# Comparison of 16 reactors neutronic performance in closed Th-U and U-Pu cycles
# Dr. Jiri Krepel, PSI, Switzerland

**Berta Oates**
Doing today's introduction is Dr. Patricia Paviet. Dr. Paviet is the group leader of the Radiological Materials Group at the Pacific Northwest National Laboratory. She is also the chair of the GEN IV International Forum Education and Training Working Group. Patricia.

**Patricia Paviet**
Thank you so much Berta. Good morning everybody. I hope you are doing well and it's a pleasure to have Dr. Jiri Krepel with us. He is a senior scientist in Advanced Nuclear Systems group of Laboratory for Scientific Computing at Paul Scherrer Institute in Switzerland. He obtained his Ph.D. in 2006 from Czech Technical University and the Helmholtz-Zentrum Dresden-Rossendorf for the thesis entitled Dynamics of Molten Salt Reactors.

At PSI, he is responsible for fuel cycle analysis and related safety parameters of Gen IV reactors. He is the coordinator of PSI MSR research and a representative of Switzerland at the GIF MSR project. He has experience in the neutronics of liquid-metal and gas-cooled fast reactors and in neutronics and transient analysis of thermals and fast MSRs.

He participated in numerous national and international research and development programs. And without any delay I'm going to give the floor to Jiri. Thank you again Jiri for volunteering to present this webinar. Thank you.

**Jiri Krepel**
Thank you Patricia for very nice introduction and welcome everybody to this webinar, especially nice early morning to America and afternoon to Asia and Australia. Okay, I will speak about closed field cycle today, and since there are already several webinars related to this topic, I will try to put it in slightly different perspective.

I divided it into 5 parts, my presentation. In the first part I would like to show the relationship between closed fuel cycle, sustainability, and resources. In the second part I will speak about synthetic actinides as a waste. In the third part, I will address the equilibrium and Bateman Matrix Eigenstate. And actually in the fourth part I will show the results of the comparisons of the 16 reactors divided into 3 subparts related to equilibrium reactivity, core size, and radiotoxicity.

At the end, I have four miscellaneous points I would like to do before I will end my presentation, so the expected time is roughly one hour. I hope you will survive it.

Let me start with the first point, closed cycle sustainability and resources. So I like to ask general questions, so what is actually fuel cycle? And you can say okay, it's a process chain to obtain energy. And closed fuel cycle is a cycle where some substance is cycling and does not leave the cycle. For a very nice example of closed cycle we have the nature, where nutrients are more or less cycling and not leaving the cycle. And an example of open cycle, we can take our nuclear cycle because from cosmological perspective it's open cycle. We are burning actinides which have been originated by supernova and we are producing fission products.

Okay, this was partly a joke. Let's have a look at the real nuclear fuel cycle. It has many components and its usually divided into front end where you have exploration, mining, milling, conversion, enrichment, and fabrication, and backend, interim storage, transportation, reprocessing, partitioning, transmutation, and waste disposal.

And my presentation will actually focus on what happens in the middle, so on the reactor physics aspects of irradiation and recycling of actinides. And if I say closed cycle, it means that it is closed for actinides, so actually it's actinides who is cycling in our closed fuel cycle.

The relationship between closed cycle and sustainability is trivial but not so straightforward, so let me firstly say what is sustainability. Sustainability has three pillars. There's the environmental pillar, which means we should consume natural resources with sustainable rate without damage to environment. It is economic, so we should efficiently and responsible use resources to profit in long term. And it's social pillar, so social wellbeing in the long term. So whatever is sustainable should be viable, equitable, and variable. And closed fuel cycle can potentially contribute to all three pillars of sustainability.

And since this is Generation IV International Forum Webinar, I should also mention that sustainability is a goal of Gen IV and its so-called sustainability-1 in long term availability and effective fuel utilization; and sustainability-2 which is related to minimization and managing of nuclear waste and the reduction of long term stewardship burden. So, these two points, they can be shortened as high resources utilization and waste minimization, they contribute mainly to the environmental sustainability but indirectly also to the economic sustainability through clear life cycle cost, and to the social sustainability, especially because of the waste minimization.

Now you have to know what is the relation between closed cycle and sustainability, so let's have a look on what are our resources. So our fuels are actinides, and all actinides are unstable, all actinides have half-lives and are decaying. You can see it in this chart, which is in logarithmic scale. If you put it in a linear scale, you immediately see that there are three isotopes, which have particularly long half-lives, and these half-lives are comparable to the age of our earth. And these isotopes are uranium-235, uranium-238 and thorium-232. In the next slide I will call these isotopes very often like uranium-5, uranium-8, thorium-2, so I hope it will not be a problem for you. And from the three, only one isotope uranium-5 is fissile.

Now, I would like to do small detour to cosmology because these actinides have been created by supernova and actually they have been created in the supernova by the so-called rapid neutron capture. But how you can create something fissile by rapid neutron capture? The answer is fission barrier. This rapid neutron capture goes through an area where the fission barrier is high enough that fission doesn't occur. So you can follow the red arrow and probably the process in supernova goes. And first later with alpha and beta decays, the isotopes of actinides which we know are created. And this picture is nice to illustrate that in our fuel area the fission barrier is lower than more protons, so increasing the Z axis are closer together, so decreasing the N axis, the number of neutron axis.

And fissile element means actually that the barrier is smaller than the binding energy of the interacting neutron and because there is a pairing effect, of course the binding energy is higher for odd-N isotopes, so isotopes which have odd number of neutrons. Therefore, uranium 3, 5 and 7 are fissile and uranium 4, 6, and 8 are not fissile.

Now back to our major story, so our resources are actinides and they are not renewable. So the reserves we have are correlated with half-lives to a certain extent and only uranium-5 is fissile from these two. The other two, thorium-2 and uranium-8 are fissionable, and uranium-8 is roughly 10 times better in this parameter, because it has slightly smaller fission barrier actually. But in majority of the case, these two elements are capturing neutrons and they are being transmuted, which brings me to the second part of my presentation where I would like to speak about synthetic actinides as a waste.

The premordial actinides, they can be irradiated. And when they capture a neutron, you create a new isotope of actinide which may either decay or catch another neutron, and so on and so on. So you have more or less three irradiation chains of actinides starting from 3 premordial actinides we have. And at this slide I would like to define three trivial points. When a neutron is absorbed by an actinide isotopes, there are three major outcomes. The first outcome is burning, so actinide fission, or

breeding, transportation, which is increasing fission probability, so you transmute even-N isotope to odd-N isotope. And the third option is parasitic neutron capture, which is transmutation where you are decreasing fission probability, so odd-N goes to even-N.

Now, back to the chain, so actinides are irradiated in the chain, so let's once again start from thorium, which capture a neutron and after two beta decays, you create uranium-3. This chart which I am just showing was created for molten salt reactor with fluoride salts, and the light blue color is for thermal MSR and dark blue color is values for fast MSR. But the fast MSR with fluoride salt has fast reactor but has very soft spectrum, so it's not usual fast reactor.

So the thorium can also undergo end-to-end reaction, I show it here, but this is not the major focus, so let's come back to uranium-3. Uranium-3 is low fissile, quite high probability to be fission, but still it can fail. And if it fails, you create uranium-4, which is not fissile, which will catch another neutron and then you create uranium-5. So, this is a point where thorium-2 and uranium-5 chains are merged.

Now, uranium-5 is quite particular fissile element, it's the only primordial we have. And if the fission of uranium-5 fails, it's more or less a small disaster from neutron balance because you will need 3 to 4 neutrons to create other fissile element which is plutonium-9. At the same time, particularly in this case the capture probability of uranium-5 is 27% in fast MSFR and only 18% in thermal MSR. So this is the only isotope which has higher capture probability in fast spectrum in this case.

Now, coming back to plutonium-9, this is a place that also the uranium-8 chain is merging and if the fission of plutonium-9 fails, we are building higher plutonium actinides and minor actinides, so it's a gateway to minor actinides.

Why the actinides which we are generating, the synthetic actinides are unwanted waste? So, the primordial actinides have quite long half-life so they are decaying slowly. Uranium mine [ph] is a radiotoxic place but not so strongly radiotoxic and usually often used as a reference for final waste depository. But if you generate synthetic actinides, they have too short half-life for them to be primordial; at the same time once they are generated, the half-lives are too long for them to disappear swiftly.

And the long-term stewardship burden is mainly driven by the medium half-life isotopes, because they are not disappearing swiftly, and they are not mildly radioactive. Therefore, they are the most problematic. So, typically from LWR spent fuel, it's plutonium 39, 40, 42 which cause the long-term stewardship burden but the story is not so straightforward because actinides are decaying in chain. So fast decaying curium-243 is

decaying to plutonium with medium half-life and plutonium-9 decaying to uranium-5 which has very long half-life.

Okay, now this is the last slide for the second part, let's go. Let's come to the equilibrium, the Bateman matrix eigenstate. Generally, if you want to increase sustainability you need to increase burnup because we know that actinides are not renewable and only thing we can do is high resources utilization so we should fission at best all the primordial actinides we have, on the earth, and we should minimize the waste, so we should minimize the amount of synthetic actinides which goes to the waste.

Now, for each, in ideal case, we should not let the actinides to leave the reactor. So, you can imagine as this illustration, an ideal reactor would be an infinite fire where the uranium and thorium would be the firewood, you will produce electricity and the fire will be catalyzed by plutonium-9 and uranium-3, and fission product will be continuously removed from the fire.

Nonetheless, in reality, actinides must regularly leave the reactor. So, if you want to increase sustainability you have only two options. First option is higher burnup in open cycle, and the second option is actinides recycling in closed cycle. But it actually leads also to higher burnup, so both these options are leading to higher burnup. And therefore, the material which load in the reactor is irradiated for longer time. And if you keep the mass of major primordial actinides, let's say thorium-2 or uranium-8 in the reactor constant for enough long irradiation, the composition of induced synthetic actinides will stabilize. So, in this irradiation chain the creation and destruction rates will equalize for each isotope.

Very known example from this perspective is the LWR fuel, uranium-8 mass in LWR fuel is practically constant, and plutonium-9 amount in the LWR fuel is equalized after 2 or 3 years of irradiation and then it stays constant, so it reach equilibrium.

Another example which I have is the molten salt reactor, this time started by hypothetical fuel consisting of thorium-2 and uranium-3. And the fuel is prepared so that the reactor is isobreeding or breakeven. In this case, after only 6 years of irradiation, there are many nuclides which are already equalized. At the same time there are some which will need centuries to stabilize. But you can recycle, you can repetitively irradiate this reactor after recycling it, and later on all nuclides will be equalized and converged.

The necessary condition for this to happen is that there is a stable feed or actually a stable mass of uranium-8 and thorium-2 in the reactor, and then there is a constant flux. If you impose the flux, you can reach

equilibrium also for subcritical system. This is not natural and you can say okay, why to do that? But by simulation you can impose the flux, you can reach the equilibrium even if the reactor is subcritical. And knowing the equilibrium tells you a lot about the reactor even though the reactor will be never operated at equilibrium.

Now if you go to reality, it's slightly more complicated. You need to fix fuel cycle parameters like power or reprocessing scheme, feed composition and so on so that the repetitive recycling will result in equilibrium composition. So let's say equilibrium fuel composition depends on the feed which you are refueling to the reactor. Of course, it also depends on the spectrum. At the same time, the spectrum is strongly determined or co-determined by scattering materials. So, whenever there is water in your reactor, you cannot make it fast reactor, for instance.

And fuel composition and neutron spectrum determines the multiplication factor. So, equilibrium is inherent core state, it's Bateman matrix eigenstate which is determined by fuel composition spectrum and reactivity. And the equilibrium reactivity can tell you, indicate the neutron efficiency and the reactor capability for sustainable breeding or burning.

You can easily design a reactor which will be breeder in first or second cycle, but often in the third cycle it stops to breed because many isotopes tend to equalize and the equalized version, the equilibrium is not so good for being as your initial fuel, so you should know what is your equilibrium if you are designing breeder.

There is one feature of equilibrium which is obvious but let me point it out. In equilibrium, the fuel composition is constant so breeding gain is by definition zero because the fuel composition is not changing. At the same time, the multiplication factor doesn't need to be 1 because we didn't ask for criticality, we imposed the flux.

If there is excess reactivity, you can use this excess reactivity to estimate the breeding performance of the reactor. And to do this estimate, you can perturb the capture of the fertile material so that K effective will be 1, and breeding gain will be different than zero. Okay, I don't want to go into details. If you combine these four equations, you obtain the relationships which was known already for our grandfathers, so easy relationship between breeding gain and reactivity.

Now, this was the last slide of the third part where I was trying to speak a little bit about Bateman matrix eigenstate, let's start the 16-reactor comparison part of my talk.

Before I start, I have one disclaimer, and the disclaimer is that this comparison was done purely from neutronic perspective of equilibrium cycle. So there is no chemistry, there is no technology included here. And I have initial two slides before I really start to speak about our study, where I would like to show again the irradiation chain of thorium-2 and uranium-8. And already from the nuclear data of these isotopes, we can do some conclusions, so let's start with the fission probability.

Uranium-3 has very high fission probability up to 90% and it doesn't matter in which spectrum you are, if it's a thermal or fast reactor. For plutonium-9 it is only 60% to 75%. Okay, this high fission probability of uranium-3, the biggest advantage of thorium cycle depends on the library. There are some libraries where the probability is slightly lower but it's still very high. Another parameter is the fission ability of uranium-8 which is 10 times higher than for thorium-2 because of the lower fission barrier.

And the third parameter you can also discuss here is the neutron production per fission. And in this parameter plutonium-9 is excellent because we have 2.9 neutrons per fission, whereas uranium-3 provides only 2.5 neutrons per fission. So this is the biggest advantage of plutonium cycle, you have lot of neutrons from plutonium fission.

In this parameter also the uranium 8 is slightly better than thorium. And the last thing I would like to demonstrate on this slide is that if the transportation rate for thorium-2 and uranium-8 is the same in these two chains, then there will be 11 times more protactinium in the thorium cycle than neptunium in the uranium cycle. This is based simply on the half-lives but this may have consequences for protactinium parasitic capture.

Coming back to the 16 reactors comparison, we selected 16 reactors and we looked on both fuel cycles. The idea was to cover major neutron spectrum types. So we selected all Generation IV reactors and major commercial reactors. But in Generation IV there is one reactor, it is MSR which is not really one reactor. It's a family of reactors with many different concepts and many different spectrums actually. We selected six cases which is quite a lot, but still not enough. I will later have one slide more for this. And we ended up with eight thermal and eight fast reactors and I must admit we forgot Magnox. So the Magnox spectrum is kind of forgotten in this study.

The assumptions for which we reached the Bateman matrix equilibrium were quite strong. We have been assuming infinite lattice, so no neutron leakage. We neglect the fission products, so each fission results immediately in refillment of thorium 2 or uranium 8 atom. So as a consequence there is no bench-wise installation and everything is smooth and converging. These two assumptions are very strong, at the same

time they have not so strong influence on the equilibrium composition and you can still do conclusions based on these assumptions.

The third assumption was designed as is, no additional optimization and we use ENDF/B-VII-0 library for the simulation. So let's have a look on the reactors we selected. For the thermal reactors, it was helium and salt-cooled pebble-bed reactor, HTR and FHR. It was CANDU moderated by heavy water. It was high performance light water reactor, RBMK, and light water reactor represented by VVER-1000 rate.

The liquid fuel was represented by graphite moderated MSR, with lithium beryllium carrier salt, so more or less the design from Oak Ridge National Laboratory. And the same lattice but salt without beryllium, so lithium fluoride carrier salt. The four fast systems have been with solid fuel and four with liquid fuel. The four systems with solid fuel are the three usual suspects, so it's lead, gas, and sodium cooled fast reactors. And for the sodium we selected also the case with metallic fuel. The liquid fuel reactors, here we pick up homogenous molten salt reactors, but there is more or less only salt in the core, no structural materials or dedicated coolant. And two salts for the fluorides, it was the lithium beryllium salt and lithium salt, and two salts for the fluorides. It was a eutectic of sodium fluorides and actinide fluorides and it was pure actinides fluorides.

The last case, it's a little bit extreme case, there are people in the audience which will immediately say yes, but the melting temperature is too high. You can more or less forget it but it was still included as a maximum achievable, let's say from neutronic perspective.

So, let's have a look on the results. So, the first part, let's have a look on the equilibrium reactivity. And here it is. We have 2 times 16 values of K-infinity for the 16 reactors and two fuel cycles. Obviously, what is learned from literature, thorium is better in thermal spectrum, uranium-plutonium cycle is better and faster too.

But you can also see that the actinides Eigen-composition in uranium plutonium cycle is subcritical for all thermal reactors. You may also ask on this chart what is the reactivity gain option because there is in the legend somewhere written reactivity gain option so I should say it. It has two components. The first one is not recycling of higher actinides, and the second one is protactinium and neptunium decaying outside of the neutron flux. Of course, both these options are not realistic options for solid fuel reactors but they are included because they may play a role in MSR.

Looking on this chart, you can also see that in plutonium cycle the dependency on the spectrum is much stronger. The reactors in this chart are sorted based on the spectral indices so that on the left is the most

thermal reactor and on the right is the most fast reactor. So you see that the plutonium cycle depends more stronger on the spectrum than thorium cycle. In thorium cycle case, it is caused by the very low capture probability of uranium 3 in any spectrum.

But you can also see that breed and burn cycle which I will little bit address at the end of my talk is possible only for uranium plutonium cycle, and K-infinity of 1.2 is a kind of threshold for the breed and burn operation. Then there are two reactors, high performance LWR and FHR which are really bad performing. In the first case, it's caused by the stainless steel cladding in thermal spectrum. In the second case, it's the combination of lithium beryllium fluoride salt as a coolant which doesn't absorb high capture cross-section. But the combination with low density fuels makes it really visible for the neutrons.

You can also see that the HTR, RBMK and CANDU are on the edge of breeding in thorium cycle, but here I would like to recall that leakage and fission products are not accounted for in these results.

Now, looking at the molten salt reactors, there are six selected reactors, so two of them are graphite moderated. They are also on the edge of breeding. And usually if you want to operate graphite moderated reactor as a breeder, you need intensive fission product separation, and sometimes also consider that protactinium will decay outside of the core, so that you can really breed.

In the molten salt fast reactor with fluoride salt, the performance of thorium and uranium cycle is almost equal because the spectrum is fast but quite soft, and you still need some intensive separation of fission products. For fluoride fast reactors, you obtain maximal reactivity from all MSR cases in both cycles, and they are in these criteria performing as well as the best solid fuel reactors.

Now, this result as such is quite interesting but doesn't provide enough insight, so we decided to use reactivity breakdown method to understand how these results are created. And we break down reactivity into three components. It was available neutrons, then the bonus from fertile material, so whenever direct fission of fertile material or end-to-end reaction occurs, it's a bonus, and then parasitic neutron capture by other actinides and structural materials. This breakdown was derived from neutron balance using four conditions. I don't want to go through these equations but first three assumptions are kind of general and easy to fulfill or easy to assume.

The last one is not so trivial because it's a consequence of equilibrium. The last condition is saying that any other actinides than the major fertile is created from the major fertile and therefore the reaction rate of these

actinides must be equal to the transmutation of the main fertile. Okay, if there are some questions, you can send me an email later. It's really so in equilibrium.

So now let's have a look on the components of this breakdown. So, first component available neutrons depend on the average number of neutron per fission. And this is quite surprising results of the simulation. What you find out that you produce 2-1/2 neutrons in thorium cycle, in equilibrium, and it doesn't matter in which reactor if it is fast or thermal reactor. Of course, if the spectrum is harder, you produce more neutrons by fission of one selected isotope, but at the same time your equilibrium composition is slightly different and this compensating effect makes it flat. So surprisingly, you produce 2-1/2 neutrons in any reactor in thorium cycle when it is in equilibrium.

And the same results we obtain for plutonium cycle even with more stronger compensating effects, but in all reactors it's roughly 2.9 neutrons. And this is the biggest advantage of plutonium cycle and this gives you hypothetically 31,000 PCM reactivity excess in plutonium cycle, and 20,000 PCM excess in thorium cycle.

Now let's have a look on the bonus from fertile material. So, this bonus is caused by fission and end-to-end reaction on the main fertile material. So in thorium cycle, the fission of thorium can be up to 4% related to the total fission. In plutonium cycle, the direct fission of uranium-8 can be up to 15% and so the plutonium cycle is a better cycle also from this perspective. And you can use this chart as a measure of very fast neutron welfare in the reactors. So, if you look at it carefully, you find out that light water reactor and lead cooled fast reactor, they are almost equal from the perspective of fast neutron welfare. So, the fission of fast neutrons over the fertile material is roughly 9% in both of them.

At the same time you can see the MSF molten salt fast reactor with fluoride salt, it's acting more like thermal reactor than fast. Okay, let's come to the last component of the reactivity breakdown is the neutron capture by actinides. It strongly differs between the cycles, it's roughly 20% in fast reactors in thorium cycles, and up to 40% in thermal reactors. Again, MSFR acted more or less like thermal reactor. And in plutonium cycle, it is rather 30% in fast reactors and up to 120% in thermal reactors, so this is the major reason why plutonium cycle cannot be operated in thermal spectrum.

Let us put these three results together in one chart, so we have excess reactivity which gives us a certain level around 20,000 PCM in thorium cycle, and then we need to subtract the parasitic neutron captures. This time also inclusive of the structural materials. And what is left is the excess reactivity which we already know from the previous charts. But

now we have much more insight, so you can see that the actinides, [Unclear] composition in thorium cycles is critical in all cases, and the reactors are subcritical thanks to the structural materials and coolant.

If you look at the same results for plutonium cycle, the excess reactivity is higher, up to 36,000 PCM, but in thermal spectrum all the reactors are subcritical, just because of the actinides, you don't need to discuss the structural materials because already the actinides [Unclear] composition is subcritical alone. And in MSFR case, in the case of beryllium salt, it is subcritical the reactor, and in case of lithium salt it's critical. So, it's the reactor on the edge of breeding for plutonium cycle.

And you can basically conclude here the thorium cycle has high efficiency, and uranium cycle has high economy, have more neutrons to spend but you are also spending them more.

Okay, now I have said that we selected six MSR systems but of course, there are many other designs. So for the moderated designs we did study also for five different fluoride salts and six different moderators. There result is shown in one compact chart which is crowded where you have five different salts on the top, six moderators on the side. And since the designs of this system are not realty fixed, it was a parametric study where on the X-axis there is fuel to moderator ratio, so on the right of each square it's fast reactor, on the left there is moderated reactor, and the Y-axis is heterogeneity so general size, where if you go up the channel, size increase.

What you can see is that the lithium fluoride is the best case, neutronically, and that beryllium based and heavy water-based moderators are the best. Light water doesn't work because of the consumption of neutrons because parasitic capture of hydrogen is too high. And graphite is not at all the best moderator but is only moderator which is compatible with the salt. Now we try to look on what happens if you use heavy water of beryllium and you separate it with some structural material from the salt, so we considered Hastelloy, stainless steel, and silicon carbide and the conclusion is that only silicon carbide can work from neutronic perspective. So as a joke, I always propose that we can design heavy water boiling thermal thorium MSR, and if there is some volunteer Ph.D. he can make a thesis on it probably.

Okay, this was the equilibrium reactivity. Now, let's have a look on core size assessment. So what we did was migration area calculation. Again, it's a crowded result but you can see immediately that the migration area is roughly the same in both fuel cycles, it doesn't depend on the fuel cycle. So, migration area is the blue columns. Then there is orange column showing the major fissile specific density, and the yellow column showing the actinide specific density.

You can see that the fast reactors have medium to small migration area. In graphite moderated reactors with low specific fuel density, the migration area is very high. In graphite or heavy water moderated reactors with reasonable fuel density, the migration area is medium. And of course, the smallest one is in water moderated reactors. Yes, that's clear.

Now looking on the three groups of MSR systems for the MSFR, the lithium and fluorine in the salt are scattering and the actinide density is reasonably high so the migration area is quite small. The graphite properties and the relatively low fuel density makes the migration area slightly higher, but in fluoride fast reactors the migration area is enormous. There is more or less absence – even though the density of actinides is quite good, there is absence of scattering cross-sections. The scattering cross-section is very small so the migration area is huge. Now since we know the migration area, and since we know the K-infinity, we can use the Fermi theory of bare thermal reactor. Again, I will not go through the details in equation, we pick up the most reactive cylinder, which is roughly the same height and diameter. And for these parameters, you can estimate the criticality lines which are the functions of the core radius versus K-infinity, and then you can show there the points, the results of our study, the K-infinity which we obtained from the study. And from these points you can read the core radius. But again, it's a core which has no reflector, nothing.

But still, you can do the same for plutonium cycle where the K-infinity was slightly higher, so of course the resulting core size is smaller. And then you can compare it in one chart to make it more visible.

And let me do here just three conclusions, one is that MSFR is really strange case where the core size is almost the same, the plutonium cycle is even slightly bigger. But for all other cases, if the breeding is possible, the plutonium core is smaller. And sodium fast reactor is the most compact core, and molten salt fluoride reactor, so MCFR is the biggest in both fuel cycles.

Now, it's not reflected of course, so what we did, we tried in another study to use Hastelloy reflector for MSFR and MCFR, this time comparing it with classical pancake fast reactor. So here you see the lead, sodium, and gas cooled fast reactor as a pancake. Now we can compare it with reflected MSFR in thorium cycle and in plutonium cycle. In plutonium cycle it's slightly bigger but is still quite compact. If you compare it to MCFR in plutonium cycle, it's just slightly bigger than MCFR in plutonium cycle, it's still quite compact. But in thorium cycle, where the K-infinity is much lower, the core is already quite bulky.

Last but not least, we can include in this comparison also the MSBR concept proposed by Oak Ridge National Laboratory, which was also quite big. At the same time, more than 80% of the volume of this core was filled by graphite.

Okay, this concludes the discussion about core size and let's speak a little bit about radiotoxicity. Radiotoxicity is caused by the actinides which are leaving the cycle. They are leaving the cycle because you can never recycle 100% of them, there will be always reprocessing losses. And using the reprocessing process and using the burnup in fission material percent, you can say that utilization is one minus losses, and you can come to a formula which is shown, and you can plot it as a parametric curve. So reprocessing frequency or actually the burnup of the fuel, versus resource utilization and reprocessing losses.

Now if you take the typical case in fast reactors where you can reach, let's say, 10% burnup, if you don't recycle minor actinides, your losses are around 1%, so your resources utilization is around 90% or bigger than 90%. You can also change this curve into parametric curve where you use the burnup divided by losses, and you know that if you want to go above 90% of utilization, your burnup should be 10 times higher than the losses. And I am stressing this because in molten salt reactors we are often focusing to reprocessed fuel which has very low burnup so we should be careful that the reprocessing losses are 10 times lower than this low burnup.

Okay, so this quantifies a little bit the material, which is lost, which is going through waste, but how radiotoxic is the material which goes through waste. So we did simple study, we say okay, let's take 10 to 30 fuel atoms of all the equilibrium compositions we have. And you can calculate the radiotoxicity evolution. In this chart it is shown for thorium cycle. But you can immediately see that thermal reactors are better. They have lower radiotoxicity because there is less of synthetic actinides. At the same time, many of them cannot be operated in a closed cycle and we don't know how will be the reprocessing process.

And we can also see that there is secondary peak. So the radiotoxicity of thorium spent fuel has secondary peak. In plutonium cycle, conclusions are quite similar but there is no secondary peak. So if you do the ratio of these two cycles, if you want to see the relative radiotoxicity, you will see that the thorium cycle is better at the beginning, but ultimately at the end the plutonium cycle is better because of the secondary peak, and this secondary peak is caused mainly by plutonium-8 and neptunium-7 decay chains.

And I must stress here again that this result is exclusively valid for cores with equal amount of burnup and treatment of the fuel. Now, this is a

look [ph] chart, so not much of physics is shown. If you put it to linear scale it's slightly better, and the conclusion is yes, thorium cycle is less radioactive initially, but it's nothing so tremendous.

So, this more or less finishes the comparison part of my talk, but I still have the four miscellaneous points I would like to do because they are not always presented, let's say it this way.

First of all, fission product importance. In our study we neglected fission product so let's have a look on fission product importance from general perspective. So, often you can hear that fission products have higher cross-section in thermal spectrum, so they are more important in thermal spectrum. That's true. But the cross-sections of uranium 3, 5, or plutonium-9, they are also higher in thermal spectrum. So in the reality you should have a look on what is the share of fissile material in your fuel. So, let's say in thermal reactors in closed thorium cycle, you have roughly 2% of uranium-3 in the fuel. For fast reactors in thorium and uranium cycles, in both, it's roughly 10% of fissile material share.

Now imagine you have 5% of fission products. Yes, so if you put 5% of fission products in these two systems, in thermal spectrum this 5% will correspond 250% of the fissile share. And in fast spectrum it will be only 50% of the fissile share. Accordingly, the tolerance of fast spectrum system for the fission products is strongly supported by this feature. It's not only the relative cross-sections of fission products but it's also the higher amount of fissile share which enable us to reach higher burnups. So, this was the first point.

The second point, I would like to do is close cycle doesn't mean breeding, and for that I have a slide where I try to classify reactors by neutron economy starting with burners, but there is no fertile material so the neutron economy is quite relaxed because you don't need to breed, you don't have parasitic absorption of fertile material. The second level is converter. I like to define convertor as reactive at the capture on fertile material is around or more than 50% of the fission rate. But some people will object that converter should be at least 90%.

And breeder, in breeder the capture rate of the fertile material is equal to the fission rate, so more or less the fuel you load to the reactor, you remove from the reactor later on.

And the ultimate case is the breed and burn cycle where you have no fissile at the beginning and you are discharging fuel with fissile. So now, from the closing of the fuel cycle perspective, you can close the cycle in burner, converter, and breeder. It doesn't have meaning in breed and burn because it's against the philosophy of the cycle.

And we know that recycling is the ultimate waste reducing option, so if you recycle in a breeder you have high resource utilization. We discussed already now before that it depends only on the reprocessing process. If you would be recycling in a converter, you have medium resources utilization, and it is limited by the enrichment process actually. So I would like to do an example here. Imagine you have 5% enriched uranium and you burn it to last atom, your natural resource utilization in this case would be only 10% as you can see on the bottom right chart, because 90% of the material was left in the reprocessing plant. Now, recycling in a burner is not really for material utilization, it's mainly waste minimization. And this closed the second miscellaneous point I wanted to do.

The third one is similar. It's saying that open cycle now doesn't mean burning and you can imagine what I mean by that, because there is something called breed and burn cycle. So in breed and burn cycle you are breeding, you have an initial fuel assembly which doesn't include anything fissile and you are discharging spent fuel assembly where there is fissile material inside. In this case, which is shown, the reactor in overall is critical and the spent fuel you discharge is the most burnt assembly. You can do something similar with molten salt reactor, with a slight difference that the salt is homogenized in the core and you are discharging average fuel composition.

So technically you can collect this salt and later on you can start another reactor with it. But to increase the burnup, or to decrease the core size, you may consider to use more and more liquids and you may discharge the most burned liquid.

Now, the criteria why there should be some threshold for breed and burn cycle is quite trivial. I was considering that the fissile fuel share you are discharging from the core must be equal to the new fissile fuel which was bred in the discharge fuel during the burnup. So, the amount you are discharging should be equal to the burnup multiplied by breeding gain or conversion ratio minus 1.

You can plot such a parametric curve and you have the space where there is conversion ratio and discharge burnup, and fissile fuel share. Now, you can change it to parametric curve where you will do the ratio between burnup and fissile fuel share. And typical example may be for conversion ratio 1.2. Let's assume that the fissile share is 10% as usual for fast reactors. And as you have conversion ratio 1.2 and fissile share of 10%, you need a burnup of 50% to be able to operate for breed and burn cycle. If you would have let's say thermal system which has 1% of fissile share, you will need to reach 5% burn up if the conversion ratio would be 1.2.

Now, I have one more slide about breed and burn which shows the results for MCFR, molten chloride fast reactor, and I would like to use this slide to show roughly the performance of breed and burn cycle. So you see on the right the chart where the discharge burnup is used as a parameter for equilibrium K-effective. So equilibrium K-effective is plotted as a function of discharge burnup. And you can see that at the beginning you don't have enough fissile, you didn't breed enough fissile and at the end you have too many fission products, so your neutron balance is again not so good. Somewhere in between it may work but you can conclude it doesn't work for thorium cycle. The reactivity excess is too low. Maybe it works for mixed cycle.

It seems to work for fluorides and the plutonium cycle – okay all the reactors are with fluorides. It seems to work with uranium cycle and it seems that the more actinides you manage to pack in your salt, the higher is the K-infinity and the smaller is then your breed and burn rate, so there is a trend like this.

Okay, before I end, I have a very last point to do and it's the transition to equilibrium, and the aim of this point is to show that there are 5 major fissile materials available on the earth. It's reactor-grade plutonium, which has medium availability and medium proliferation risk. There is low enriched uranium with high availability and medium proliferation risk. And then we have three materials where there is high enriched uranium with let's say high availability but also high proliferation risk. Then there is uranium 3 with very low availability and high proliferation risk, and weapon-grade plutonium with medium availability and high proliferation risk.

But because of the proliferation resistance or proliferation risk, you can exclude the last three materials, so we are left with reactor-grade plutonium and low enriched uranium.

Now, if you would like to start uranium-plutonium cycle, both these options are fairly natural. You start with enriched uranium and in one of two cycles you converge to uranium closed cycle. The same with MOX fuel. If you use LWR plutonium vector to start fast reactor in uranium plutonium cycle, after one irradiation you have already the equilibrium vector, so it's very natural and fast convergence.

In thorium cycle, it's not so straightforward. If you use enriched uranium, it means that inevitably you will have mixed cycle at the beginning. It may be so that you will have the same amount of uranium and thorium in your initial fuel. Slightly better it is for the MOX fuel if you use light water plutonium vector with thorium, but still both plutonium and uranium-8 do not belong to equilibrium composition of the thorium, so the transition in these two cases may last for a century, so maybe you build two reactors

before you reach equilibrium and the equilibrium fuel will be used in the third reactor.

Okay, now I have one slide to conclude and then I will be open for your questions. So, to summarize results of uranium-8 and thorium-2, not really an argument for preference, we are lucky to have both. Features of uranium-8 and thorium-2, uranium-8 is slightly better. Features of plutonium-9 and uranium-3, plutonium-9 has higher number of neutrons per fission but also higher capture. Uranium-3 has produced less neutrons but has also lower captures. Breeding and thermal spectrum, no, not in uranium cycle but yes in thorium cycle. Breeding in fast spectrum, yes in both cycles. Breed and burn capability only in plutonium cycle. Radiotoxicity at equal conditions, initially slightly higher in uranium cycle. Core size for fast reactors, smaller in plutonium cycle, with exception of the MSFR. And transition to equilibrium is much more natural and fast for uranium-plutonium cycle, and it may take a century for thorium cycle.

So this was my last slide. Thank you very much for your attention, and I will be open for your questions.

**Berta Oates**
Thank you Jiri, thank you very much for putting this presentation together and sharing your expertise. If you have questions, go ahead and type them into the chat box, and while you are doing that we'll take a quick look at the upcoming webinar presentations that we have scheduled. In July, a presentation on the Overview of Small Modular Reactor Technology Development. In August, MSR Safety Evaluation in the United States. And in September Integrated Energy Systems Laboratory Initiative.

Bear with me, I'll just expand my screen a little bit, I can't quite read. Here we go.

Jiri, the first question states, current theory no longer believes supernova created the actinides, astronomers now have consensus that these were created by neutron star mergers with other neutron stars.

**Jiri Krepel**
Yes, it's another option, but probably it will have the same consequences, the question will be still the same, how you can create something fissile by neutron capture. No, no, no, this is fully right. We don't actually know how it was.

**Berta Oates**
Did you consider Seaborg Tech's sodium hydroxide moderator and thermal MSRs?

**Jiri Krepel**

Zirconium hydride, let me see, I think it was presented there, but you speak about something else. You speak about hydroxide. No, we didn't consider it but we know that hydrogen itself is not performing well. So yeah, I expect that the parasitic capture of this salt will be too high to be self-sustaining as a breeder.

**Berta Oates**
There is a question. Neutronic performance of MSR strongly depends on salt temperature density. How would you determine the salt temperature for different salts to make fair comparisons? Second question, how did you treat FPs and equilibrium calculation, are they continually removed at certain speeds or was this comparison between various reactors made assuming the same burnup.

**Jiri Krepel**
Okay so I will try to remember these questions. So for the salts, the lithium beryllium salt was adopted from Oak Ridge concept, so we know well the operating temperatures, we know well the density. The lithium fluoride carrier salt was adopted from MSFR design, the European fast reactor, so is the same. You know roughly the melting temperatures, operating temperatures, operating densities, and of course the lithium fluoride salt include more actinides in the eutectic composition than the lithium beryllium salt.

So I think we included these considerations. For the chloride salts, we rely on the literature, so we find out the properties of eutectic composition and we went above the melting temperature to be on the safe side.

Now, for the second question, if I got it well, more or less it is related to the specific power. Because we have infinite cells and the question is, if I understood it well, it's specific power so the irradiation rate. And here for many reactors it is fixed, but for some MSFR we needed to estimate it ourselves, so I think we said roughly what are the damages of the reactor, and we said, let's assume the reactor will have 3 gigawatt total power.

I am not sure if this was exactly the answer for the second part of the question.

Removal, okay, how did you treat fission products in equilibrium composition, okay. Yes, there is one other question in this. We didn't include fission products at all in our study, so whenever fission occurred, fission products, immediately disappeared from the system and have been replaced by fresh atom of fertile material. So in our study, in the 16 reactors comparison there are no fission products. In the later study I showed for MSR, for this 6 by 5 cases, we included fission products, but not for the 16 reactors.

**Berta Oates**
What about MSFR draining system? Did you calculate criticality of the draining systems in MSFR?

**Jiri Krepel**
In our fuel cycle simulation, MSFR was represented by, let's say, a reflected cube [ph] and we have been looking at fuel cycle performance, so we didn't do any thermohydraulic or safety study. Of course I can give you some answer if you wish about MSFR and draining system, but it's not really a part of the presentation.

**Berta Oates**
Which codes have you used for those calculations?

**Jiri Krepel**
Sorry, I didn't mention it. We used Serpent coupled with MATLAB script. On several slides of my presentation you can find out the links to references, so you can have a look on the papers. It's MATLAB script, which is more or less serving to Serpent, so the neutronic calculations are based on Serpent, and ENDF/B-VII Library.

**Berta Oates**
Did you study FOPR?

**Jiri Krepel**
Did we study what?

**Berta Oates**
It says FOPR.

**Jiri Krepel**
FOPR? FOPR, is it a reactor or? I don't actually know what the shortcut means.

**Berta Oates**
Okay, we will move on to the next question and then maybe the person who asked it can put some clarification in the box. Given that the transition to equilibrium is long, when looking at parameters such as uranium utilization, is it misleading if one doesn't include all the natural uranium needed to generate the fissile material that must be supplied for the initial core or the subsequent cores before equilibrium is reached?

**Jiri Krepel**
Actually, if you focus on the major elements which are important for the fuel cycle, they are converging quite fast. I mentioned the case with LWR, but after 2-3 years of irradiation you have already equilibrium for

plutonium. So what takes a long time is if you start with mixed fuel cycle, it takes really, really long time to get rid of the uranium cycle, to have pure thorium cycle. But otherwise I would say all actinides are our friends, all actinides are fissile or can be transmitted to something fissile. But we need to design more or less two different reactors, one reactor for equilibrium and one reactor for transition.

**Berta Oates**
And then a second question is, you said the equilibrium times for the thorium core were over a century, exactly what are those for uranium and plutonium? Just decades?

**Jiri Krepel**
If you start let's say sodium fast reactor with MOX fuel and MOX was taken from light water reactor, after first reprocessing more or less you have your equilibrium. Of course, the discussion is, is it 99 or 99.9 convergence, but rough convergence already after one cycle. The same is probably valid for enriched uranium. If you start from enriched uranium and you operate it in uranium plutonium cycle, then once you reach the integral burnup of 20% or 2 cycles, you are in fairly equilibrium yes. The problem is mainly with thorium.

**Berta Oates**
Did you study for bubbling time?

**Jiri Krepel**
This is the same question as before. We have, you can call it extreme bubbling case or whatever because we don't consider fission products. Fission products are simply not accounted for. Whenever fission occurs, instead of producing two fission products, we simply put a new atom of thorium or uranium in the system. So we are neglecting fission products. This is a strong assumption of the 16 reactors comparison.

**Berta Oates**
Given the current uranium-plutonium thermal spectrum usage, what is the cost impact of switching to another more sustainable cycle?

**Jiri Krepel**
I didn't get the beginning of the question. Can you please repeat that?

**Berta Oates**
Given the current 'uranium-plutonium thermal spectrum usage' what is the cost impact of switching to another more sustainable cycle?

**Jiri Krepel**
So probably referring to the current reactor burning uranium-5. Okay, this is economical question and it's very hard to answer because the first

generation of light water reactor was quite cheap but it was cheap because the safety systems were not so advanced. Nowadays, even light water reactor is becoming to be quite expensive because of the safety system. And now, if you ask about how much it will cost to use closed fuel cycle where you need to consider, let's say, a reactor like sodium fast reactor and reprocessing facility, of course, it will be more expensive. My hope is that once you really will use it in bigger scale, we will learn the lesson and there will be some scaling factors and it will become cheaper. Yes. But it's an economic question, I cannot answer based on this study.

**Berta Oates**
Okay, thank you. Did you suggest the uranium-237 is fissile?

**Jiri Krepel**
Actually, I didn't check it myself, but it should be fissile because it's odd-N isotopes, so why not. But it has so short half-life that probably nobody cares.

**Berta Oates**
How are you managing the creek that will be there when the cladding material if we ran the reactor for a longer time?

**Jiri Krepel**
Again, it's a little bit outside of the scope of this presentation. But yes, if you would like to operate in breed and burn cycle, you need to reach burnups like 50%, and that's not so easy. So the major research for the breed and burn cycle in sodium fast reactor is dedicated to the material which will withstand such irradiation times.

In MCFR, there is not such a material but of course there are other issues. Probably you will need to replace the reactor several times. But yeah I cannot answer more. I am not a material expert.

**Berta Oates**
Do you have any calculations or suggestions of the radiation dose outside of the reactor core?

**Jiri Krepel**
Our simulation have been not focusing on such a radiation dose, and we simulated infinite lattice, so it's probably not the best option to take our study to simulate or to analyze the radiation dose. Yeah, so I cannot provide any statement. But from these 16 reactors, 10 are more or less well-developed concepts, so probably you can try to search for literature which gives you the answer.

**Berta Oates**

Thank you. There was a comment that reads that FHR may have a better performance if it uses solid fuel assemblies rather than trees or particles or pebbles, or prismatic fuel. There are some papers written by Charles Forsberg and colleagues are design permutations to the FHR?

**Jiri Krepel**
The biggest problem is that if you use TRISO particles, you have very low specific actinides density. If you have this very low specific actinides density and at the same time you go to equilibrium where in equilibrium the fissile share is prescribed by the equilibrium. So normally you operate FHR with 8% enrichment. But if you go to equilibrium in plutonium cycle, there will be less than 1% of fissile plutonium. So you have low specific density of actinides and you have less than 1% of actinides is plutonium, then you really have enormous flux so that the coolant is visible for the neutrons. Whenever you make the fuel more dense, you can of course increase the performance.

**Berta Oates**
Harder spectrum by chloride MSR has higher K-in but it needs more initial inventory than fluoride MSR? Interesting.

**Jiri Krepel**
Yes, that's a correct statement because the inventory is driven by the core size and the core size is product of migration area and K-infinity. So, yes, you have hard spectrum which gives you very high K-infinity, at the same time you have hard spectrum because there is nothing scattering the neutrons, so the migration area is enormous and to end up by slightly bigger reactor than in fluoride case.

**Berta Oates**
There is a request for any study, could you suggest any study for evaluating criticality calculations of the draining system for MSFR for your work or maybe the others?

**Jiri Krepel**
Okay, again, not me. Of course, I am aware of such studies. Here in Europe we have projects on going on MSFR but this is rather safety and thermo hydraulics oriented question which you cannot really…

Okay, what may be relevant to this study is that if you have equilibrium fuel composition, you know K-infinity, you know that it's critical in the reactor. The reactor has, I don't know, in case of MSFR let's say in 10 cubic meters of the salt inside of the reactor maybe the same as outside. What happens if you have draining system and there would be more than 10 cubic meters of salt collected? Of course you should design the draining system so that you have never bigger amount of the salt than in

the core. But that's more or less the only point I can do from neutronic or reactor physics perspective of this study.

**Berta Oates**
We have response on the fissile U-237, sorry U-237 is not fissile. Thermal fission cross-section is 1.48 bars, capture cross-section is 391 bars.

**Jiri Krepel**
Okay, yes I should probably correct this slide. If you recall, the fission barrier chart, so uranium-7 is already quite on the right of this chart, so it can really be that the fissile barrier is already too high. And then the neutral pairing effect doesn't help.

But probably something similar to neptunium-7. Actually now if I remember well, neptunium-7 is quite well fissile in fast spectrum but not in thermal yeah, okay.

**Berta Oates**
That's the questions that I see that have come in. Again, thank you very much for spending your time with us in putting this presentation together, sharing your expertise. It was obviously very well received from the response in the Q&A.

**Jiri Krepel**
Thank you very much for following it, and for early waking up.

**Patricia Paviet**
Thank you again Jiri for a good, good presentation, and for volunteering to give this webinar.

**Jiri Krepel**
Thank you too for inviting me Patricia.

**Patricia Paviet**
Okay, have a good day everybody.

**Berta Oates**
Bye, bye.

**Jiri Krepel**
Bye.

**Patricia Paviet**
Bye.

**END**