuss the details with you. Thank you very much. Thank you.

Bertha
Thank you, Dr. Wang. As questions are coming in, we'll just take a quick look at the upcoming webinar presentations that we have scheduled. In December, Development of an Austenitic/Martensitic Gradients Steel by Additive Manufacturing, that presentation will be given by Dr. Villaret. She is the winner of the Pitch Your Ph.D. Contest. In January, ESFR SMART, a European Sodium Fast Reactor Concept including the European Feedback Experience and the New Safety Commitments following the Fukushima accident by Dr. Joel Guidez. In February, Artificial Intelligence in support of Nuclear Energy Sector by Professor Nawal. We do have some questions. Let me set it so that you can see them as well. All right, so you should see a pane that has the questions listed, both you and Patricia, Dr. Wang. The first question is, do you consider the thermal properties of vapor, wick, and wall constant with temperature?

Dr. Jun Wang
Thanks a lot for this question. For sure, the vapor, the coolant and the temperature adds to change because ignition status – you are asking some properties. For the wick, and also for the wall, we are using a constant temperature, and for a current, we are using constantly some properties for a material, and for the 2D sodium, I assume in the 2D heat pipe model in SAM, some properties could be changed due to different temperatures, but we have to check with our code developer from Argonne National Lab.

Bertha
Thank you. The second question was what is the wick material?

Dr. Jun Wang
The wick material, it could be very different from the different design. If you want to check with details, I suggest you Google a company's name called Advance on coolant technology, and it's specific, it's an industry supply for different types of heat pipes. There are many wick materials, can be considered there, and our modeling, and since we are using the same material with the MAGNET facility from Idaho National Lab, so wick material we use here is stainless steel as it will be very different from the reality and the industry use. Thanks.

Bertha
Thank you. How do you model HP inside two phase flow?

Dr. Jun Wang
For this question, so we are using a 2D heat pipe model, which is developed by SAM, so this work is published in SAM user's menu, which is released, and also we published the book introducing different software application in nuclear power plants. The book name is nuclear power plants, software development and verification and application, and in one of the chapters, we explain on the heat transfer modeling of heat pipe.

As you can see, it separates the heat pipe into nine different parts. Its three blocks from internal to outside, is the coolant, wick, and wall. From left to right, it’s vapor, adiabatic, and condenser. In each of the block, it's something like a node and the layout could be energy and mass transfer between each nodes. If you want to check more details, you are more than happy to read SAM's user's menu, and the book chapter I just the mentioned. Thank you.

Bertha
Thank you, and the follow-up is can you predict HP failure due to internal two-phase flow limitation?

Dr. Jun Wang
Okay, thanks a lot for this question. Since SAM is the system network calculation code, so we can see this problem, and we did a transient case from a system network. In this calculation, with [Unclear] heat pipe flares and when it flares, there is no heat transfer from a heat source to a heat sink. If you want to predict and look into more detail, so for heat pipe of an internal model, I don't think SAM is a good option. Another software I would like to suggest is Sockeye. Sockeye is a software, origin from Los Alamos National Lab and it is specific to look into the details, including the two-phase flow in a heat pipe. Thank you.

Bertha
Thank you. What would you expect the efficiency of heat pipe to be?

Dr. Jun Wang
Okay, thanks for this question, so expectation at this moment is 2 kilowatts per heat pipe. That is the calendar suggestion and expectation. As I mentioned, we are also making efforts to try to improve the efficiency of heat pipe. It depends on some parameters. I think the most important parameter affects the efficiency is the diameter of heat pipe. Just to think like you have limited volume for coolant, and you can increase it to a large volume, so more liquid sodium could be containing like in a heat pipe, so more energy could be transferred and some other parameters could be things like similar properties of the wick and the wall which decide how much energy and calculation speed from a primary system into a heat pipe. Thank you.

Bertha
Thank you.

Female Participant
Dr. Jun, did you have a chance to simulate the effect of power increase on heat pipe performance, power transient, and if so, this sheds light on the following, and did you model the startup or shutdown of transient? Can you see that one? Do you want me to read it again?

Bertha
I am okay, it's a long question. I'm still reading.

Female Participant
It is long, yes, I was going to say it, yes, it is a lot harder to read. It's not easier to read.

Dr. Jun Wang
In this calculation, I mentioned we focused on a system network calculation, so we mostly are looking for a hot pot in the micro reactor system. Audience asked how we can see the effects on a heat pipe performance, so the answer is we didn't consider this situation, but we have some parallel projects to study the heat pipe performance individually. For example, our collaborators from the other ones, the current technology and Argonne National lab, we are making a lifelong time, performance test for the heat pipe, which means we put heat pipe layer, put into radiance environment and change a bunch of parameters and check the situation of how it affects the situation of heat pipe, but it's not a part of the numerical work.

In my model, yes, my model is startup and the shutdown transient, so it's a very simple model, so we can see it. For example, for the group two, on calculation, we assume some of the heat pipe, it starts to flare at 400 seconds, and then absolutely flares at 500 seconds. There could be a linear difference of the power. This is how we consider this startup and shutdown transient in our calculation, but of course, the real case from the experiment is much more complete, and our collaborator of the SAM developer is there and working in another group, so both of the group in Argonne National Lab and University are working together to improve the heat pipe model in this code. Thank you.

Bertha
Thank you. Do you think to consider in the future other types of heat pipes and fluids different from sodium?

Dr. Jun Wang
Yes, sure, so there are many fluids that could be used, so of course we can use light water in a heat pipe and the sodium, and we can also use some other current in heat pipe such as silver, and there are also some different options, but currently we are mainly focused on sodium because sodium performance can match the demand of heat pipe micro reactor, and the cost of sodium is acceptable. For the other different coolant, we also still meet some proposals to try and to check and to try some different fluids, but different materials have different limitation. From a safety side, from the cost side, and yes, we can see it, we built some proposals changing the fluid. Thank you.

Bertha
Thank you. Will the thermal property of the base flat be considered in flat pulsating heat pipe simulation?

Dr. Jun Wang
Thanks a lot for this question. I don't think we can see it in flat pulsating heat pipe simulation.

Bertha
Thank you. What is the orientation of the core heat pipes in the magnet?

Dr. Jun Wang
Okay, yes, it's a very good question. In our modeling, at least in our modeling, currently we can see that it's water and the [Unclear], so different from the other different types of reactors such as cooled by water meter. This heat pipe micro reactor, we have to cool the solid structure, fuel rod is solid, modulator is solid, and heat pipe, you can also consider, it is outside, it is also canceled to solid components. I don't think that our retention of the coolant or heat pipes will affect the results too much, but I think it's a good point that we can check like in the future. Thank you.

Bertha

Thank you, what were the state-of-the-art efficiency on the electricity generation side? How mature are different kinds of TEG technologies and what would you recommend, thermal property?

Dr. Jun Wang
Yes, the different TEG, so it depends on heat transfer condition, so yes, I don't have too much study on TEG technology, but I know the heat transfer condition should be from 10% to 15% for this technology, and of course the higher, the better, and also for the TEG technology, one of the most important thing is trying to reduce the voice and trying to keep the voice in the lower limit. That is two important parameters, one is heat transfer coefficient, and the other one is the voice. Thank you.

Bertha
Thank you. Can you comment on the heat pipe response with increasing number of rings failed?

Dr. Jun Wang
Yes, of course. Thanks a lot for this question. Of course, each heat pipe can still take 2 kilowatts of energy and when more and more heat pipe fails, the remaining heat pipe has to take in higher burden. No matter heat pipe, not only the heat pipe temperature were increased, but also energy transfer of each heat pipe were increased. To some point, it will reach us to a limit point and then state the integrity of the system. At this moment, as we already discussed, the calculation is based on experimental facility, so a lot of materials such as monolith, fuel, and stainless steel, so it’s still different from the reality.

Next step, we were working with Westinghouse, eVinci Group and using uranium and we used graphite for the monoliths, and then when we are checking, I think some results are closer to industry. At that point, I think we can reduce the risk to respond to this question. Thank you.

Bertha
Thank you. Are there wells in heat pipes that might be failure points?

Dr. Jun Wang
I don't have answer to this question, but we have experts in our campus, name is Professor Mark Henderson. I think he will know if there could be any wells much better. You can Google Mark Henderson at UW-Madison and whoever you can to give some comments to this question.

Bertha
We appreciate your time in sharing your expertise with us Dr. Wang, very interesting presentation of your research. That's all the questions that have come in at this point. Thank you to the audience for having such a lively and engaging question and answer period. It's always impressive to see

this kind of enthusiastic response to the presentations, and I really appreciate your engagement.

Hopefully, the system is setup to launch a survey after this webinar presentation. It'll be the first time I've tried this, so I appreciate your feedback, and I’d appreciate everyone's attendance. Patricia, do you have anything to add before we close the session?

Patricia Paviet
No, I don't have anything to add, but again, I would love to thank Professor Wang for giving a great webinar. Also, it’s so interesting, the Q and A session. Thank you so much for taking the time to ask questions and thank you Professor Wang for answering those questions.

Dr. Jun Wang
Indeed, thank you. I also would like to thank you for the invitation and also thanks for all audience’s patience and your time, and they were all great questions. Thank you very much.

Patricia Paviet
Thank you very much everyone. We wish you a good day. We will see you on the 15th December. Goodbye.

END