MicroReactors: A Technology Option for Accelerated Innovation

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Berta Oates
…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 is also the chair for Gen-IV International Forum Education and Training Workgroup. Patricia.

Patricia Paviet
Good morning, good afternoon, good evening everyone. It's a pleasure to be here with you. First of all, I wish you to stay well, safe. And as Berta told you, we are going to have 3 presenters today. So, it's the first one. The first presenter will be Dr. Dasari V. Rao from Los Alamos National Laboratory. He is nuclear and mechanical engineer with 25 years of experience in safety and safeguards of nuclear and high hazard facilities. His technical areas of expertise include computational fluid dynamics, neutron and radiation transport, and risk assessments of nuclear energy system.

He has over 30 publications in these fields. He is presently the Director of the Office of Civilian Nuclear Program at LANL. He is also the Technical Advisor to Dr. Jess Gehin, the National Technical Director for DOE Microreactor Program and he is the Principal Investigator for NASA's Fission Surface Power project.

Our second speaker today is Holly Trellue. She received her Ph.D. in Nuclear Engineering from the University of New Mexico in 2003. She is a Team Leader at Los Alamos National Laboratory; the Technical Area Lead for Technology Maturation for the DOE-NE Microreactor Program and she has experience in reactor simulations and safeguard.

Finally, our third speaker of today is Yasir Arafat. He is currently serving as the Technical Advisor to the DOE Microreactor Program from the Idaho National Laboratory. He has 10 years' experience in leading and executing research and development project, primarily in advanced reactor development. He was the founder and technical lead of the Westinghouse eVinci Micro Reactor Program, where he was responsible for leading the overall product design, technical and programmatic development of the microreactor design.

So without any further delay, first of all I actually thank all three presenters with their enthusiasm to present to you this webinar and I give you the floor, D. V. Thank you again for volunteering.

Dasari V. Rao
Thank you, Patricia, for the opportunity, and I also would like to thank Patricia for taking on or organizing these fora. This is an exciting opportunity for us to present our vision and what we hope to achieve in microreactor R&D. And before I go too far, I also would like to thank Berta and of course others who have helped me put this presentation together which is Holly and Yasir.

So, before we go too far, I wanted to define what we mean by microreactors and the context. If you see at the bottom of my slide, that is the energy in terms of in keV or kV. So, what you are talking about there is the kilowatts. The nuclear comes in all sizes, all the way from sub-kilowatts, so hundreds of watts, tens of watts, to thousand megawatt electric reactors, that are the standard. Most people are aware of the 1000-megawatt electric plants. These are the big LWRs such as the AP1000 units that are under construction in US. Many of you are also aware of the next one which is referred to as the 'Small Modular Reactor' where each unit is small but at the site there are 12, 18, 24, whatever number of units bringing it to about 1000 megawatts.

Other extreme is where Mars 2020 or various other NASA missions you keep hearing about. That's where you have jointly Los Alamos, INL, and Oak Ridge under DOE leadership have been producing RTG sources and those RTG sources are anywhere between ten to hundreds of watts of electricity. So there is a big area between those small modular reactors and all the way mmRTG. The microreactors are as a program and as a product designed to fill that gap, that gap between what's a SMR and what's a micro RTGs that are there.

So, the topic of discussion for us today is any reactors that are somewhere around 1 kilowatt electricity to somewhere around 10-20 megawatts of electricity. There is a reason why we've done that and one of them is that reactors in this particular energy range, they generally tend to have low volumetric heat generation and also have certain neutronic features so that you can actually control them much more effectively compared to reactors, especially the 1000-megawatt reactors.

And a vision here is that taking advantage of those controllability aspects of these small or microreactors, we can achieve a lot in terms of remote operation, be it in space or at remote locations. So that's what drives the national interest right now. Because they are so small, you can bring in innovative designs and through development cycle make them affordable and development cycles can be rapid. Both DoD and civilian industry is looking for reactors such as this to power the microgrids. Such microgrids may be to help provide resilience against storms or against cyber issues, all kinds of things. Or they could be simply renewable microgrids. And those are the national drivers that are really providing enthusiastic support to this effort.

As we go through here, in addition to national drivers the R&D that's being reviewed or being presented now has two other intersections. One is with the nuclear facilities. In particular, small startups do not have the nuclear facilities or access to the fuels or access to multi-year research programs that can give insight into new materials, be it nuclear materials or not. So one of the things that our labs are bringing to the microreactor program is so that private companies, small or big, can use the nuclear facilities that are at the labs.

And finally, there is also the other intersection which is that it really aligns with the science priorities of the labs and the nuclear industry, which is can we accelerate innovation? Innovation can be accelerated through either through manufacturing, it can be accelerated through completely new way of thinking in how to enable heat transfer or using new heat transfer methods or materials. These are all the priorities that have been there, and I think microreactors provide an opportunity to put them to test. So as a result, we view microreactor R&D right now as being the intersection of these three national drivers, nuclear facilities, and the science priorities for the DOE and the industry at large.

Given that, what are the things that we do regularly in that is we go out to industry and seek their input. And based on their input, in a technology neutral way, we investigate materials, fuels, or high temperature moderators and we are also getting nuclear data on some of these materials. We are making prototypes and the prototypes are to demonstrate can we make advanced manufacturing, can we embed sensors, and can we demonstrate at different scales the ability to do simulation and experiment at the same time?

In the end, we are hoping to come up with multi-scale nuclear validated codes and have test beds and of course also give access to National Reactor Innovation Center.

So, let's go to a typical microreactor design. I am sorry for that interruption. It's usually the microreactors here could have high assay LEU. Some are using metallic fuel. Some are using ceramic, which is another way of saying uranium dioxide or uranium nitride or uranium carbide, and some are using TRISO fuels. So, the research we are doing actually is to help all those designs.

The second point of it is few companies are designing the reactors to operate in the fast spectrum but many are operating in the thermal or intermediate neutron spectrum, and that is those choices are made in each case to suit their market niche that they would like to go into as well as fuel availability. A fast spectrum reactor in general gives you much longer timeline but you have to start with full reactor core loads of maybe 1 ton of HALEU as an example.

A thermal neutron spectrum may not give you such a long life, but you can start off with few hundred kilograms of HALEU. Those are the type of marketing as well as product designs that the companies are making. A large reflector surrounds, that is the reflector in here. This is the core and that's the whitish and it's lighter. That is the reflector. And usually the reflector is made out of either beryllium or magnesium oxide or a variety of different materials depending on people's choice again, the size, weight etcetera.

It does two important things. One of them is that because these reactors are in this particular case [Unclear] limited, the reactor only becomes critical when it is surrounded by the reflector. So you can put lots of controls such as control drums, control rods etcetera in the reflector and you do not have to put or engineer the control drums, control rods, etcetera inside the core. That makes core design and core fabrication and assembly much easier. And after of course it achieves criticality, heat generated in this core is extracted out either through channels that exist in here, so you can circulate air or molten salt or gas, or you can use heat pipes to transport heat from the core to a heat exchanger. Or in certain cases whether there is a heat exchanger or it could be a direct Brayton as well.

So structural material options for this type of designs or high temperature creep-resistant steels. People are using molybdenum. People are using various other new and innovative steels that are being part of our tube. And not only that the materials are new in some cases, but also the way it's made such as using additive manufacturing and others is being brought into this as well. So, there are some companies that are looking at advanced ceramics or metalized ceramics and some companies that are using graphite for the structural materials.

Key technology enablers for microreactors. And this is in many ways make or break type of thing for these reactors. One of them is that those reactors and the internal components have to be factory built. What I mean by that is that building a reactor at a site as we do today with 1000-megawatt reactors. That's very expensive. As it is microreactor economically, they become viable only if you could cut down the cost of fabrication and factory building, and assembly lines is the way to do that.

Equally importantly, it also has to be easy to operate. What I am showing here on the right is where although I don't go into the details, a reactor that is operating at steady state if for any reason the power draw needs to go down, which is what that yellowish line is, then the reactor power draw means how much heat are you drawing from the reactor so you can generate electricity, the reactor power should automatically follow. It's called 'load following.' And how it follows the load and returns to stability real fast, that is the important aspect here. So, the power draw going down, reactor needs to self-adjust power with very little need for controls. And in this case, 20% draw and then another 40% increase.

I'm just trying to show you that the reactor and the temperature of the fuels, everything else returns to safety with no need for any active controls. Now, these are kinds of things that we like to assure that the reactor can perform. That does not mean we are campaigning that there are no operators needed. But you want to figure out a way so that the reactors self-govern themselves and the operator and active controls become back up. And that is then they are easier to license and that also means as part of the reactor development we have to think about methods to demonstrate such self-governance. And a big part of test beds is to enable people to demonstrate that their reactors can do self-governance and that their reactors are safe so that the regulators in return can have the confidence they need to license it.

So what we do is we figure out various different ways the designs may be done and we try to collate those challenges. But our R&D focus in the end tends to be concept and technology neutral, focusing on these types of things. Can you make this type of a core internal? How would it perform under intense temperature and cycling conditions? And is it controllable, is it walk-away safe? These are types of research that we are doing.

Why is this research? And the importance of it is that in many cases when original nuclear innovation was going on, I have this one slide where on the top left you can see nation as a whole with three big companies: Combustion Engineering, Bettis and CAPS. They were up to – if you actually pay attention, at any given year they reached a maximum of about 18 criticality facilities in the country. They were of different complexity all of the way from zipper to places where they could actually demonstrate reactors. So at the time of innovation we were driven very much by experiments. Because behind that was the philosophy that unless you built one, you really didn't know how well it performs because our computational ability to compute criticality and others was very limited then.

And many people that are in the senior regulatory position right now have that background, that you should be able to demonstrate the technology.

But over time, starting in 80s, the number of places where we can do experiments has gone down but the ability to do computation has gone up. So now we really have very few nuclear experimental sites. And one of the things that we are trying to achieve through R&D in microreactors is what's the right mix for these two to merge and where can we get away with just doing limited amount of nuclear experimentation like the criticality benchmarks and others. Where can we get away with using non-nuclear test facilities and where do you really need ultimately a nuclear demonstration? And what nuclear demonstrations can be done at the National Reactor Innovation Center?

So that is what we are trying to put all those pieces together and I believe we made a fairly good start which Holly and Yasir will show you. But that is really the bigger challenge, how do we merge the theory with the experiments, try to bring along people that have always relied on purely experimental data to certify or to feel comfortable about their designs.

Here is an experiment that we've done. It is the kilopower of KRUSTY experiment and this one was done for NASA. It can be an example of types of things we could do in the microreactor. When I say we could, I mean the whole nation. I do not mean the 3 speakers that are here or the three labs or the two labs that we are talking about. It is that we needed a solution for the reactor. We first figured out what are available resources and how do I buydown risk, risk to force through – how do I buy down risk by making smaller cores using existing facility where I can't wait to bring a new facility online. What can we do?

The next is how do I bring in advanced fabrication and demonstrate that the advanced fabrication or the products that came from the advanced fabrication will actually take the thermal stressors and all the rest of them so that you are buying down the risk. So, the microreactors give you an opportunity here to be able to do an engineering demonstration unit that is full scale. You do not have to compromise on that aspect because it is small enough. So you buy down the risk again until the last step then is a very limited amount of nuclear testing that you need to do that actually demonstrates that it can load-follow and perform. Lessons learned can be used to improve but the idea is how do we make innovation cycle, how do you shorten this cycle, and that's where we hope through various design maturation efforts that are underway, we hope to demonstrate that.

This is the KRUSTY experiment, the so called the 'Admiral Test.' Because we have gone through many of those steps I described to you, the KRUSTY experiment we were able to do just for few days and show in these cases, although I will not go into detail, the experiment is fully instrumented. And here when you start drawing down the power and are going up in the power and you can see the fuel thermocouples, the reactor self-governs power. When you go down by whatever percentage, I believe that's about 20%, in power draw, the reactor feels just a blip and gets back to steady state, feels a little blip, gets back to steady state. That's what we expect, the return to steady state, so you need very little amount of operator control.

My colleagues Poston and Pat McClure, they are publishing much of these results in a journal article that is to come. But this is a demonstration of things that we can achieve as labs and as a community to shorten the innovation and to revitalize the nuclear.

So, with that, I've set the vision and I am actually turning to Dr. Holly Trellue. So, Dr. Trellue says she is just a team leader. I and the whole program counts on her to run this program, especially the tasks related to technology maturation.

As Dr. Paviet introduced, when she introduced she let you know that Dr. Trellue received in Ph.D. in nuclear engineering from University of New Mexico. She's been at LANL forever and it is my pleasure to introduce you to my colleague and dear friend, Holly Trellue. Holly, please take over.

Holly Trellue
Thank you, D.V. Hello everyone. I am Holly Trellue, the lead for technology maturation area of the DOE microreactor program, which involves a great number of people across the nation including D.V. and Yasir but also others at many different laboratories to be able to work on these great challenges for microreactors.

Today I will be discussing some of the materials and technologies that we are researching.

First, the fuel types being examined include uranium, molybdenum and nitride with enrichments up to about 19.75%, otherwise known as high assay low-enriched uranium fuel. Uranium oxide that is commercially fabricated with enrichment below 5% could also be of interest. Finally, metallic and TRISO fuels offer potential. As part of the DOE-NE microreactor program, we are researching advanced moderator material to significantly reduce the fill mass by slowing neutrons down and increasing the probability of fission [ph] and thus optimizing energy production.

Moderator materials that are being examined include zirconium hydride which has a low neutron capture cross section and optimal system performance but suffers from hydrogen diffusion at temperatures above 500 degrees Celsius. Yttrium hydride can retain hydrogen at higher temperatures and still offer good neutronic performance and we will discuss that here in just a moment. Also, other alloys could be of interest.

And in other reactor types, microreactors will have control, structural material, and shielding. Because the system is so small, as D.V. mentioned, we use a reflector to help contain neutron within the core.

Metal hydrides that are being considered in the microreactor program have been machined in the past as shown in the pictures below, both for zirconium and yttrium hydride. Different techniques exist for the fabrication of yttrium hydride including direct hydriding which is well known and shown on one of the pictures to the left, and powder metallurgy which is a promising new technique that produces stable material with fewer cracks, as shown by sintered material to the right.

Where these have been used, some a little bit in reactors such as zirconium hydride and others have been used in the past, we need to develop these materials even further through some other programs which we will discuss here shortly.

The reason that we are researching yttrium dihydride is for its ability to retain hydrogen at higher temperatures than other moderator materials. As shown in the figure to the right, where the hydrogen atom density is on the Y axis and the temperature on the X axis, lithium comprises a larger hydrogen concentrations at higher temperatures than the other material. As you can see there, water is listed on the chart. We also have other types of hydrides that really drop the hydrogen concentration, meaning if the hydrogen diffuses out or removes it from the material as the temperature heats up in the system.

To be able to produce power efficiently in a microreactor, we would like to be able to operate as high a temperature as possible, thus having yttrium hydride is a benefit for the system. Yttrium hydride also has thermal stability compared to other metal hydrides, a relative low thermal neutron absorption cross-section and good elastic properties.

There are some challenges associated with yttrium hydride fabrication and the fact that near net-shape parts are difficult to achieve for complex geometries and large amount of hydriding may result in structural degradation. In particular, we have some issues with cracking on occasions, but there are lots of different multiple fabrication techniques and advancements that have been made to reduce these concerns.

The behavior of yttrium hydride under neutron irradiation environment is also something we are interested in. In particular, we have been looking at tests of irradiation in research reactors such as in advanced test reactor at Idaho National Laboratories.

Let me go back up to that slide. Test characterization on yttrium hydride has occurred refresh material but now properties such as heat capacity, thermal diffusivity, microstructure, elemental composition, and elastic properties will be examined during post-irradiation examination. For this particular test, we will be putting in various samples of yttrium hydride fabricated using both techniques: the powder metallurgy and direct hydriding at several different temperatures and irradiating it for several cycles as possible. We will be looking at those results and characterizing the measurements at the end.

Additionally, we will be testing the behavior of yttrium hydride through an integral critical experiment at Los Alamos' National Criticality Experiments Research Center. The goal of this experiment is to understand the transient reactivity feedback of yttrium dihydride such as that D.V. discussed earlier. High-enriched uranium material will drive a criticality experiment and a central region of yttrium hydride will be heated at various temperatures and behavior of this system with and without the yttrium hydride at short timescale after startup will be analyzed.

Beyond moderator material, we will explain different technique for heat removal from a microreactor system. Removal of fission heat from the reactor core will probably occur through either heat pipes or gas coolants, but possibly other options. Such heat transfer concept includes latent or a phase change of a working fluid, sensible or changes in temperature, and physical mechanisms such as thermoacoustics. In particular, we are initially designing our nuclear test articles with heat pipes as the heat removal mechanism. We will expand to other test articles in the near future.

Yasir will be discussing some of our testing capability with which we will be placing these test articles to obtain data to help us with microreactor technological development.

So, the first test article that we will be discussing is a 7-hole stainless steel, 316L monolith test article will be used for single heat pipe experiments. These test articles of up to about half a meter in length comprise a central hole with a single heat pipe and six outer holes with cartridge heaters to simulate nuclear fuel. Both additive and traditional manufacturing techniques have been researched for fabrication purposes of these articles.

An 11-inch long additively manufactured parts are shown to the right and they have been joined together using electron beam tier welding as shown in the picture at the bottom. These articles are fabricated with a laser additive manufacturing technique – a powder bed technique and we did several different renditions of these to be able to understand the straightness of the hole, how it tapers a little bit from the plate up to the very top, and then methods that we can use to correct for that and come up with test articles that need very little tolerances and will be used to produce data on a single heat pipe that we can use to help validate codes that we are developing through various programs.

The next test article being fabricated is a 37 heat pipe, 54 heater design that will produce thermal output. As shown on the far right, a 1-meter long section of core block would exist in the bottom half of the core with the heaters and a heat exchanger exists in the top meter of the article. Heat pipes span both regions of the core to provide heat removal core facility to the heat exchanger. Fission occurs in the bottom half of the core, and in the top of the core the heat exchanger removes heat which is sent to the power conversion unit.

On the bottom left are machine parts with 91 holes for the core block region and 37 holes for the heat exchanger region. To the right are approximately 11-inch tall additively manufactured parts. Once these articles [Unclear] we will perform experiments with an NMR nuclear test bed. In the meantime, we are performing analysis of these articles to understand their straightness and their ability to be joined.

We are also analyzing various instrumentations and sensors for use in microreactors in conjunction with the Nuclear Energy Enabling Technology Advanced Sensors In-Pile Instrumentation Program. Sensors initially being researched includes thermocouple for temperature measurements, fiber optic and acoustic distributed temperature sensors, differential interface contrasts for structural integrity and other sensors for stress and strain measurement.

I am now honored to present Yasir Arafat who will be addressing the testing and demonstration areas of the program for further upcoming plans in the DOE-NE microreactor program. Yasir, I will hand this off to you now.

Yasir Arafat
Thank you, Holly, for the introduction here. Hello everyone. This is Yasir from the Idaho National Lab. Like D.V., I am currently serving as the other technical advisor to the DOE-NE microreactor program.

Today, I will be covering two short topics that you will find very complementary to what D.V. and Holly talked about and is the need for integrated testing and demonstration capabilities of microreactor technologies. And we need such capabilities because microreactors are essentially a new technology and we don't really have any operational experience and they are often phenomenon that requires more than just modeling and simulation. And for such new technologies one needs to perform what we call two kinds of tests called 'separate effects test' and ‘integral effects test’ both for standup from a design manufacturing perspective and also to answer regulatory queries.

So today I will talk about two of these test capabilities that we’re currently working that are designed to help industry developers conduct such tests. And finally, to wrap up on how everything we talked about ties into the overall DOE microreactor program focus.

The first test that I’m going to talk about is called SPHERE which stands for Single Primary Heat Extraction and Removal Emulator. So, this test is designed to conduct separate effects test particularly on a particular heat removal technology. All the microreactors can of many different types. Nowadays, we kind of see most of the microreactor designs are either heat pipe reactors or gas cooled reactors or either of these types of technologies. You can test what is happening at both the hot end and the cold end of the heat transfer technology, whether they are heat pipe or a primary cooling channel.

So, it’s a fairly simple setup. We have a quartz tube which can maintain inert environment using a combination of a vacuum pump and an inert gas supply as you can see in the process flow diagram. We can simulate the reactor’s hot end using [Unclear] heaters and heat removal through a heat exchanger that uses a core water loop and has a turbine flow meter, a delta T-meter and about a 2.5 kilowatt chiller system.

And with this setup, you can simulate almost any type of primary coolant technology. Now when we started setting up this setup, the first test article that we are testing currently is actually a high temperature heat pipe. You can certainly simulate gas-cooled reactors as well using a primary coolant flow channel.

If we look into the next slide, besides sort of its fancy name, this rather simple setup has a lot of benefits and uses. First, we can test, conduct thermal performance evaluations of the primary cooling technology like a heat pipe for example under a wide range of operating conditions. Second, which I think to my mind is very important is to characterize a particular cooling technology in various transient conditions and take measurements like temperature or strain during various operation modes of a reactor like startup, shutdown, what happens during load fluctuations.

Now the nice thing about this setup is the chamber where the test articles lies transparent and you can use different instrumentation and sensor technologies like thermal imaging and techniques like digital image correlation to look at what is happening to the test article, things like displacement and thermal expansion.

You can also simulate a heat removal with your particular primary heat exchanger type that's built into your test article. And then third of all, if there are any specific thermal coupling methods which are particularly related to the pipe technologies, you can mitigate the conductors challenge. If you are developing technologies to mitigate that, you can basically try out different methods and test it here in this test platform.

And finally, all the data that you can collect from here can be used to benchmark your modeling and simulation tools.

The next one that I want to talk about is basically a larger setup with yet another fancy name called MAGNET which stands for 'Microreactor AGile Non-nuclear Experimental Test-bed.' And using the MAGNET we basically want to "attract" industry developers and regulators to basically come to the test platform and perform what we discussed, integral effects test. This is basically a bigger and stronger version of the SPHERE. It's rated for a 250 kilowatt electrically heated microreactor test bed. And we are currently targeting to complete this setup by the end of the summer. It is currently located at the Energy Systems Lab here at Idaho National Laboratory. Now, this is a multilab effort which INL is basically taking the lead at developing the overall test platform. And as Holly mentioned earlier, LANL is working on a 75-kilowatt heat pipe reactor test article. This is basically a 37 high temperature sodium heat pipes with cartridge heaters to simulate fuel. And we have an integrated heat exchanger on the other end to remove heat from the condenser portion of the heat pipes.

And also have Oak Ridge who is working on some embedded sensor technologies to diagnose what's happening basically to the test article and measure things like temperature strain across the test article profile.

Again, several benefits of this technology. This is obviously a first of its kind non-nuclear microreactor test platform that is capable of running integrated tests and so it's a pretty big deal. And we can look at our overall system performance. On the right-hand side, there is P&ID diagram of the system. I apologize you cannot read much, it's in very small writing there. I guess it was sort of intentional, so you can come and talk to us directly after this. I supposes I could explain on a high level. So, if you look at the P&ID diagram in the center, you basically have a vacuum chamber that houses the reactor test article. It's a pretty big chamber. If you think about it, it's 5 feet x 5 feet x 10 feet and this chamber can also get pretty hot. It's built in a way so it has hydro-cooling which basically helps to maintain the outer cooling surface of the vessel. It has a very elaborate cooling loop that you can see in the system in the P&ID with starting with from a heat ejection, heat exchanger which is basically in this location, a compressor to provide the [Unclear] force, you got the coolant around. That's at the bottom here.

And by the way, the system can get pretty high pressure, which can achieve as high as 0.2 megapascals. So pretty much you can try out any different kind of coolant types and pressures.

We also have a recuperator to pre-heat the inlet stream going into the test articles. And one of the best features in this system is there is an optional connect for a power conversion. Now you can run the system without a power conversion but if you have one, it's very easy to plug in to understand overall system dynamics between your reactor side and your power conversion side.

So, what do we do with this? Let me go over some of the benefits here. First, it can simultaneously simulate the core and the heat removal sections. You can look at the temperature profiles and the displacements at various operational conditions. And obviously you can compare them with their modeling and simulation. If you have tried out any kind of an advanced manufacturing method to make the test article, this is a great setup to actually hook it up and test it. Same goes for unique heat exchanger design. And you can drive almost any test article. If you want to drive it to failure, you can do that provided you can clean up the mess afterwards. So if you are developing advanced sensors and instrumentation to achieve things like autonomous control, there are enough penetration ports in the vacuum chamber to allow for that basically.

The second item that I want to talk about you can also look at and evaluate structural integrity of core sections like monoliths for example and other core materials to look at what's happening at the thermal side of things like stress, deformation, to understand creep behaviors.

Third, if you are trying to interface between heat pipes of both the core on one end and the heat exchanger, you can understand the dynamics between the two. And last but not the least, you can look at and study cycling loading with a simulated reactivity feedback system like we did in the past with space reactor prototypes, and D.V. has gone over some of that in the previous slides. So, the most important part to me is this setup is basically technology agnostic. You can basically bring any test article and any power conversion system that represents your particular microreactor design, and you can merge this overall system behavior before we go ahead and build a nuclear demonstration.

So now I want to just pull you back and shift your focus to 10,000-feet level and look at the bigger, broader picture. Let me go back to my slide here, I kind of jumped here. So, I'm going to talk about now how this all kind of ties in together. So in this slide I am going to summarize what Holly and I and D.V. basically talked about and how they all fit into the three technical areas within the DOE-NE microreactor program and that are shown on the left hand side of this slide here.

Now, even though we are currently working on all 3 areas in parallel, they do somehow align themselves in what I call a 'microreactor innovation pipeline.' So if you look into the first area called System Integration Analyses, this is where we have a concept when you look at the market research, when you look at regulatory requirements you do some integrated modeling simulation, and then identify the technologies that need to be developed in the next stage. And that gets passed along in the technology maturation area and this is what Holly primarily talked about. Currently, we are trying to mature technologies that may be useful for industries like heat pipes, high temperature performance heat pipes, moderators that allow the reactor to run at high temperature but still allow moderation, advanced heat exchangers, instrumentation and sensors, things like that. Once you have matured those technologies, you can pass them along into the test beds that I talked about to see how they all together work synchronously in a single system. That's the current focus of our program right now. Once we have achieved that, eventually what we want to get to is shift our R&D focus to the R&D needs for microreactor application demonstrations. Things like hydrogen co-generation, how do we do a district [ph] heating, what are the R&D challenges required for autonomous operation or remote monitoring, etcetera.

And at my last slide here, as conclusion slide I want to take you back to what D.V. was talking about in the first slide of how all this effort and work that we are doing helped us achieve. What does it basically help us achieve? All the R&D that we are currently undertaking is geared towards fulfilling these three basic notions of what defines microreactors. First, they are factory fabricated. I mean they are entirely fabricated and assembled in a factory. So, question is how can we design microreactors to enable ease of factory fabrication?

Can we use things like advanced manufacturing for that machine? The second distinguishing factor is basically the microreactors are transportable and they are transportable typically as a single, fully assembled unit. Some of them are actually considered mobile where they can move from location to location. And question is, how can we achieve all these challenges associated with the transportation of a fully assembled and fueled reactor.

And lastly, microreactors are supposed to be self-regulating, so we don't need to worry about controlling it for safety or for operability. So, we can make them somewhat walk-away safe to the point where we don't need any more operators. If we can achieve all of that, we believe that microreactors can truly redefine how we generate energy using nuclear.

And in the current DOE microreactor program, it's a very focused program. We're not trying to tackle everything but we are trying to undertake the most challenging and impactful R&D needs that national labs can work on, that can accelerate the deployment of microreactors as quickly as the mid-2020s, and that marks the end of our talk. Thank you all very much for listening in today.

Berta Oates
Thank you D.V. and Holly and Yasir. If you have questions, please go ahead and type those into the Q&A pod. I see that there are some questions already in there. While people are still typing in those questions, we'll just take a quick look at the upcoming webinar presentations. In April, a presentation on the GIF VHTR Hydrogen Production Project Management Board. In May, Performance Assessments for Fuels and Materials for Advanced Nuclear Reactors. And in June, a presentation on the Comparison of 16 Reactors Neutronic Performance in Closed Thorium-Uranium and Uranium-Plutonium Cycles.

So, the first question D.V., let's take the first question directed to you. Dr. Rao, what is the thermal and electric power output of a microreactor? The IAEA has defined small modular reactor but not microreactor.

Dasari V. Rao
We have at the start of the effort spent quite a bit of time looking over what could be the range over which one would call it to be a microreactor. First, let me talk you through how we came up with a limit and why the limit by itself may not be the biggest discriminator. It's what makes a microreactor that's the discriminator.

We envision a microreactor where reactor system should be self-governing and walk-away safe. In other words, what are the features of the reactor that provide ability to control the reactor with controls located outside the reactor, the control drum, etcetera, and what are the features that are required so that the reactor can self-govern and is walk-away safe. In other words, even if the control is lost, it reaches a steady state where it's just generating enough heat that can be compensated by the losses through radiation and others. Approximately, these features can be met when the reactor power is limited to somewhere around 20-megawatt electric or less.

Higher than 20-megawatt electric, you could get one microreactor with these features, but they are extremely difficult to perhaps design and operate. So for the microreactors, we typically refer to them as anywhere from kilowatts or hundreds of kilowatts to a maximum of 20-megawatt electric. And that is our definition if I could use the phrase very loosely of the microreactor.

Berta Oates
Thank you. There is a question. There are lot of companies that claim to be working on the development of a microreactor. Which companies are actually close to bringing one to market?

Dasari V. Rao
Let me take and then maybe I'll also refer that to Yasir and others. There is one company that has very recently, as in last week or last 2 weeks, filed a licensing application. It's called COLA to NRC and that company is Oklo the product name is Aurora. And there are few other companies that are actively pursuing as you probably saw in a recent announcement that three companies were listed there – one of them being Westinghouse, the other BWXT and a third yet was X-Energy. These were listed in an announcement by Department of Defense. Other than those, there are various other companies. However, NEI, that is the Nuclear Energy Institute perhaps is a better source for who is closer to releasing a product. I personally do not have that knowledge. And either Yasir or Holly, if you want to take, that I welcome your contribution as well.

Yasir Arafat
D.V., I don't think I have any more to add to what you've answered. I've seen as high as 15 microreactor developers just in the US and Canada, between those two countries. You've mentioned the ones that are more on the mature side of scale but there are different other microreactor vendors. Some of them are R&D developers, some of them are also pretty matured. NEI reported a pretty good sources to look into. There are other references where we can look as well to understand who all are playing this. It's actually a very good thing. There's lot of top developers out there that are working on microreactors.

Berta Oates
Holly, do you have anything to add?

Holly Trellue
I do not have anything. They covered it well.

Berta Oates
The next question. In the case of uranium nitride, is the nitrogen natural N14 or highly enriched N15?

Dasari V. Rao
Great question. I think people prefer to have enriched because of the lower neutron absorption cross section. However, until that resource is available, perhaps the first set of reactors that use uranium nitride will probably have regular old atmospheric nitrogen, so natural in other words.

Berta Oates

Great.

Yasir Arafat
I just want to add a little bit to that question. So, the supply of enriched nitrogen is somewhat of a demand-supply issue. Right now, I think the nuclear industry pretty much is one of the only industries that is providing a demand signal for that. There are technologies or companies out there, particularly the ones that supply compressed liquefied gases. They have the technology to enrich nitrogen but it's all a matter of demand and supply. If enough demand signal is created from our side, there could be suppliers better available to provide that in future.

Berta Oates
Are you going to reactivity criticality test at 1000 plus degrees Celsius where they operate and hydrogen is more likely to migrate?

Holly Trellue
I can try to answer that. I am not sure that we are planning on any tests above 1000 for the most part...

Dasari V. Rao
Yeah, I was going to say that...

Holly Trellue
...will be 335 Celsius and below. There are other tests we can perform on materials at higher temperatures, but yes, at some point when the hydrogen migrates you have to make sure that's done safely and in different environment. We've done some tests where we've looked at yttrium hydride and we tried to look at the vacancies for this in the materials as a small amount of time at a higher temperature so that we can start understanding where those problems might occur before we design bigger tests.

Dasari V. Rao
I was going to add to that is there have been experiments done way back in the nuclear aircraft space. Whether hydrogen leaks out of yttrium hydride at 1000 degrees or more depends on the stoichiometry of hydrogen versus yttrium. For example, if you have to have yttrium to hydrogen stoichiometry of 1.2, I don't believe too much hydrogen comes out at 1000 degrees Celsius. But that is a design knob that the designers have in their arsenal to design based on what's the temperature that they expect to go to, both regular as well as normal and what do you give up by going lower stoichiometry. Next question...

Berta Oates
Additive manufacturing should be assumed for future core design that comment on the issues. For example, is laser powder bed fusion safe or

will the laser negatively affect the fuel? Can in situ monitoring be dependent on to ensure acceptable fuel characteristics? Are mixed materials suitable? How about ceramics and a metal matrix? How about built-in instrumentation?

Dasari V. Rao
I will take the last one because the first few of those I simply answer that that's what the research program hopes to find out. The last one, that is the metal ceramic is of interest to many for the structural materials because you could embed sensors in the metal ceramic matrix. And realistically, when you want to go up to temperatures of interest here, as previous question was 1000 degrees Celsius, etcetera, there are very few metals that you can rely on.

So, I think that is something we are going to study and we are studying and that's of interest. Maybe others can take the questions on the first set of things. But those are topics of interest to us. I don't think I have any insights into the actual – any research insights.

Holly Trellue
There is a question on the powder bed and additive manufacturing. Right now, additive is just being used – part of the research is to understand what type of material it produces, how structurally stable that is. And that is just doing non-nuclear testing and not involving the fuel at the moment, so we would capture research how it performs in the fuel environment later. The other part about instrumentation, yes, we are looking at in situ monitoring and other types of sensors to help ensure those characteristics. One of the challenges we have and especially in integral microreactor system is that its built initially and we can't get in very well to put sensors in later. We need to think about that during the design process is understanding what we can put in there to see neutron counts and/or other parts that are going on in the system, the integrity stress and strain. All those questions I think they were researching.

Berta Oates
Thank you. Anything to add, Yasir.

Yasir Arafat
I have nothing to add there.

Berta Oates
Okay, great. We have quite a few questions now. The list is getting longer. What about the needs and time for R&D testing and for fuel side of micro-reactivity?

Dasari V. Rao
Can you repeat?

Berta Oates
What about needs and time for R&D and testing for the fuel side of microreactor?

Dasari V. Rao
So, I would like to take that question first and then turn over to others. One of the advantages, if I could call it, of many of the microreactor designs we are looking at, they typically have very low burn-up and as a result the fuel data that we need for many microreactor designs, the fuel itself that is, is well characterized from other programs unless of course the fuels to be talked about are something like molten salts and others, there is some data that's needed. So as of right now, our emphasis has been on can you make the fuel and provide infrastructure so you can scale up fuel production. That's more of an emphasis than what data do I need to qualify fuels. But I could be corrected and I'm going to turn to other two, Yasir and Holly if they want to add something.

Yasir Arafat
Yeah, I want to add. As far as fuels are concerned, majority of the microreactor developers that we are seeing right now, they are trying to leverage all the work that has been done in the nuclear industry for the last couple of decades in fuel development. So we are trying to maximize that effort. And so we've seen folks using metallic fuel, most of the reactors that are being looked at by Strategic Capabilities Office that D.V. mentioned in the announcement last week for the mobile reactors, those are trying to leverage all the work that's been done in the AGR [ph] program on TRISO fuel which there has been a lot of work done in the past to qualify that fuel. So all in all they are trying to leverage what has already been done overall. And as DV mentioned, the focus is primarily on the deployment side of things rather than on the development and the R&D side as far as fuels are concerned. So, people are trying to focus on the production levels more than how to develop a new fuel for microreactors.

Berta Oates
Holly, any last thoughts?

Holly Trellue
I do not have any more comments beyond what they said besides that that is something that needs to be focused in the long run as we start trying to – vendors are going to have to take that into account in particular designing their plan to be able to get a system operational. We will support them as we can.

Berta Oates

So, economics, how affordable are NMRs compared to conventional reactors?

Yasir Arafat
D.V., do you want me to take that?

Dasari V. Rao
Yes.

Yasir Arafat
Microreactor economics is a very complicated topic. But in a nutshell, the way most of the vendors are trying to look at microreactors – obviously there is a lot of pros and a lot of cons when it comes to economics of microreactors but in summary in general microreactors are being sought to initially be deployed in non-grid type applications where if you want 1000 type or large scale nuclear power plants are currently providing electricity. Rather, microreactors are being looked at for niche applications like decentralized generation. Now why are they doing that? Because it is essentially a new technology, and like most new technologies that are deployed, they are going to be expensive. So, we are trying to tackle markets that pay higher amounts of dollars per kilowatt hour for energy. So things like remote communities, islanded communities, some commercial remote industries like mines for example, some defense applications that requires high resiliency, they actually a higher premium for power. That's the initial market entry.

The thought on the idea is once they are feasible and they are able to reduce the cost, then they can tackle other more mainstream energy markets once they are able to bring the cost down. But initially most of these applications – and they are going to be based on preliminary numbers, they look very competitive for some of the niche applications like remote communities and others.

May be D.V. and Holly can add anything to that.

Holly Trellue
I have nothing to add.

Dasari V. Rao
Yeah, I do not have. I think we usually rely on those – you are an expert on those things.

Berta Oates
How would the waste management efforts differ from conventional large-scale reactors?

Dasari V. Rao

Go ahead. I was going to refer it to you.

Holly Trellue
Okay. One of the things that certain designs have included is once you put the fuel in there and you do a radiation, it is again all contained within one vessel or containment area, is that we may not get to the fuel at the end and it would all be disposed as one big unit. So that would have a little bit of extra volume. But because of all the extra shielding and things are involved, they may think it's safer to do some things such as bury it underground. Now that being said, only certain designs may look at that, others may have ways that we need to pull the fuel out in the long run and it would have to be treated as any spent nuclear fuel. The burn-up may not be as large as in conventional large-scale reactors and thus we would accept it to treat it a little bit differently. That's all I have on that.

Dasari V. Rao
I have nothing to add.

One thing I would add is I think the – let's call it the 'shielding strategy' is a matter of what the customer is willing to take on on their sites and also economics. So if the economic allows, the easiest thing to do, as Holly mentioned, is to replace the entire reactor section which is the reactor, the reflectors around it, the control systems, all of that. And it is somewhat in a similar package as to how we store currently LWR fuels in dry casks. They have similar configuration, similar geometry, similar heat load. If the economics does not allow and there are benefits to recycling most of the other parts of the reactor besides the fuel, that is something that often some of the vendors are looking at to perform refueling not at the site but at a central location like a factory where they would transport the entire reactor, pull out the fuel, put new fuel in, and send it back to the site or a different sites. So, there are different strategies, and again the drivers are not technical, rather on the marketing and the economic side of things.

Berta Oates
If I were looking to test a reactor design in SPHERE or MAGNET, what information would you need, Yasir?

Yasir Arafat
We would like to know what the dimensions obviously are, what kind of a thermal power we are going to mimic as power inputs. We would also like to know what types of instrumentation and sensors that you would like to use. So we can understand if we can have enough instrumentation and sensor portals in the chamber. So basically parameters like what are your cooling conditions for example. That will help us understand what type of a gas we would want to use to extract heat out of the test article. Just those high level parameters. If you have any additional specifics,

feel free to reach out to me directly and I can certainly provide contacts to the subject matter experts of the MAGNET and the SPHERE and they can certainly give you a list of parameters that they would like to know before you go ahead and test it.

And the other thing is obviously there has to be a development of a test procedure which will have to happen between you who will bring in the technology, and us who has the platform, sit together and then figure out what does the test procedure look like overall. So, feel free to get in touch with me directly.

Dasari V. Rao
This is D.V. I just want to add one thing. There are two other people that I would like to acknowledge, especially any of these decisions related to how we would do the testing. One of them, and I don't know if they even joined in because it's such an early call, but Jess Gehin. He is National Technical Director. And also of course the DOE, the sponsor for this is Tom Sowinski. The reason I am giving you those names is so this decision on how to engage with the industry and what's the best way for us to engage with the industry, etcetera. I think we will provide you all the technical data you need, but they both will have a final say on those things. And I also want to thank them for all their hard work.

Berta Oates
Absolutely. I am not exactly sure why I've lost the video, but I do believe the audio is still functioning, so bear with me please if I can – here we go. That was very bizarre. That's a new experience for me. So hopefully we are still online and moving forward. Dr. Trellue, how long do you plan to run the ATR tests for YH, the yttrium hydride, to check the hydrogen diffusion from the material?

Holly Trellue
The initial test in ATR will probably be just one cycle for the first one and then we would like to plan 2 or 3 cycles beyond that which is 132 days. It would be two cycles but initially I think we will pull them out after probably about 60 days and just look at the initial performance of the material. Then if we need to design things further on, we will do that.

Berta Oates
So new reactors require a special training for operators. Is that part of the microreactor development program?

Dasari V. Rao
That is a question that we haven't come to cross yet. The reality of it is that there are certain times the questions come for which I don't have an answer and this is one of them.

Yasir Arafat
Maybe I can add a little bit to that. So currently our focus is primarily on the three areas that I talked about. We currently do not have any work packages related to operator training. Now having said that, there are other DOE programs that are very recently put in place like NRIC, for example, that stands for National Reactor Innovation Center. They are primarily in place to help with things like this, like not only just initial demonstrations on DOE sites, but also how does some of these initial demonstrations facilitate things like operator training etcetera. And again the NRIC and DOE microreactor program are very tightly integrated. So, going forward, I think both these programs will be working together. As we go closer to demonstration, we would be working towards getting some operator training exercise done.

Berta Oates
How do you simulate reactivity feedback in electrically heated test core?

Dasari V. Rao
Actually, there are a couple of papers from the past. An example of a paper was by Shannon Bragg-Sitton and others when she was doing her Ph.D. But a quick review of it would say that you first want to have a quick running kinetics model. It could be multi-point kinetics or point kinetics or others. And you figure out a priori what the power distribution in each pin or in each spatial area of the reactor. And you provide thermal heating in terms of electrical heating of induction heaters, etcetera at that location and they are precisely controlled and they can then be turned on and off and ramped up and down the power using the point kinetics as a kinetics model.

It was very effective in tests and that is actually one of the biggest advantage of the micro reactor is the reactor core is small enough that you could do those experiments very precisely even. And like I said, if you look under Shannon Bragg-Sitton, she was the primary author on that article from early 1990 or mid-1990s or may be 2000 actually. You will see those articles. And we also have additional articles, that Los Alamos National Lab reports on that, on uncertainty assessment and the difference between EDU that is the Engineering Demonstration Unit and the Nuclear Demonstration Unit and how do you scale up and down. So there is lot that was done on that and the key principle still is you use models to figure out where you want the energy, how much, and what its transient should be a priori and you simulate that and then you qualify the complement that it performs well. Anybody wants to add?

Yasir Arafat
No, I think I couldn’t say it better.

Berta Oates

How to perform core self-governance, use of artificial controlling units?

Dasari V. Rao
No. One of the things that – well, first of all, yes you could do that. That makes your certification and others then will be given by the software certification. But the most important aspect of microreactors, if they are designed right, is that as many nuclear engineers know, reactors themselves are inherently self-governing. That is when you design it right, as the temperature goes up the reactor criticality goes down and vice versa. As the temperature goes down, criticality goes up. So as the power is drawn more and less, the reactor, the materials, their expansion, their cross sections, you design amplify those features and time them so that self-governance is done naturally by the mechanisms that are inherent to the reactor. For example, in a fast spectrum reactor as you start operating at a steady state. Let's say your turbine trips, that is you are not drawing any power from the core, what happens immediately is that the reactor heats up, and during that heat-up, the reactor core expands ever so slightly. And that expansion is enough for the neutron leakage so that the reactor becomes subcritical. So reactor is no longer generating fission power, you are just removing the decay power.

And that situation reverses when the temperature matches back to when the turbine comes back up and the reactor starts cooling down. Once again the reactor contracts, and you reach steady state. So, this type of a mechanism is what we refer to as self-governance or inherent load following. Sometimes you may use an artificial control to actually enhance or amplify that. But a lot of times these reactors are designed with that behavior in mind and they do it with advanced modeling and simulation tools. They figure out a way to time these feedback mechanisms and amplify them. That's what self-governance is. Anybody wants to add.

Yasir Arafat
No, not particularly.

Berta Oates
Is heat pipe failure an expectable event during the operation life of a microreactor? What consequences could it bring? For example, sodium leakage thermal gradients on the monolith, etcetera. There are actually a few questions on the safety such as that one.

Dasari V. Rao
Okay, so let me take that particular question. In the life of a reactor, a reasonable well-designed heat pipe, sodium or sodium potassium or potassium, we don't expect to fail. However, that does not mean we don't design for its failure. In case of a failure, most failures that are known for heat pipe – so for those of you that are listening in, a heat pipe

has a 3-meter long heat pipe for example, about 1-1/2 to 2 centimeter diameter. That heat pipe can extract about 7 kilowatts of thermal energy and it has less than a tablespoon of sodium. So, sodium release first of all is not the mechanism for the heat pipe failures. Heat pipe failures happen mainly because wicking [ph] gets lost, it gets cladded or corroded by sodium if you didn't clean the sodium right. So, sodium release is not an issue. Even if sodium is released, a heat pipe contains very small amount of sodium, so let's put that aside.

The way any reactor is designed or should be designed for the heat pipe reactors is that we call it 'delta failure' that is the heat pipes in the closest three heat pipes forming a delta shape or a triangular shape. They fail, you still should not have any failure of the fuel. You may have to lower your power level so that the thermal stressors and others are not a major issue. But it should not lead to accidents of either the fuel temperatures or the monolith performance temperatures. That is a basic fundamental aspect of heat pipe design that at least we follow at LANL. And I am pretty sure good engineers all across, that's the kind of safety they would use. And by the way, one of the experiments that Yasir and others will be doing in the near future is actually creating these failures. As Holly described in the test bed that we are standing up, we intend to fail the heat pipes and see what happens to the stress and strains of the monolith. Anybody wants to add.

Holly Trellue
Yeah, the only addition is that yes we have looked at modeling what the failure of a particular heat pipe will do to the temperature in surrounding heat pipes and looking at some of the thermal stressors. So the main thing is if one is not removing the heat, the power that's going to be going to the others around it will increase and we have to make sure that it's in the design margins to be able to handle even a 30% increase or something. And that's a part of the safety analysis that will be done in the design process.

Yasir Arafat
One thing I want to add about heat pipe failures in general and obviously I want to acknowledge Dr. Bob Reid who is like in my mind the world expert in heat pipes at LANL. We've had a very short cause recently and he talked about some of the failure of mechanisms on heat pipes. One is, you can break the heat pipe cladding or the pipe itself either through different stresses or other mechanism, or if you have impurities within the heat pipe itself in the form of oxides. Now, the term 'failure' it's a little bit black and white when this question arises. I think if you look at some of the data, there's been a lot of testing done with heat pipes in the last couple of decades. And if you look at some of those experimental work, there have been very few failures and a lot of them were associated – and I want to point to a very quick example. There was an instance where

one of the pipe had a puncture on the heat pipe and that was due to some external particles or oxygen moving in from a quartz tube into the tube. But even though there was a puncture, the heat pipe continued to function as normal due to the liquid surface tension.

So there is a lot of work that needs to be done to understand what heat pipe failures, what the real mechanisms are and what are the consequences look like. Do they fail in their function or what are the failure modes in general? So that's an area that we're trying to actively look into through the program in the near future to understand what the failure modes and effect analysis look like for heat pipes.

Holly Trellue
Thank you, Yasir. The other point to add on safety in general is for one of the systems these are designed with very low amounts of fuel for the commercial reactors and types of thermal powders that are designed for these small systems that have been tested in space reactors or other technologies in the past.

We will of course be making sure that those groups and things to the public will be as low as possible with shielding with other types of containments. And the goal in some of these cases is to put them in applications that are remote for the most part. So, we would have even design it such that if people who are walking around outside, the risk to them is very small. And of course looking at all sorts of different failure modes within the system, especially if something does go wrong, in the core we're going to have shutdown rods. They will be inserted that will shut down the reactor and keep more visioning [ph] from happening and then other types of system design with the thermal loops that will be developed.

Yes, convincing the public is important and that that will be part of what we will be – we, meaning the whole nation, vendors and/or any other programmatic support that we have, will have to address.

Berta Oates
Thank you. Those two that are similar discussion. What is the length of the longest heat pipe manufactured in industrial maturity and what is your best coupling method of heat pipe to a source or sink?

Yasir Arafat
Maybe I can take the second one. May be Holly can take the first one, I don't know and then we...

Dasari V. Rao
Let me do the first one and then perhaps we can hand off. The longest heat pipe is a difficult to answer because Alaska I think has been

operating heat pipe that is several hundred feet long. And the longest it's operating at LANL, that's an alkali metal heat pipe, is about 30 or 40 feet in that range for the solar farm, solar thermal.

In reactors itself we are kind of looking about somewhere between 2 to 3 meters long in the length of the heat pipe, the dimensions of the diameter is about 1-1/2 to 2 centimeters or may be sometimes even lowering diameter. And throughput tends to be, if it is a single ended heat pipe about 5 to 10 kilowatts in that range. I will turn this over to Yasir regarding the thermal bonding, etcetera. Yasir, it's yours.

Yasir Arafat
Let me focus first on the problem or the challenge first. I think the heat pipe is a solid heat transfer component. Typically, it is connected both on one end to the core and the other heat to a heat exchanger which are typically solid components as well. Now it turns out, if you make everything is in same material for example, then the challenges are smaller because they expand, their coefficient of thermal expansions are very similar. But a lot of the times you don't have the same materials, so either you are bonding with a ceramic or a graphite or some other steel material or metallic parts on the core side, on the heat exchanger side which have different CTEs. So as you are heating up from room temperature to operating conditions and also in some transients, you are going to have that gap conductance chained or [Unclear] with a gap in between the heat pipe and the source and the sink. There are multiple solutions that industry and the lab complex are looking into.

Obviously, if you look into the solutions, there is a solid bonding material that people are looking into that can bridge that gap. There are people who just – folks just leave a gas gap in between which has somewhat of a high thermal conductivity like helium. It's not a solid gap but it does a solid job. And then the last thing is the liquid gap. The liquid gap one, it all depends on what orientation the heat pipes are, vertical or horizontal. It's a bit more challenging on the horizontal side but there are other ways folks are looking into, to keep the liquid in there that allows this gap to change and the liquid will adjust to that but it will prevent the liquid from flowing away from it. There are different solutions being investigated. There isn't one single answer for that. There are multiple, and folks are looking at that right now.

Berta Oates
Thank you. Holly, do you have any thoughts on that?

Holly Trellue
I do not have any further…

Berta Oates

Okay. Which type of power conversion system is more suitable to microreactors. Brayton cycle Stirling engine or Rankine cycle.

Yasir Arafat
Maybe I can start with that.

Dasari V. Rao
There are three of us online. I think there will be 4 opinions on it. Why don't you take that, Yasir.

Yasir Arafat
Maybe D.V. and Holly can supplement this but on a high level I think there is not a correct answer which one is the best one. It all depends on what your reactor technology is, what is your operating temperature, and how you want to integrate with the power conversion system. So, if you look at Stirling engines for example, I will just talk about the power conversion technology itself and some of the challenges associated with the integration. Stirling engines typically are somewhat mature technologies but they are small power level and their power densities are small. So if you're looking at a very, very tiny microreactor, that could be the way to go because they are self-contained. They are frictionless parts, most of the engine that are commercially available. So that's a suitable technology very, very small micro reactors in the kilowatts range. If you go to larger systems, both Rankine and Brayton systems are feasible. It all depends again on the temperature range. If you are working at medium temperatures like around 300 degrees Celsius, Rankine works. But most of the microreactor initial applications you are looking into are trying to come up with solutions for Alaska and the Arctic and some of the extreme environment conditions. There Rankine systems don't really work very well because they freeze up. For those applications, gas-based Brayton systems work. Even in the gas Brayton systems there are 2 types. One is a closed system. People looked at helium Brayton systems or s-CO2 systems and there is open Brayton systems which basically use ambient air to be pulled into the power conversion, get the heat from the reactor and then basically drive a turbine to generate power. They all have their pros and cons based on efficiency, size, complexity. So, I would say in general for larger microreactors, gas is probably the way to go. For very, very small microreactors, Stirling is probably the way to go. But again it all depends on what people trade off with their design parameters.

Dasari V. Rao
I will add to that is that Lee Mason, she is an investigator at Glenn Research Center in NASA, has listed this much systematically. And the answer really doesn't change much from what Yasir said. But it provides you a structural way of looking at what power range and what system is best. If your issue is with the weight, you have some options. If your

optimization needs energy efficiency, you may yet have a combination too. Don't forget that some of the gas cooled system could be co-generation along with coupling to water.

So I think there is a lot of anticipation on power conversion that needs to happen. And believe or not, I strongly believe that microreactors is one way for us to open up that area for power conversion vendors to get their innovation going in this power range. I am done.

Berta Oates
Thank you. We still have probably 15 questions in the queue, so we may not get to them all, but perhaps we could follow up by email, split them up or share them and you could respond through email. We could post them on the GIF webpage. There are several questions related to security and the level [Unclear] do you want to just take a high perspective discussion of that?

Holly Trellue
I can discuss that briefly. One of the topics we are looking at for security on these systems is again it's harder to get into the actual core to do traditional material accountancy measurements done in Vienna [ph]. So a lot more will be physical security designing campers or other indicators that the system has been breached by any point. Also making sure there is enough physical security. If this is mobile type of power source, we need to have people around protecting it at all times and treating just as you would any type of material during the transportation are some of the things we're looking at. And again, if you are going to be putting this, instead of having a big commercial power plant with fences, you may have to design something that you could construct at whatever point you are out into the field if you could actually put up whatever physical security measures are needed at that given time.

So it's just a different type, the same general concerns as any reactor but how we implement it still needs to be researched.

Dasari V. Rao
I think one clarification that's worth mentioning on that front is that concerns qualitatively are seen but quantitatively in some reactor designs that I have seen, that I have done, net amount of fissile [Unclear] protonium produced and at the end of cycle is less than the SQ quantity.

That's a bigger difference too is that you are not expecting to have in each of these microreactors very large amount of protonium to start with. So, additional features are all important as well. Now that is not to say there will be no microreactors that would have that. But in general, because they are lower power levels etcetera, they do not have as much protonium at the end of cycle as you would expect in other rectors on a quantity wise power reactor. But otherwise, I completely agree with what Holly has said. Any other questions.

Berta Oates
Bear with me here, sorry. Dr. Rao, you were talking about transferable. Does it mean transferable only before installation? If it is so, the benefits can be very limited save settlement time [ph] if not, how do you concern about the shielding after operation which would be very high to be transported.

Dasari V. Rao
Very heavy, yes. But I believe in almost every design they will make those decisions. But I have looked at and I can think of reactors in the 5 megawatt electric range they operate. And after you shut down and you wait for a week or two, may be about a month, your direct radiation from the reactor can be easily handled through shielding and they are transportable.

A lot depends on the logistics of how one chooses to transport and what type of shielding they like to attach. But concerning that there are trucks that can – these days are multi-model that can move around 50-100 tons, I don't expect the shielding after to be the biggest issue. I am not minimizing the technical challenge. I am just saying I don't believe it's a problem that's not solvable if I could use the phrase.

Yasir Arafat
Shall I add to that may be. Typically, microreactor shielding is broken down or I would say the physical shielding is broken down into 2 functions necessarily. The first one is for normal operations which typically does not involve integrated shielding. The integrated shielding is typically used for when– as D.V mentioned, when you shut down, you wait for a few days. The whatever gamma level that you have left, you can have integrated shielding [Unclear] to stay under the 10 CFR intensity over 20 I believe is the over 71 limits. The majority of the challenges regarding shielding is due to normal operation and folks have use different methods for that. Due to the high neutron levels, you can have concrete barrier around the reactor or some have designs to stick into the ground to have inherent shielding. So essentially for normal operation and after operation, you break those shielding to integrate an in situ shielding.

Berta Oates
Is there any customer other than DoD and as NASA, NASA I guess we should say.

Dasari V. Rao
I will leave that to Yasir. He looked at that much more than I have. I have been following those two, DoD and NASA, and we do get some

request for information from many university campuses and others. But Yasir, why don't you take this on?

Yasir Arafat
Yeah. So as far as the customer base besides DoD and the defense side of things, on the commercial side the majority of the customers seeking microreactors are the ones that are using diesel generators. Like if you get some remote communities in Alaska and northern Canada, there are a lot of communities out there that currently use diesel generators. And it's not a trivial market compared to the size of each microreactor. That's relatively a very big market.

For example, in Alaska there are 200 plus remote communities that use diesel. Same in Canada. There's about roughly 200 plus megawatt power needs. There are also elements, and like Puerto Rico and other areas that also rely on diesels that are trying to look for alternative technologies because importing liquid fuel is very expensive. So to summarize, there are a lot of customers and we have had conversations with some of them, both on the government side of things and also from the utility side of things as well. So, the answer is yes. There are a lot of issues market-based, even for the initial deployment I would think.

Berta Oates
I am been signaled that we are out of time. There are a handful of questions that we didn't get to. But if we didn't answer your question, please be patient. We will follow up by email and I will share those written questions with each of our presenters and we will respond by email and posts at the webpage.

Again, thank you very much D.V., Holly, and Yasir for your time and expertise in sharing everything that you know and putting together such a marvelous webinar presentation. At the end of 2 hours, we still have over a 115 people in attendance, and that's remarkable.

Dasari V. Rao
I will just add to that. Thanks to of course you, Berta and Patricia. And if Jess got himself out of the bed and if he's there – Jess Gehin. And I don't know if Tom Sowinski is dialed in, I do not know that. But if he is, Tom, thanks for giving us the opportunity. And it's a very exciting area and thanks for all this opportunity.

Berta Oates
Patricia, any last thoughts. I know your phone is dying.

Patricia Paviet
Can you hear me?

Berta Oates
Yes.

Patricia Paviet
Okay, yes I wanted to thank you D.V., Holly and Yasir. And it has been a really great turnaround and thank you for your expertise. Again, these are webinar archives. I really encourage you to go back to www.gen-iv.org in our webinar archives so you can watch them and you have access to the PDF files. Also, we have a survey. Let us know if you have other ideas for webinar topic. Thank you again the three of you for a great presentation. Stay safe.

Holly Trellue
Thank you and thank you for everyone in the audience and everyone else who supported the program. Okay, bye bye.

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