Molten Salt Reactor Safety Evaluation - A US Perspective
Dr. David Holcomb, ORNL, USA

Berta Oates
Doing today's introduction is Dr. Patricia Paviet. She is the group leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She's also the Chair of the Gen IV International for Education and Training Work Group. Patricia?

Patricia Paviet
Thank you so much Berta for the introduction. Yes, Dave, you are on. It's a pleasure to have you today with us. Dave is a distinguished member of the technical staff and distinguished inventor at Oak Ridge National Laboratory. He currently represents the US and serves as a vice chair of the provisional system steering committee for the Gen IV International Forum on MSRs, Chairs the American Nuclear Society's working group, developing a design safety standard for liquid fueled MSRs and provides technical oversight of DOE's university project on MSRs.

He is a past Chair of the American Nuclear Society's Human Factors, Instrumentation, and Controls Division. He has been a staff member at Oak Ridge for more than 25 years and is currently a member of the Reactors and Nuclear Systems Division. He has in the past served as the Oak Ridge team lead for space reactor instrumentation as part of the Jupiter Icy Moons Orbiter program.

Since 1995, he has served as an Adjunct Assistant Professor at the University of Tennessee, Knoxville in the Nuclear Engineering Department. He is a current member of the nuclear engineering program advisory board for the Ohio State University.

Without further ado, I give you the floor, Dave. I thank you very much for volunteering and presenting this webinar. Thank you so much.

David Holcomb
You are more than welcome Patricia. Welcome everyone. The topic we already had, which is my perspective on safety evaluation methods for molten salt reactors. I have to start with a disclaimer on here that while this is my perspective around safety analysis, this is not necessarily the perspective of the US Department of Energy or the US Nuclear Regulatory Commission. Perhaps it should be.

Well to get started with, why do we need this? Well basically, efficient and effective safety evaluation is critical to reduce the financial risk for investment in MSRs. Right now MSRs are transitioning to being commercial devices and they need substantial amounts of investment capital. Significant time and resources are required. Existing LWR-centric framework would be really difficult to apply because the characteristics of molten salt reactors and light water reactors don't match very well. There are currently multiple initiatives to modernize advanced tractor licensing.

Liquid fueled reactors are distinctive even among the Gen IV nuclear energy systems. In the box you can see the goals for Gen IV nuclear energy systems. In the second one, you can see a low likelihood of reactor core damage. So even among the Gen IV systems, we still look at things like core damage which really doesn't make sense for a liquid fueled reactor there. So we really have to look at how do we go ahead and align safety evaluation with the actual characteristics of the reactor as opposed to the characteristics of other and solid fueled reactors.

Now keep in mind, however, that liquid fueled reactors are not new. All the way back in time of the Manhattan Project, two of the Nobel Prize winners there argued that we should be using liquid fueled systems right from the beginning. Some of the first critical devices were done with liquid fuels. This isn't a Johnny Come Lately technology. It's just a very different technology.

US Federal Law really doesn't say, how you demonstrate adequate reactor safety. Instead of being that prescriptive, it goes ahead and delegates the authority to the Nuclear Regulatory Commission. The Regulatory Commission has issued two guidance documents recently. Red Guide 1.232 and Red Guide 1.233 supporting commercial advanced reactor safety adequacy assessments.

Overall both deterministic and probabilistic methods remaining acceptable methods for demonstrating adequate reactor safety. The methods remain based upon, okay, you develop some principal design criteria, identify licensing basis events, classify your system structures and components, safety related, non-safety related, and then consider their defense in depth against accidents. There is an alternate safety evaluation path available for non-power reactors. That's in NUREG 1537 where the safety adequacy is based upon limiting effects of postulated maximum hypothetical accidents. There's an MSR specific version of this currently under development.

Safety analysis is a required part of licensing, but it's not all of licensing. Licensing has a lot to do with the financial and the environmental impact and stuff in addition. But commercial nuclear power plant safety analysis requires an applicant to provide sufficient information to the NRC to reach a conclusion of reasonable assurance of adequate protection of the public and the environment. Basically the NRC safety goals are no significant additional risk of life and health and no significant addition to other societal risks. We go ahead and we need to look at what is the risk of building and operating the plant.

Well, the risks for a nuclear plant are exposing the public to radiation. So the basic primary safety function for any reactor is avoiding the release of radionuclides. It's the basis for NRC's quantitative health objectives. It's in Title10 of US Code of Federal Regulations. It's Part 20 provides some specific how much you can release to the general public. There is a couple of supporting safety functions because cascading accidents are possible. That's control the reactivity and reject the decay heat because if you fail at either one of those, you are going to start releasing radiation.

Safety analysis starts by developing an understanding of the plant and designing the operation. What are the intended functions of the plant system structures and components? How do the requirements change for the operating state? For example if you are doing maintenance on a molten salt reactor, you've opened up the outer containment. Well you've got things like the cover gas system which is right in there and if you opened up the cover gas system while the containment was open, you'd have a direct access path for a lot of noble fission products which would be a very significant release, so you have different rules based upon what are the different state that the plant is in, whether it's in refueling, maintenance, decommissioning.

A preliminary hazard analysis is where you start. You get a basic understanding of what can go wrong. Where are the radionuclides? Where are the energy sources on there? What's the potential energy? You've got stored high pressure. You've got reactive chemicals. Oh, gee, I've got cooling water somewhere near a hot thing. I might get a steam explosion. What are the relevant common and external hazards if there's a fire, there's a flood, there's an earthquake, there's a blackout? Just basically break the system down into small pieces and look at what can go wrong with it.

Deterministic MSR safety adequacy stems from the current LWR licensing pathway. Essentially, you take the LWR general design criteria which are in 10CFR Part 50 Appendix A and then you apply there to advanced reactors. Well Red Guide 1.232 does this. It creates some advanced reactor general design criteria which are largely technology independent. But it doesn't really go into the specifics of what is required then for an MSR, because an MSR is not a generic reactor, it's a specific reactor. Red Guide 1.232 does include specific criteria for both sodium and high temperature gas cooled reactors. Well, as a result of this the American Nuclear Society has been working in working group 20.2, is attempting to formulate some MSR specific design criteria. Right now, we have to include some substantial conservatism in the initial version just because we don't have very much operating experience, very limited operating experience. And unfortunately, significant time and effort was required to develop minimum acceptable design criteria for HTGRs and SFRs even with their much greater degree of experience on this. So we may come up rather rapidly with a rather conservative set of design criteria. But then if we could go ahead and get a minimum set, it'll probably take some more time.

Probabilistic MSR safety adequacy is based upon quantitative accident and risk modeling. It's a data-driven approach that provides high-fidelity understanding of nuclear power plant risks. Essentially gives you a rational basis for making decisions about what’s safety unacceptable and what's acceptable. Unfortunately, MSRs have much less reliability or accident progression data than other advanced reactors, making it more difficult to apply a data-driven model. They have got much more diverse potential configurations than other advanced reactors.

If you look at things like direct contact of the fuel and the coolants in the core in some people's designs, or you have PRACS, DRACS, you have RVACS type decay heat removal systems, where no other reactor class has as diverse a set of configurations with possible exceptions of water reactors that include things like aqueous homogeneous water reactors.

In addition to that, the reliability of passive safety systems, particularly the ones that include moving coolants has been proven to be more difficult to quantify. We just don't have proven methods for some of the passive safety system reliability quantification. They are under development but the progressive and partial degradation which is characteristically it really doesn't align with conventional PRA techniques. The advanced methods which do exist haven't yet undergone regulatory scrutiny. Things will be better once they have matured a bit.

The existing regulations provide an alternative pathway for safety adequacy assessment for advanced reactors. There is actually in the traditional wings 50.43e indicates that reactors that use simplified, inherent, passive or other innovative means would only be approved for their safety functions if performance of each safety feature has been adequately demonstrated, interdependent effects among the safety features have been demonstrated to be acceptable, and sufficient data exists on the safety features. Analysis, test programs experience or prototype reactor can be employed to acquire the required information. So you've got another path where you might be able to build, for example, a prototype reactor that operates at reduced power or with additional safety features initially until you've acquired adequate data to provide a reasonable assurance of adequate protection.

Unfortunately MSRs required some additional safety performance to really to go the 50.43e route of demonstrating adequate safety.

Evaluating risk sort of is the central component of a nuclear power plant safety analysis. Risk is the possibility that something undesirable will happen. Well, what can go wrong? What is its consequence? How likely is it? How you determine what the risk is in a quantified manner? Defense-in-depth is a primary mechanism for us to accommodate what if we are wrong. Because if we don't have the evaluation correct and something unexpected happened, well, we put another layer and sometimes another layer to go ahead and accommodate the fact that we remain uncertain about things that are new.

Functional containment is another concept which has recently been approved for all advanced reactors. Functional containment essentially is actually apply the physics of the system entirely to containment, not just bulk barriers. If you look at how that worked for an MSR, basically you've got multiple layers some of which are not normally stressed, and so you've got pretty good ability of inspecting them. It's very difficult at the moment to inspect the salt-leaded barrier simply because of the radiation field and the harsh environment. The barrier performance requirements depend upon their safety function. So if for example the drain tank containment system, which is a separate cell, needs to contain the fuel when it's not critical but it doesn't have the same requirements about containing it during a critical system. And part of the way that a functional containment sort of conceptually works is almost like a hot cell facility where you've subdivided things both by layers and individual cells and into separate cells so that each one can be considered separately.

It's a segmented system. Then the independent barriers. One of the nice things about MSR because of their low pressure system and most of the way that the barriers communicate is through pressure relief, so the failure of a single barrier does not substantially stress the other barriers. This is very much unlike the large light water reactor where you'd have a large brake LOCO where you'd immediately get a lot of pressure on your large dry containment. That really helps to minimize potential for cascading or escalating failures. Essentially MSRs has some very desirable inherent safety characteristics.

Everything however depends upon quality. Quality in all of the design criteria is always the first criteria. In things like, was the design correct? Did you actually do what you thought you were supposed to be doing? Are the materials correct? Has the plant been operated and maintained according to the plan? Unfortunately, little historical MSR data was acquired under a modern quality assurance plan. A lot of the stuff that we think we know about fuel salts comes out of the fact that, well, halide salts have a lot of other purposes. They are used in heat treatments and aluminum smelting. So we've got a lot of historic data as well as the large historic US molten salt breeder reactor program. But it simply wasn't acquired where we've got a QA tied to it so that we can really say what's my uncertainty in there. And that's right now presenting a challenge to how do we incorporate this into a fuel qualification plan.

MSRs present different safety analysis challenges than other reactors classes. The radionuclides are distributed across the plants. In most reactors you just look at the core and the used fuel pool and you basically solve – well, as long as you watch those, you don't have significant radionuclides. Gaseous fission products in our systems separate inherently from the fuel cell. The nobles just come right out. That's pluses and minuses on there because while they come out, you can go ahead and treat them and capture them. They are in a different location. They are not available to release during an accident. On the other hand, if you have an accident, the stuff that's in between being produced and being captured, that's coming out and that's a fair amount of stuff. There are also things like integrated fuel salt processing is possible. The processing system could also have accidents.

The salt wetted components have limited lifetimes. You end up with an unconventional high activity waste stream which presents a safety system, whether it's your graphite or your reactor vessel, your heat exchanger which have got plated out fission products all over them. It's an extremely high radiation amount that you just don't get in other reactor classes. We have really less and substantially dated operating experience. We've only operated one MSR reactor for a significant period. That was the molten salt reactor experiments which was about 7.5-megawatt reactor which operated from 65 to 69. Well, it did operate quite successfully on there so we do have some confidence that we can actually operate things stably and successfully with high availability. But we've had no large-scale reactor or component demonstration, so large pumps, large heat exchangers, we just simply haven't done that.

We've never demonstrated a fast spectrum molten salt reactor. Several of the vendors are very interested in exploring the advantages of the fuel cycle that are obtained through the fast spectrum, a really minimal prior accident performance demonstration. We've never done the equivalent of pouring large quantities of fuel salt on the floor, which is sort of the equivalent of these fuel melt experiments that we have done for light water reactors and sodium reactors.

MSR risks have substantial overlap with those of fuel cycle chemical processing facilities. Simply, we look a lot more like a chemical plant than other reactor classes. Both of these systems contain large quantities of radionuclides without large quantities of accessible high pressure or pressure generating fluid. Yes, we will have a power cycle that will have high pressure fluids whether that's a supercritical CO_2 or a supercritical steam system. But they are separated by heat transfer loops with rupture discs. Rupture disks are something that have a high confidence we're going to take the pressure away from the plant.

That difference is a really key conceptual separation between fuel cycle facility and reactor risks. There is a modern set of rules and safety evaluation methods for fuel cycle facilities under 10CFR Part 70. It's basically used process hazard assessments is central to this. NUREG 1513 describes how to perform the process hazard assessment. In that, it's referred to an integrated safety assessment on there. But it's a proven method to provide reasonable assurance of completeness for accident identification. However, it doesn't really quantify the risk, so you can't really say, well, are my probabilities of risk adequately low based upon performing PHA? For that you would need to use a PRA, Probabilistic Risk Assessment.

The original reactor safety adequacy evaluation method was based upon containing a maximum credible accident. Safety adequacy of the first commercial reactors was evaluated by a combination of hazard assessment and containment of this maximum credible accident. That worked well until large light water reactors were developed. When they got bigger there was a credible potential for catastrophic accidents where the containment did not contain everything. Because we did not have very good accident evaluation tools, we did conservative estimates of what was going on and they ended up with really severe potential consequences. That was a large part of the drive for developing enhanced accident modeling to give a higher fidelity representation of the accident. So we would actually protect against what's going to happen, not some highly conservative fictitious accident.

Escalating and cascading accidents really are a big issue with systems that have a large amount of internal stored energy. However, reasonably designed MSRs lack the historically identified mechanisms that could result in catastrophic accidents, high pressure. Essentially there is no reason to throw the radionuclides out. They are just sort of sitting there in a pot. Even if you didn't have the cover on it, they wouldn't tend to go anywhere because they are not at high pressure. There's no interaction of hot metals with water. Steam and hydrogen explosions have been of concern since the 1950s or 1940s even. It's just MSRs have a very advantageous set of inherent characteristics.

MSRE did employ a maximum credible accident for citing evaluation. It was based upon a dual independent containment layer failure. The failure has a little bit of a caveat on it. The second one of these, what we did was we had a water spill within containment sufficient to induce significant leakage in the second containment layer along with gross failure of the fuel salt boundary. Basically they poured the core out on the floor and at the same time put enough steam in the system to go ahead and induce a 1% per day leakage on there.

What they actually did to make this really work, they put a large line to a suppression pool on a gas retention tank which are quite large tanks so you couldn't build up more pressure because they did use water cooling both of the cell walls and of the components within the cells. One of the challenges on this is they didn't have any very much proven information yet on the interaction of iodine with the condensing tank. It turns out that if they'd been able to put the actual chemistry and physics on there, they'd had a much smaller accident. But even with this where they were leaking this out into the confinement on this, their maximum credible accident where the confinement was a vented confinement because people were around that, and the only way they got a real serious accident was to leave the fan on to actually vent all the things that were coming out in the containments. So you had to actively vent the reactor to disperse the radionuclides; otherwise not much would happen other than right at the site.

MSRs have a readily apparent high degree of passive safety. Readily apparent is really important because it helps develop confidence in both the regulators and the public that what we are saying is very likely true that there isn't something else going on. It's a strong inherent retention of the radionuclides that's both chemically and the fact that they are at low pressure. There's a large mark in to boiling on this. There's no way of developing the multi-atmospheres of pressure. There are minimal amounts of water or other phase change materials within containment in this. We are probably going to cool with gases. We are probably going to have some form of nitrogen cooling cycle. The power cycle is separated from the core with rupture discs along the piping. The fuel salt contains many of the radionuclides. While some are really nasty ones, the strontiums, the cesiums form really stable chlorides and fluorides. However, up to 40% can be released into the cover gas because as you create a fission product, it's not on the stability curve for the isotopes that beta decays, re-beta decays and re-beta decays, and someplace during that decay path there often is a noble gas. Those noble gases do not stay in the fuel salt. Some of them will decay before they get there and then will be trapped in the fuel salt. But once they've decayed and they've been released from the fuel salt, we can trap them outside of the fuel salt. There's only an hour or depends upon what your design and your flow rates are. It's how much of the fission products that are available to be released in the event of an accident.

Many of the other things also that don't bind in there, turns out are high melt point solids and refractories and noble things that played out on the surfaces are also not available to be released. Another good thing is that the fuel salt is in a low chemical energy state. This is distinctly unlike sodium. It's like low Gibbs free energy, really don't interact with the environmental materials. You throw water on to it; well it becomes more corrosive and you get a steam explosion. But it doesn't do anything like have a fire. Having a low chemical energy state is a useful property.

MSR, again, readily apparent degree of high passive safety, very good negative reactivity feedback. It's about the only fast reactor where because essentially as the fuel salt heats up, it becomes larger at the volumetric expansion, you decrease the amount of fuel in the core. The fuel is normally kept in its maximum reactivity configuration. There's no fuel consolidation. There's no way of getting these huge positive feedback accidents. There's no hypothetical core disruptive accident, there's the substantial margin to structural damage. Actually we considered MSRs as prompt to burst reactors before triggers were developed on there simply because they give you a very good strong negative reactor feedback.

MSRs really have the potential for effective passive decay heat rejection. A lot of that starts with the fact they are hot and it's easier to get, whether it's radiative or convective cooling starting with a hot source is easier to reject the same amount of heat from than something which is cooler. But fuel salts got an advantageous combination of heat capacity, thermal expansion and viscosity to drive natural circulation cooling. There are no operational cliff-edge effects we've ever had. It looks like that there's no at whist. There's no departure from nuclear boiling. Simply we don't have the features where you are really worried about a fast response.

MSRs also retain the potential of containing all credible accidents at any scale. It doesn't suffer from the same issue that LWRs have when you’ve got really a large containment probably wasn't going to be an adequate response. So avoiding potentially cascading accidents, especially accident sequence of pressurized containment is a key consideration.

An MSRE type suppression pool capture tank system would be quite large for a commercial scale plant. But it's a possible design. I think basically most folks are going to conclude that they don't want to use water cooling. If you end up with a suppression pool and capture tank system, it wouldn't need to be as big. The system immaturity really still necessitates some additional conservatism in the design requirements to ensure that containment will survive. There's a high degree of passive safety which will help minimize the additional cost of the system. Reliable quantitative performance data and models would decrease the required amount of conservatism. We are hoping to get more data so we can reduce the conservatism in the models. Additional requirements are intended to prevent a single event from damaging all the containment layers. One of the things that you will look at is you probably want a core catcher so that if you pour the fuel salt out or a guard vessel so that you can still continue to remove decay heat, even following a severe accident where you've had a large break within the fuel salt system. We really are trying not having a cascading accident where you are damaging all the layers is central to being able to maintain credible containment.

Assuring that the bounding accidents then envelope all credible accidents is key then to demonstrate adequate reactor safety. You cannot just use really simple obvious accidents because there can be synergistic and combinatorial effects in the accidents to say well this plus this was actually worse. So we need to use things like process hazard assessment to incorporate multiple methods, whether it's HAZOPs or Failure Modes and Effects Analysis, Layer of Protection Analysis as well as expert judgment from multiple people with diverse technical backgrounds to develop our accident sequences.

It's the same basic process as early phase probabilistic risk assessment. In any case, in order to have consequences, which is our definition to release radionuclides out to the environment, an accident needs to rupture or bypass all the containment layers. The high resiliency of MSRs enables the use of rather unlikely postulated accidents. You say, well, yeah, I am going to have my large break LOCA and in addition to this I'm going to rupture my cooling line to look at my safety assessment. Commercial molten salt reactors, however, have not had a single maximum credible accident like the MSRE but a series of bounding accidents. Basically because we have a lot of radionuclides in a lot of different spots and you could have a potential for environmental or harm to the public from rupturing any of these systems. If you just rupture the cover gas system, that will look different than rupturing the reactor vessel. But both of them could end up releasing radionuclides.

In this way it kind of looks like all the multiple design basis accidents for large light water reactors. The advantageous characteristics of MSR is really lower the plant capital on operating expenses on here. If you look at, okay, we've got to protect against multiple accidents. Well, low pressure, still it's much lower cost than these large high-pressure dry containments. You are ending up with thin walled metal tanks versus massive reinforced concrete structures. Everybody is designing things below grade these days because of the requirement to accommodate large civilian aircraft impacts on there. That's just easier done by putting everything below grade, kind of looks like if you've seen a munitions bunker where you dig a hole in the ground put a hoop over it, pile dirt on top. Passive decay heat rejection, not using the power cycle, avoids the requirement to use the power cycle system structures and components as safety related. If you can confine your safety related systems to the nuclear island, well more than half the plants view nuclear islands as a small part of the plant. Most of that is just according to industrial standards, not according to nuclear standards.

There's really a large margin to damage. Reactivity accidents are unlikely to damage the system structures and components just because of the inherent negative reactivity feedback. There's a large margin to fuel salt boiling, so it's unlikely to develop high pressure and rupture things. There's really no equivalent to an anticipated transient without scram in this. We've really met no one despite having a fairly extensive look at this have identified any accidents requiring a rapid operator or an active equipment response. So it looks like we've got days and we just rely upon physics rather than upon people.

Maintaining low pressures is key to avoiding a potential rupture of containment layers. The MSRE substantially reduced its pressure through interconnecting a large tank through rupture discs. Largely they did it that way both because it was cost acceptable and because it was built – the aircraft reactor experiment, they actually reused an existing containment even the time they were doing that and to avoid building a building, they put a big pipe in another tank.

The process, physics, and chemistry dictate the pressure generation mechanisms without a large amount of phase change material. Water is a big example on this or sodium. MSRs lack mechanisms for significant pressure generation. Lack of adequate decay heat rejection could fail all the containment layers without requiring pressure generation. If you look, you can essentially melt through everything or just pressurize the atmosphere, even the air, PV equals NRT, could get hot enough if you can't reject the decay heat. So, adequate decay heat rejection under severe accident conditions is required to avoid radionuclide releases on this.

We just don't really have the amount of data that we would like to have on these severe accident releases. A dual simultaneous containment layer failure employed at the MSRE provides a baseline maximum credible accidents. Again, the failure has got some caveats on it. It is not the true gross rupture but it is stressing that next layer enough to go ahead and give out a significant leak. It's much more conservative than the conventional signal failure criteria. However, the basic physics and chemistry are quite similar for any MSR. The lack of adequate data has resulted in very conservative source term estimates. Again, as I mentioned, the iodine trapping and suppression pool was unaccounted for. And electricity-generating MSRs will have high pressure power cycle fluids connected by a heat transfer loop. So we'll be using rupture disks to isolate the pressure.

MSRs currently lack adequate decay heat transport data to provide reasonable assurance of adequate protection for larger systems. We need to understand well enough what happens under a severe accident that we can continue to provide adequate decay heat rejection. The lack of this could cause multiple layers to fail. Right now there are diverse types of systems under consideration, whether it's a direct reactor auxiliary cooling system, a reactor vessel auxiliary cooling system, a pool type reactor auxiliary cooling systems. Some folks use drain tanks and guard vessels and core catchers. Because of all these different variants we really have to understand the fuel salt property very well as well as the performance of their systems. Demonstrating technologies for adequate decay heat rejection under degraded conditions is the key next step to enable MSR safety evaluation.

Qualified fuel salt is also key to reliably modeling MSR system performance. If you look at this, you have some accident scenario, well, the fuel performance tells you how it attacks the barriers and how it reacts to the barriers on this. You only understand the fuel performance adequately by having a qualified fuel to know what is there and what are the characteristics of the things that are there. Does it do something you were not expecting it to do? That's what qualification really is. It's adequate understanding of the fuel performance able to model its operation both normal and accident conditions. Currently that's a key focus of the US national MSR activities to develop adequate data to qualify fuel salts. The NRC is currently supporting activities to define exactly what are acceptable liquid fuel salt qualification methods.

Fuel salt data quality assurance represents a potential stumbling block for fuel qualification. As I've mentioned little, if any, of the historic data was generated under a nuclear quality assurance program. Data has been generated by multiple institutions worldwide. Some of this is historic so that the quality assurance information may no longer exist. Right now, it remains unclear how to make most appropriate use of the prior work. The regulations require appropriate level of quality assurance reflecting the importance to safety and fuel performance is very important to safety. Basically we're going to need sensitivity and uncertainty analysis as well as accident progression modeling tools to establish data requirements.

We'll do variations of okay, if the density changes to this or if the heat capacity changes to this, do we still get an acceptable accident performance, and then work our way backwards to what do we have to know about the fuel with what quality based upon its accident performance requirements. But the amount of validation data to go ahead and say well, we've got this huge sea of data, I don't think we're going to validate every single piece because there's a continuum within this data. But we'll have to see exactly how much validation is going to be required.

Mechanistic source term methodologies for MSRs is key to understanding containment performance adequacy. The NRC has established requirements for advanced reactors to employ a mechanistic source term. Essentially, performance of the reactor, fuel under normal and off-normal conditions is sufficiently well understood to permit a mechanistic analysis. Transport of fission products can be adequately modeled for all the barriers and pathway to the environment including specific consideration and containment. The events considered in the analysis develop the source terms, bound severe accidents, and design-dependent uncertainties. Essentially it's a bounding accident model for developing a mechanistic source term.

Simulation and modeling tools are in practice needed. You could do this with pen and paper but today we really would like to be able to do variations. If I change this a little bit, what's the impact of that? That's what tools are good for. You first have to provide some initial conditions to start your accident progression evaluation. How many radionuclides are where at the start of your accidents? Is this solidified here? You get things from that from reactor physics – radionuclide generation, consumption. The fuel salt and cover gas motion and heat transfer, auxiliary systems, fueling and defueling systems, salt treatment systems, plate out systems, they are all parts of how do you set up your problem. Then you need to automate this to look at different designs and scenarios, to look at every accident. Then the wide diversity of the configurations, a PRACS system looks very different than a drain tank system there.

The NRC has reactor physics and hydraulics tools that are suitable to model MSRs. Those things like SCALE is the reactor physics code and TRACE, for doing thermal hydraulics analysis. But we really need some additional tools to develop radionuclide accountancy because traditionally we didn't have radionuclides in lots of different places so the accountancy of where things are doesn't really exist in a proven manner but there are substantial current activity development tools.

Implementing mechanistic source term models in the NRC accident modeling tool, which is MELCOR, is underway. The NRC has been sponsoring this as well as DOE considering what the accidents and what are the configurations. Distributed radionuclide configuration is a distinctive component for MSRs. MELCOR requires further capability extension to accommodate the diverse set of potential configurations, essentially how do you describe what the reactor is to start the accident off is you need to have those building blocks in there to allow the stakeholders, whether it's a designer or regulator or a safety analyst, to be able to evaluate particular designs under specific scenarios.

MSR safety adequacy evaluation capabilities are advancing on many fronts because MSRs are a topic of current interest. We don't yet have a complete and mature set of capabilities. The preferred method for MSR safety adequacy demonstrations will evolve as experience is gained of the technology. We will be able to do higher and higher fidelity models which will allow us to decrease design conservatism as we develop more and more experience with the system. We need to continue to advance the fuel salt property understanding, modeling tool capabilities, as well as safety evaluation methodologies. The distributed radionuclide configuration during normal operation necessitates a new material accountancy tool. We just need to get that validated. Currently, in my opinion the most significant experimental hole is lack of data to model decay heat removal following a fuel salt boundary rupture, essentially under degraded conditions continuingly be able to model the decay heat removal, we need more data and better tools. I believe that's all I have and now I am open for questions.

Berta Oates
Thank you Dave. While questions are coming in, let's take a quick look at the upcoming webinar presentations. In September, a presentation on Maximizing Clean Energy Integration: The Role of Nuclear Renewable Technologies in Integrated Energy Systems. In October, we anticipate Global Potential for Small and Micro Reactor Systems to Provide Electricity Access. In November, Neutrino and Gen IV Reactor Systems.

If you do have questions, go ahead and type those into the questions pane. Here we go. Make this a little bigger so that I can see it.

Dave I'm not sure if you can see the question.

David Holcomb
No I can't.

Berta Oates
Since MSRs are low pressure systems, are vendors still planning to include a traditional containment building?

David Holcomb
Well I'm not going to be able to speak to any particular vendor, but I certainly think that you would design your containment to suit your reactor on this, and safety function. Things that look like 1-1/2 meter thick of reinforced concrete, well the only safety function I could think that it would have would be if you went above grade and you were worrying about a large aircraft impact. My guess is that most reactors are probably going to go below grade and then not have this reinforced concrete. Though keep in mind because we don't have the downcomer which is the water and the six inches of steel shielding, we will need

substantial amounts of shielding between the fuel salt and the environment on there. So we're probably going to have whatever be non-reinforced, big concrete blocks or some form of shielding or perhaps it's just sand and dirt for shielding.

Berta Oates
Thank you. Do you have an opinion about the ThorCon design?

David Holcomb
I really can't comment on specific commercial designs on there. I mean they are implementing a traditional graphite moderated fluoride salt fueled system that is the current design has got a drain tank and an RVACS or actually a series of drain tanks and an RVACS there. But without real evaluation, I just don't have anything specific. It looks like a traditional fluoride salt thermal spectrum design.

Berta Oates
Thank you. What are the potentials of reducing decay heat significantly by removing fission products online?

David Holcomb
You do actually get something like a 40% of the short-term stuff. It does go down. The problem is that molten salt reactors are not necessarily small. Some folks are talking multi-gigawatt systems. You then have to remove that decay heat anyway from the cover gas instead of removing it from the fuel salt. You haven't really gotten rid of the decay heat removal thing; you've moved where it is. So perhaps you do it in two different systems. The ways to decrease the amount of decay heat removal are just basically to get less power out of it, have fewer fissions. But it may be easier to remove the decay heat in two places instead of having a large single system. Those are design variants.

Berta Oates
Thank you. In your view what are the most important knowledge gaps related to the chemistry of fission product bearing salt?

David Holcomb
Well, certainly we probably don't understand in fast spectrum systems that have a lot of actinides in them. We worry about are things going to solidify right at the outside of the heat exchanger. Are we going to get played out on this? Because we just have not run fast spectrum systems. A demonstration, essentially a fast spectrum version of the molten salt reactor experiment would give us an awful lot more confidence about that. Otherwise, the fact that we have run a thermal spectrum fluoride salt reactor gives us a pretty good confidence that we have an adequate understanding of the chemistry of the fluoride salts. Whether we should have more to give us a better design is of course we want to improve our

designs. But we are only talking about the safety of the system and we have a fair amount of understanding for things like well, is it going to boil? What are the heat capacities? In general, we'd like to know more about this to expand our potential range of designs. We run our prototype reactor, our first of a kind.

Berta Oates
Thank you. How important is the risk of freezing and re-criticality of fuel salt?

David Holcomb
It's difficult to imagine how you are going to freeze fuel salt once it's been run for a while. Simply put, there's a lot of decay heat out there so I'm not really worried about freezing fuel salt that's been run for a while. I'm also not really worried about re-criticality too much in a low-pressure system. Even safe shutdown might be critical at low power. We don't even define safe shutdown so much in a molten salt reactor. It might not be the same thing in a light water reactor. Part of this is we have such good negative inherent reactivity feedback mechanisms. Whether it's spectral shift or thermal expansion, there's nothing like a departure from nuclear boiling accident to say well going critical is likely to cause an off-site dose or a damage to the components.

Berta Oates
Thank you. Is molten salt safe to handle in an experimental book?

David Holcomb
If you go ahead and molten salts are hot, that's the primary hazard on there because in order to get molten none of these things melt. Some of the chlorides melt as low as 400 degrees Celsius but most of these things melt at around 450-500 degrees Celsius and we are running them at 700-800 degrees Celsius. This is very thermally hot. I'm not going to say anything that's hot. It's got a high heat capacity. It'll transfer a lot of energy is particularly safe there. I mean our big challenge is keep everything dry on there. In many ways the challenge is from the stuff on the outside because the salt can become very corrosive if it gets wet on there, actually if it gets even a little tiny bit wet there. It needs to stay quite dry to continue to be in a reducing condition so it doesn't oxidize the container components on there. As far as can you handle your uranium…

Berta Oates
Dave I think we lost you.

Patricia Paviet
Yes we did.

David Holcomb

...uranium as a natural product you can look at what it's decay.

Berta Oates
Dave, I think your mic might be intermittent. Did you disconnect a little bit?

David Holcomb
I am still here. Do I need to repeat the last one or some problem?

Berta Oates
Yeah I think you broke off midway on the last answer, so perhaps that would be best to repeat.

David Holcomb
Okay. Is there anything especially unsafe about handling molten salts for an experiment? Biggest challenge is just they are hot. Being at 700-800 degrees Celsius having a high heat capacity is certainly something which could give you pause about what can you do for safety. In addition, if you are looking at a fuel salt, you'll have something like uranium in it. Uranium is a radioactive material but it doesn't become more or less radioactive by being in a fuel salt. If you have conditions for handling uranium in another form, you likely have the conditions for handling uranium in fuel salt.

I suspect your transuranics and other actinides have got their own safety issues and you'll need to deal with those. But most of the chemistry is not dependent upon the radioactive nature of the fuel, so you can use non-radioactive surrogates as, say, cesium that's not radioactive. You put that in a subset of cesium that is radioactive.

Berta Oates
Thank you. There's a question that's kind of a follow-up to one that you've just answered a bit ago. Do you think there is a case for arguing that re-criticality preventing freezing should actually consider a positive safety factor by regulators?

David Holcomb
Eventually you have to deconstruct the plants. I mean the fact that it stays in a stable condition for a very long period of time, again the only thing that you really worry about is, are you going to release the radionuclides to the public? Otherwise your plant owners want, hey, don't destroy the stuff inside, we want to generate power on this. I don't think that there is something inherently wrong about maintaining the plant in a low power critical configuration for a very long period of time. That doesn't seem to cause a release of radioactive material into the environment.

Berta Oates
Thank you. Has there been a cost analysis of the MSR to determine its economic competitiveness?

David Holcomb
There have been a number of analyses. The problem is what the assumptions that go into them and what to believe in them. Some of the analyses look very favorable to the point that it is unwise to go ahead. Essentially we get painted by being unduly optimistic.

Berta Oates
Thank you. What experimental facilities are needed to validate safety models?

David Holcomb
Well one of the things, I think Argonne National Laboratory has a pretty nice setup for essentially doing the equivalent of a fuel salt spill. Because their natural decay heat removal facility which looks like the RVACS facility they have got. That's I think is our biggest thing right now. I do not believe that we are going to be able to say that a large fuel salt spill is adequately unlikely that it will not occur. Therefore we have to be able to show we can maintain adequate safety following that fuel salt spill. Most of that is decay heat removal, well criticality as well for fast spectrum systems that have large contents of fissile material. Both of those are handled classically, lots of absorber around, unfavorable geometry for criticality and continuing to look at – well have I developed a fog or a mist, so I don't get adequate radioactive cooling. Do I get a crust on this? Does it freeze on the bottom surface so it doesn't flow anymore? The classic types of things. And those are done with accident type facilities. Fortunately, the US has already invested rather significantly in parts of those. It's just that there has not yet been the interest and the investment for a long time to apply them to molten salt reactors.

Berta Oates
Thank you. General question, are there uncertainties at this time that may impact the DCA if a given MSR reactor design was submitted today? For example, are there uncertainties in reactivity control that impacts a regulatory position?

David Holcomb
Well, certainly if you are trying to go ahead and say what's my reactivity control mechanisms? That I am aware of, none of the reactors are designing their active reactivity control systems as a safety related system. They are entirely intending as a passive system for safety purposes. What does that mean? Do we know adequately that we would not get re-criticality? Probably not. There are some possibilities of doing played outs particularly in fast spectrum systems where we might get a

criticality. Question becomes if we have an unplanned criticality what are the safety implications of doing that? That is where molten salt reactors really shine. Because there are no people nearby and it's within a highly shielded environment because during normal operations it's supposed to be critical in there and you have to have the shielding to deal with the criticality.

There are a number of potential accidents like filling accidents where you leave your filling pump on too long. That ends up with an excessive criticality which ends up melting the reactor vessel which ends up pouring things on the floor. The entire accident chain sequence, do we have adequate information to deal with the entire chain sequence? No. Some of this starts with having more power generation than you wanted to. That's involved with criticality. But as far as a prompt feedback, we don't really have much issue about a rapid response, response negative reactivity insertion requirement.

Berta Oates
Thank you. What's the approach to dealing with the waste salt at the end of the lifecycle?

David Holcomb
Largely, most of the reactor folks are saying that we don't have waste salt because the salt doesn't accumulate radiation damage. We essentially reach an equilibrium amount of fission products as stuff burns in and burns out on there. If you read some of the papers that Terrestrial Energy has done, what they are doing is saying is we start with a fuel salt with about a 2% enrichment and then we refuel for 7 years and we add volume to this fuel salt over time. Then what we do for our next reactor course, we split this over time into two different reactors and we use this as a means of breeding or creating or fueling our next and our next and our next generation of salts. That doesn't eventually get rid of the waste salt because eventually people will stop using molten salt reactors as a reactor class and everything becomes waste at once. But that may be perhaps 1000 years from now before we end up with creating our first major fuel salt waste.

So, most folks are saying, well, we just keep reusing the fuel salt on there because it doesn't radiation damage like solid fuel on there just because it's a liquid. It's a matter of how much do you accumulate in it? It turns out after 60-70 years you end up with an equilibrium amount of radionuclides in there where you are burning things out and breeding things in and decaying things together.

So our challenge is on the waste tends to be things like, well, gee, I have a heat exchanger. I had a little bit of a heat – and by the way, a whole bunch of stuff plated onto it, so I've got this heat exchanger which is extremely radioactive. It only lasted 20 years. If I have a 100-year plant on here, I've got five of these I got to deal with. I've got an unconventional really high activity waste stream but it's not so much a fuel salt waste stream.

Berta Oates
Thank you. What kind of new radionuclide material accountancy tools are under development?

David Holcomb
There are several of these range that are being supported from the Nuclear Energy Advanced Reactor, the NEAMS program, as well as through the MSR national campaign. And there's a Modelica based tool there where it's called TRANSFORM is the particular name of it. There are also some efforts to implement this into SAM which is another one of the NEAMS tools. It's basically a model of process physics and chemistry, and then interfaced with the domain specific codes, scale, and the like. If you look at the leading effort on there on a practical basis is, is the transform tool being done by the US national MSR campaign.

Berta Oates
Thank you. Do you have a qualified thermal hydraulics code for MSRs?

David Holcomb
Well, TRACE continues to have molten salt properties within it, but it doesn't have a wide set molten salt properties within it. Certainly, we would like to expand the number of molten salt properties within it, but that's not so much – that's the traditional type. But once you have the properties, you can put it into almost any thermal hydraulic code. There's not in your COBRA or something but it's a matter of having the right properties to stick in. We are developing properties. My answer is that TRACE exists. It has a limited set of the thermal physical properties in it. That will probably be used for a lot of the accident progression modeling. But otherwise, this is a single-phase heat transfer problem sometimes with a little bit of bubbles. But single-phase heat transfer with a fluid is not really exotic heat transfer problem.

Berta Oates
Thank you. Similarly the next question is neutronic codes and thermal hydraulics codes exist to compute MSR, but what about chemical fields?

David Holcomb
If you are trying to do a design of a fuel processing system, you'll need to understand things like how many stages of extraction and elements of that. Otherwise, largely this comes on a composition and gives free energy. What are the things you need to know in a chemical field? Some of this is if you want to process the fuel, then you'll have to know

additional information about this. Otherwise, what we really want to know in a chemical sense typically is, is the fissile material going to play it out. That's a solubility question, which we established bounding parameters on. Having kept it in to and a reducing environment set up, because fission is an oxidative process, so we have to keep overall things in reducing condition so that we don't cause excessive corrosion. Typically, what we do is we actually monitor the corrosion of the most sensitive component in the boundary material tends to be chromium. If the chromium composition starts going up, we add a little bit more of a reducing metal, what we were doing in FLiBe salt was contacting with beryllium. So it's more Edisonian than a first principles knowledge of this.

So, question is how much do you need to know the fundamentals to operate a reactor? I would make the point that understanding the fundamentals is good for advancing the designs and advancing things, but probably not necessarily for safety evaluation of the reactor.

Berta Oates
Thank you. This question reads, in MSR there's no cladding. In addition operation will probably involve online extraction of gaseous fission products, lanthanides, etcetera. Thus, how can we define a first safety barrier?

David Holcomb
Well you are correct. There's no cladding on this. The gases have almost no solubility in the salt. There is a limited trapping in the carbon and so but there is a first boundary. Essentially, it's the reactor vessel in the cover gas system on there. Certainly, the cover gases will come out or the fission gases will evolve out, you'll probably either use a scrubber or a trap system and then a series of carbon beds essentially to hold the fission gases for decay. Eventually you bottle the krypton 85. We have way too much krypton 85 able to vent. LWRs tend to vent some of the fission gases just because there is a little bit, because most everything is retained in the matrix or inside a cladding, it's only if there's a leak where it comes out. Essentially all of ours come out, so we have to bottle.

The first barrier is the stuff where under normal operations there are radionuclides inside and under normal operations there is not radionuclides outside. That's a pretty simple definition.

Berta Oates
Thank you. How's the molten salt manufactured and delivered to the site?

David Holcomb
Good question. Making fuel salt is an interesting issue which is not entirely resolved. Certainly, some of the methods, for example, Kairos

which is not a liquid fuelled MSR, but it does use molten salt – would be getting their FLiBe salt from a particular vendor and just shipped to them. And the methods for manufacturing lithium fluoride and beryllium fluoride have not changed. You can look at the historic techniques done in the 1950s, the number of reports on that and then the classic chemical processing. FLiBe has announced a partnership with Materion which is our largest beryllium supplier for making their salt. But one of our real challenges is that there is not a supplier pipeline. It is not obvious who vendors are going to be able to buy their fuel salt from. Is it going to be shipped probably as a solid block or are you going to ship it where the actinide portion of it is shipped separately? Because you could start up your reactor with barren salt where it wouldn't be critical initially, but it would be hot and then you would put in a concentrate of salt. Or you could get something where it is 99% of criticality and then you just put in a little bit more to get to critical. There are just a number of different options for this. There have been a couple of companies there including one which got an organic route for producing uranium chlorides as a different chemical process, which have announced that they are embryonic companies going into business. This is not a resolved issue on there and nor are even things like standards for trade. Things like, if you get salt, how much oxygen was in it? How did you measure that? How did you establish this? They are very different corrosion performance based upon what are the content of that actual salt. Then, if you get to somebody who wants to do things internationally, you make things much more complex because all the ownership of critical materials about being transferred and transported as to who owns what, when, and who is responsible for it gets very much more complicated. This is exactly how the fuel salt gets delivered and removed is a significant unknown in the future of MSRs.

Berta Oates

Thank you. For effective decay heat removal under accident or off-normal conditions, for example, salt drains into the tank, what is the target delta T for the salt? Is the intention to freeze the salt simply lower or significantly below operating temperatures? I think some of this already addressed.

David Holcomb

Okay, I mean long term eventually salt freezes. But if you look at things – well, there's a lot of decay heat in the salt and that depends a lot upon things like a high-power density reactor. Some of the fast spectrum systems are talking 300 megawatts per cubic meter type power densities. There's no way this is going to freeze in a reasonable timeframe here. So there's not a single answer to that because it depends upon the reactor design. It depends upon mostly it's power density. It depends upon the timeframe. If you froze the entire batch of salt because it's then all below 450 degrees Celsius, well certainly nothing is going anywhere on there. If you were intending then to ship this to the next reactor site, well probably that's what you want to do. All we are trying to do in a short term for a safety evaluation is get to the conclusion on the accident. Once you've gotten to the conclusion of the accident where things are not going further south, where you are removing the decay heat reliably, the criticality is controlled, and the radionuclides are controlled, then you have achieved what you needed to for the safety purposes. What eventually the plant wants to do with the salt later is then a separate issue.

Berta Oates
Thank you. There's two that deal with GDC's 25 26 and 27. So specifically are GDCs 25, 26, 27 applicable to MSRs? How might the MSR vendor address these GDCs? And then GDC's 25, 26, 27 are generally about reactivity control redundancy and diversity and system design of the reactor.

David Holcomb
The answer is what we may have to do initially on reactivity control because their requirements have two methods for reactivity control, one of which involves rods and those continue to exist in the advanced reactor design criteria, as we may have a near-term and a long-term answer on this. Because that's part of what we're saying in the ANS-20.2 is what's an adequate response initially to get a license, because it's not incredibly difficult to do a control rod system with a reactivity feedback system to provide negative reactivity control in this. So it may be that first-generation plants have a reactivity control system which is considered safety grade simply because we have not provided adequate evidence that the inherent reactivity control is adequate. I can't comment on any specific design because I don't know what the design is and how they are doing the design criteria. I indicated that normally what you do initially is put additional conservatism in your design and then you decrease the conservatism as you get better understanding of the physics.

Indeed, reactivity control may involve a short-term component in the first generation of designs, designs that I suspect as we develop additional models and additional confidence in the performance of the reactor if you can show adequate confinement of the radionuclides. If you can achieve the safety functions without this, you can make a credible argument that you don't need them. But that's another argument you have to make. Do you want to get your plant built today or do you want to get your plant built after you've gone through having an argument about an exception?

Berta Oates
Thank you. Would you explain DEC for MSR?

David Holcomb
Design Exception Conditions? The design extension conditions, essentially if you look at what the ACRS has recently been saying is that for some of the advanced reactors the design extension conditions and beyond design basis accidents are sort of a continuum. They don't really stand out so much from design basis accidents there. I am not sure that we got a defined set of particular accidents for a particular plant. I don't know that beyond design basis or design extension conditions really are much different than what you would have as a bounding accident. But I think this might involve some significant more discussion. So I don't think I've given a very satisfying answer to that.

Berta Oates
Thank you. Has it been demonstrated that denatured thermal MSRs can guarantee a negative temperature coefficient in operation and casualties with much higher fertile and fission product poisons to HALEU, especially LA LEU fissile ratio than MSR? If I post it, you'll be able to read it better, it's kind of long to read out loud for you.

David Holcomb
Okay yeah, I didn't get what the question really is.

Berta Oates
Do you see it now that I've posted it to all?

David Holcomb
Posted it? Okay, what I see is noble metal fission plates out in the heat exchanger, is it identical to thermal or immediate spectrum fluoride as far as the spectrum – for the fast chloride MSRs unlike was stated. Plate out thickness is proportional to the power and inversely proportional to the heat exchanger tube entrance surface area?

The only thing I had to say about whether plate out is that solubility is different in chlorides and fluorides. Chlorides tend to have high degrees of solubility, so plate out does have something to do with chemistry on there. Fluorides and chlorides are different. You are correct, the amount of production is proportional to the power but whether it plates out has to do with what's the solubility.

Has it been demonstrated that denatured thermal MSRs can guarantee a negative temperature coefficient in operation and casualties with a much higher fertile and fission product poison to HALEU, especially low assay LEU fission ratio than MSR?

I don't understand. Has been demonstrated that denatured thermal MSRs. So a denatured thermal MSR essentially has a large amount of either even isotope plutonium or U-238 or non-fissile uranium. It can guarantee a negative temperature coefficient in operation. Casualties with a much higher fertile and fission product poisonings to HALEU, I don't have an answer for that on this. I don't know whether specific reactor physics questions have been answered on this. I don't have a specific reactor physics response to whether fertile and fission product poisoned. I don't understand the part of it 'than MSRs' in there.

Berta Oates
Thank you.

David Holcomb
Yeah. It says most thermal MSRs do not assume indefinite fuel life and reuse, at most 7 or 8 years. Well certainly some of the vendors are indicating that you can. Terrestrial being a leading vendor. Only chloride has infinite life and near 100% burn up. Not all fast chlorides, some use feed and bleed once through. Indeed, that's true that some thermal spectrum MSRs are intending to continue to use fresh fuel on there and then they have a waste form on there. One of the leading candidates is to use an infinite life system and that's the Terrestrial design.

In the waste forms for fluorides and chloride salts are, still that's a topic of discussion. In forms of terms of adequate stability and emplacement, it's in some ways similar to the questions about storing of actinide materials for any other reactor class.

Berta Oates
Is the impurity level in the fresh fuel salt specified?

David Holcomb
It should be. There's a question about that as to whether it actually is and how do you verify that what the impurities are in there. Because certainly some impurities have very negative performance aspects on them. Just measuring things like how much oxygen is in the fuel salt is non-trivial and there hasn't been an acceptable ASTM practice that this is how you do that. That's one of our challenges.

Berta Oates
Thank you. There are two regarding thorium fuel. One asks about advantages for using thorium fuel.

Does thorium fuel have any advantages, is the question?

David Holcomb
The reason people are interested in thorium is to substantially extend our fissile resources. The challenge of course remains the same as what it always has been is that you end up producing U-233 and U-233 is a fissile material. We have to be able to produce it in a manner which is

compliant with the Part 74 and Part 75 of the Code of Federal Regulations about material control and accountability and proliferation, and safeguarding. Your President Carter's words about the fuel cycle remain in the Presidential Directive which indicates that we will direct our resources to fuel cycles which do not involve direct access to weapons usable materials, remains in effect. And provided the thorium fuel cycle continues to have that as a potential feature, we will continue to follow, to be compliant with the Presidential Directive.

It'd be wonderful to have increased use of fissile resources and that's why people are interested in thorium, that and you don't get transuranics in the waste stream in this. Not having transuranics substantially shortens the amount of time you have to watch the waste. So, yes, people are interested in that. No, it's not inherently an element of molten salt reactors.

Berta Oates
Thank you. It looks like there's about six more questions. I know we are about 30 minutes into this so bear with us. We'll see if we can run through these quickly. Is there any experimental data or study on molten salt corrosion effect on thermal hydraulics?

David Holcomb
Essentially corrosion will of course impact thermal hydraulics. Essentially whether you've got corrosion products plating out in places, you're going to change the tube diameter. You're going to change tube diameter and you also change smoothness. If you look at things like nickel is really problematic. If you go ahead and you take a non-oxidative corrosion where you take nickel out in the hot part and then deposit it in the cold part, nickel tends to grow dendritically, which means you get something that looks like steel wool in your cold part of your loop which of course has substantial impact on your thermal hydraulics.

If you run even things too reducing, the fuel salt will attack carbon and you will get uranium carbide formed. Well of course that will affect your fissions. That'll affect everything by running things too reducing. This has happened in other cases but generally speaking the considerations of corrosion have dominated the impact on thermal hydraulics other than some folks have done some studies indicating that we've deposited films on things which have decreased some of the heat transfer, but I don't think there was enough systematic study of that.

Berta Oates
Thank you. Do we have good corrosion resistant materials ready for use in MSRs?

David Holcomb

The materials, essentially we've determined if you run the salts in a reducing condition that they're not highly corrosive from an engineering perspective. That means that most of the materials are generally acceptable for their service. That does not mean we have an optimal material set. It means that we care about the chemistry a great deal. Also, I don't believe with a thin walled system with the radiation damage that you're likely to see, are likely going to have a capability of guaranteeing that your reactor vessel is not going to fail in a manner in which we have light water reactor vessels are just postulated not to fail. I think that we are likely to have potentials for failures at points where you would have leaks. But will stainless steel 316H adequately perform in a reducing salt environment? It generally is pretty darn corrosion resistant. There's not an enormous speed. I start worrying about erosion if you've got a high power density reactor and I am flowing in the velocities get to where you have in a light water reactor where you are talking 17 meters a second, you might do some erosion damage. But I don't really see a huge issue with corrosion if you maintain the salt chemistry. If you don't maintain chemistry control, we can't do any of this. You lost chemistry control and fluorine will eat anything and chlorides won't be far behind.

Berta Oates
Thank you. Has any thought been given to online salt processing and how to manage waste generated from this process?

David Holcomb
Certainly, some folks are considering online salt processing. If you look at for example FLiBe Energy Inc. is considering reinstituting the processes that were done in for the molten salt breeder reactor program. They have looked at the waste streams involved in that. That's part of some of the national campaign literature that has come out is looking at some of the molten salt waste streams. I encourage you to look at some of the more recent reports that are coming out of PNNL, some of the authors or folks like Brian Riley from PNNL or Joanna Mcfarland from Oak Ridge National Laboratory which are looking at some of the waste streams that do include consideration of potential salt processing. There are waste stream potentials. However, not every reactor does significant online processing and they end up with very different types of waste depending upon what they are intending to do. For example, if you're just doing mechanical filtering, you have mechanical filters which are very hot, which don't look an awful lot dissimilar to resin beds. So I can't really say whether any one particular design or any one particular set of processing has been adequately considered because there is such variability. The folks who appear to be coming first to the NRC which Kairos has a number of topical reports ready for engagement and Terrestrial Energy USA appears to be about 6 months or so behind, neither one of them have extensive fuel cell processing.

Berta Oates
Thank you. Is the nuclear data library in the present such as JEFF, ENDF, JDL etcetera enough to be used for the neutronics calculation model of the MSR?

David Holcomb
Well, the issue is do you have design optimization on there. My answer is of course always negative, no on there, because there are uncertainties in there. We know things like the chlorine 37 NP. There are uncertainties in the cross sections. On the other hand is this adequately for safety calculations and could we run a design based upon what we currently have? The answer is yes. The nice thing on the engineering stuff is there's a lot of margin on these reactors. We don't have to know things absolutely perfectly to have a useful and safe operation. Should we know more to improve exactly what our fuel cycle is? Yes. I have no question saying that we should get some improved and decrease the uncertainty in some of the cross sections. But I don't think anything is currently limiting someone in their application in terms of what's their safety. If we end up having to add a small fraction of a percent more fuel or less fuel over time, yes that's almost certain.

Berta Oates
Thank you. I am going to bundle a couple of these and see if we can clear out these last four or five that are here. The traditional thorium codes were developed based on water-based hydraulics and heat transfer correlations. I don't know it's ‘Th,’ so it's probably not thorium, the ‘Th code’ used for MSR safety analysis, has the salt specific heat transfer correlated implemented.

David Holcomb
Yes, there have been heat transfer correlations. I mean it's a single-phase heat transfer. There are a number of heat transfer correlations and the differences within there. Go look at Becky Romanowski's [ph] Ph.D. dissertation from MIT the last couple of years, it got some good correlations in there. Prior to that, Grady Yoder, I think it was ICAP 2016 did a very good paper on heat transfer correlations and the status of knowledge.

Yes, is there too much uncertainty in these? Absolutely. I think even in FLiBe we probably have 5%-10% uncertainty in some of the property data in the heat transfer coefficients. In the salts that are with fission products building in there, there's a substantial amount of remaining uncertainty in the correlations, and probably 30%-40%. I would like to have it a lot better. There's quite a great deal of room to doing heat transfer correlation measurement and that being a useful thing to have to improve our designs. Again, we have to put extra margin and extra conservatism in to accommodate the fact that our property data isn't as good as it should be. I would like to have much lower uncertainties on a lot of those numbers. But right now what we do is we take what we have and we apply conservatism to the design.

Berta Oates
Thank you. What is the impact of fission products on salt properties like fusion temperature?

David Holcomb
Depends on how much is in there. How much have you built in? As long as it's a small amount, not much, if it starts being a substantial fraction on there, it changes the properties. You become physium fluoride, physium chloride. But if you look at most of the thermal spectrum reactors, even very long periods of time there's not huge buildup of the materials there. So there's not a tremendous impact until very long periods of time where you get very large amounts of buildup. Some of the fast spectrum systems have higher fractions of fissile materials in them and this may occur sooner.

There are also synergistic effects that you get things like lanthanum trifluorides which displace some of the solubilities of the actinide trifluorides. So you have to be aware of the impact of the decrease in solubility by building in fission products. There are joint solubility differences. These are phenomenon which are known but perhaps not known at the precision you would like to have them. Again, the technique tends to accommodate the unknowns in there, is to generally have margin in your system. And then we need to have adequate knowledge of the fuel salt properties throughout the cycle. Yes we'd like to have more knowledge of things like what's going to happen. Are we going to approach a solubility margin before my next measurement to the fuel cell properties?

Berta Oates
Thank you. Any thoughts regarding potential material fuel salts accounting techniques from the safeguards viewpoint that could be employed by MSRs? Can we use a water-based thermal hydraulics code such as TRACE for MSR safety analysis?

David Holcomb
Well TRACE fuel has salt properties in it. They've been incorporated into some of the systems so that we can do thermal hydraulics. But for safeguards analysis for a lot of things, the challenge becomes if I sample the salt in order to measure it, that becomes a removal path. And if you're looking at one of your models as well, if I keep sampling and keep sampling and keep sampling, do I divert stuff over years to get a small diversion path? But you are going to apply the traditional methods, key measurement points, material balance areas. It's not going to be

different in many ways than how you do a fuel cycle facility. Those are questions about you know where are my measurements? What should be on there? So there's going to be a more intimate coupling between the operational history because that'll tell you how much is being produced, and then the fuel cycle system. Because if you change the spectrum a little bit or you change the amount of absorber, just going between a chlorine 35 based salt and a chlorine 37 based chloride salt will change the amount of plutonium you are producing on this because it changed.

I think anything which is going in and out of containment is certainly going to have to be measured. Now is there a definitive answer to how are we going to safeguard any one particular design? The answer is no. We do not have of that. Do I think that there is a reasonable path for safeguarding these designs? Yeah, it's going to be classic measurements of where are the fissile materials over time?

Berta Oates
Thank you. Do people pronounce the acronyms like words? Would FLiNaK use as primary fuel salt be acceptable in view of higher solubility of plutonium and transuranics for fast neutron MSRs?

David Holcomb
FLiNaK has been considered by – one of the Russian groups has been looking at because it's monovalent, you can dissolve more some of the actinides in there. I forgot his name, it's one of the Russian groups has been looking at FLiNaK based fast spectrum systems. Yes you can dissolve more actinides in monovalent than polyvalent fluorides and looking at it for fast spectrum systems. If I weren't right here being pressed right now, I'd probably remember the design lead’s name, but I can't right now.

Berta Oates
Is it ignitive?

David Holcomb
FLiNaK is not – it means potassium and it's like bananas, they are radioactive. It's just natural.

Berta Oates
Okay last question, have non-weapons grade fuel thermal MSRs demonstrated negative temperature coefficients?

David Holcomb
There have been negative reactivity coefficients in designs but we've only operated one MSR. So if you are saying demonstrated meaning in a running system, well MSRE used high assay MSRs, but it wasn't 93%. They were using plutonium and U-233 at the end which were high assay,

direct weapons usable. But they are 33% or so enriched that they were running. Originally an MSRE is by definition above 20%. That's the only demonstration we've ever had. If the question becomes demonstration, we have not demonstrated anything about because we've never run a 2% enriched MSR. Certainly the 2%, that is the Terrestrial Energy is making its case that they have a negative reactivity coefficient for a 2% enriched graphite moderated system and that they are currently undergoing licensing in Canada.

Berta Oates
Okay. Thank you very much. That was probably almost 50 minutes of Q&A and we definitely thank you David for sharing your expertise and being willing to take so much time to address all of these questions. There's not a numbering system on this. When I get done, I can pull out a transcript, but that's got to be some kind of record number of questions that we've fielded after today's presentation. So I think that shows a great level of engagement and interest in the topic. Thanks again for sharing your expertise.

Patricia Paviet
Berta, I counted. I think we have 36 questions. It's a record Dave. Thank you so much for your expertise. Thank you so much.

David Holcomb
You're welcome and hopefully this was informative and not too grossly controversial.

Patricia Paviet
Thank you very much, Berta, for all, and also for the organization.

Berta Oates
Oh no worries. All right, well until September then. Thanks everyone. Have a great day.

Patricia Paviet
Thank you Dave. Thank you, Berta, bye-bye everyone.

Berta Oates
Bye, bye.

David Holcomb
Goodbye.

END