MOX Fuel for advanced reactors
Dr. Nathalie Chauvin, CEA, France

Berta Oates
Doing the introduction today is Dr. Patricia Paviet. Dr. Paviet is the Group Leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She 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, good evening, everyone. It’s a pleasure to have with us today Dr. Nathalie Chauvin. She’s working at the French Alternative Energies and Atomic Energy Commission, the CEA Cadarache IRESNE in the Fuel Studies Department International, expert on fuels for fast reactors.

She worked for a long time on the minor actinides transmutation program, participating to the optimization of the fuel design, the irradiation experiments, and the synthesis reports. Then she was project manager for the development of very innovative fuels for the gas-cooled fast reactor with oxide/carbide fuels, refractory cladding including ceramic composites one for pin or plate type fuel element.

She is now in charge of various international cooperations devoted to fast reactor fuels development. She is also participating in several activities in different scientific committees of international conferences such as IEMPT, Fast Reactor, and GLOBAL, and she is the CEA counterpart in several bilateral collaborations with other international scientific organizations devoted to MOX fuel.

So without any delay, I am very happy to have Nathalie today presenting. So I give you the floor, Nathalie. Thank you again.

Nathalie Chauvin
Thank you very much, Patricia, and thank you, Berta. Good morning or good afternoon, everybody. I have the pleasure today to present all the activities on the MOX fuel for advanced reactor.

So I am trying to move to the next slide. Okay, thank you. So within the Gen IV initiative, several reactors have been selected: Sodium Fast Reactor or SFR; Lead or Lead-Bismuth Fast Reactor, the LFR; Advanced Driver System, ADS; and Gas Fast Reactor, GFR. We have also Very High Temperature Reactor, VHTR; and Molten Salt Reactor, MSR.

Innovative fuels have been selected, especially for the Fast Neutron Reactors and it's mainly ceramics like mixed oxide, mixed nitride, mixed carbide, and also metal fuel like UPuZr.

So if we are regarding to the operating conditions. So now some details about the conditions of fuels in these fast reactors. We want to reach quite high linear heat rate of 400 to 500 watts per centimeter, especially foreseen for the SFR, but it could be lower for the other systems like the GFR or LFR. The fuel temperature is in between 600 to 2400 degrees. And this is the main difference with the light water reactors, where the fuel temperature remains below 1000 degrees.

Another difference is a very high burnup that we want to reach, an average of 13 atom percent, but we want to go to 15. The residence time is also very high with 800 equivalent full power day. And this corresponds to a dose on the cladding of more than 130 dpa. The dpa is displacement per atom, which is the scale for the evaluation of damage on the cladding.

So now if we are moving to the criteria for the choice of materials. So, the criteria for fuel materials choice are density in fissile atom, high thermal conductivity, as well as a high melting temperature in order to have a high margin to melt. High thermal stability is required in order to avoid phased transitions or dissociation at low temperatures.

It's very important in every – it's very important in every situation to avoid as far as possible the fuel melting for safety reasons. High mechanical stability is also relevant with an isotropic expansion as well as radiation resistance. The chemical compatibility of the fuel with the cladding is very important in order to prevent from a material damage because the clad acts as the first safety barrier.

The reaction with the coolant should be acceptable in order to avoid any energetic strong reaction. The performances for the evaluation are focused on the capability to reach high burnup and the flexibility towards various operating conditions. This means, for example, the ability to operate at lower power or lower temperature ranges.

Secondly, the behavior in case of transients up to severe accidents are the most important factors to take into account. And in the case of the crossed fuel cycle, the ability to manage the plutonium or to burn minor actinide is also very important.

And finally, the cost of fabrication and reprocessing is relevant toward the performances.

So here is the content of my presentation.

It's very long to move from one slide to the next one. Berta, maybe you can help me.

So, the content of my presentation is, first, we will start with an overview of the main characteristics of the oxide fuel for fast reactors with the properties before and during irradiation; a comparison with the other fuel for innovative reactors will be presented. We will have a very quick overview of the different families and design of fuel and fuel element with a very short description.

The second part will be devoted to the fuel behavior under irradiation with the main features of the thermal and mechanical behavior within parallel the evolution of microstructure. In the third part, we will have an overview of the performances reached, the improvement of the design and the qualification.

So, let's start with the main features of the mixed oxide fuel for advanced reactors.

Okay, the mixed oxide of uranium and plutonium as a phase-centered cubic structure, fcc, with a fuel right type. The substitution of uranium by plutonium is possible until 100%. The graph defines the plutonium content and the deviation from the stoichiometry is noted X. When X is negative, it means that we have oxygen vacancies or actinide interstitials and it's most of the time the case for MOX fuel.

Berta Oates
Please for just one minute, I apologize. Because you have such a delay on your side seeing the slides advance, let me make sure that we are on the slide that you are actually talking to because I think that the visual is one slide ahead of you. If you'll tell me the title of the slide, I will advance for you and then I think the general portion of the audience will see the slide that you are talking to. It may be delayed on your side.

So right now I see slide 10, mixed oxides, uranium, and plutonium oxides. That's well in advance of what you're discussing, correct?

Nathalie Chauvin
So just before please, the slide nine, and then I will ask you to move to the next slide.

Berta Oates
Yes, so we're on MOX fuel: microstructure & fabrication.

Nathalie Chauvin
Yes, before. Yes, please.

Berta Oates
Yes. Okay, slide nine.

Nathalie Chauvin
Slide nine, yes.

So I have no time to present all the fabrication processes available for the MOX pellet fabrication. I just want to illustrate the different microstructures obtained. So a microstructure is defined by the density, the grain size, the porosity shape, and the size of pores.

So I've chosen three cases. Yes, three cases. On the left side we have the Japanese MOX fuels fabricated with a standard powder metallurgy process but with the pore formers that leads to large grains and large pore diameter.

In the center, we have our French industrial COCA process based on powder melting that leads to a very homogenous MOX fuel with a single phase. And on the right side, a more innovative process based on the internal genifications called SOLGEL that avoid powder melting and associated dust with also very good homogeneity.

A standard MOX fuel has a density of more than 95% and a stoichiometry of around 1.97 to 1.98.

So next slide, please.

So now some explanation of the phase diagram.

Berta Oates
Slide 10 is showing.

Nathalie Chauvin
Okay, because I have nine on my screen. Okay, thank you. So it's worth mentioning that the system UPUO for high content of plutonium appears more complex than initially reported. Indeed, the ternary phase diagram UPUO has recently been revisited. These references describe the status on this phase diagram.

I will try to explain in a simple manner. So at low temperature, before 1100 kelvin, here you can see that we have a phased diagram like this. This one was provided for 300 kelvin. And on this phased diagram, you can see just behind the red line, between 1.98 of stoichiometry until 2, we have a single phase, fcc phase.

If the stoichiometry is lower than 1.98, then it depends on the plutonium content. For a plutonium content higher than 18%, the blue area and the mixed oxide is composed with the two fcc phases: one stoichiometric, and one post stoichiometric.

After 53% percent of plutonium, the pink area, we have a single fcc phase, subsequent stoichiometric, in equilibrium with a cubic center phase or a sesquioxide, M2O3. And in between, there is a gap of miscibility in the violet area where we have two fcc phases and a CC phase. And for a temperature higher than 1100 kelvin, we have solid solutions with fcc phase. So this is – this was the explanation of the phased diagram. So next slide please.

So here is a list of the properties needed for fuel performance codes, so mainly structural, thermal, and mechanical properties. So mainly lattice parameters, thermal conductivity, melting point, heat capacity, enthalpy of fusion, emissivity, and so on. I will not explain all these properties.

What we have to notice is the parameters of interest in order to define these properties. It's mainly the temperature, the plutonium content, the O/M ratio and the porosities or the density, the grain size, the stress, especially for mechanical properties, and the burnup. The goal is to validate the lows for each properties with the focused range of all the input parameters. That's the reason why we still need measurements in order to cover this very wide area.

The next slide, please.

Different fuel materials have been identified to fulfill the requirements, mainly the metal fuel, UPuZr; the oxide fuel, the MOX; the nitride; and the carbide. We will see all these materials' properties matches with the criteria defined. So next slide, please.

So the next slide is on the metal fuel. It's quite important to have a very short overview of all the fuels targeted for advanced reactors in order to compare those of the oxide fuel with the other candidates. Regarding the metal fuel, a very short summary of its characteristics. You have to note a low melting temperature but a very high thermal conductivity.

Another feature of this fuel is a large swelling, which requires a large gap with the cladding, optimized to be closed at the end of the life in order to avoid mechanical stress on the cladding. But this large gap acts as a thermal barrier. It's unacceptable because it can lead to fuel melting. So, it's solved with a metal bond, the sodium, between the fuel and the clad in order to ensure a better heat transfer.

A eutectic is also expected between the fuel and the clad and it requires to reduce the operating temperature. One R&D investigation up to now is to put a liner in the inner part of the clad tube in order to avoid this eutectic. So next slide, please, on the carbide.

With regards to the carbide fuel, a high thermal conductivity plus a high melting temperature leads to a very high margin to melt. This is a real advantage compared to all the other fuels. However, high swelling and the low thermal creep leads to a large pellet clad gap. The only way to avoid the sodium bond, just like in the metal fuel pin, is to reduce the operating temperature and to adapt the pin design.

The disadvantage of the carbide – the disadvantages are mainly related to its reaction with the air, which is called pyrophoricity, and that impacts manufacturing process, demanding a perfect control of the atmosphere with only inert gases. The experience on the carbide fuels are much more restricted than for the oxide and metals. And because of this risk of pyrophoricity, it have been discarded in most of the countries. Next slide please on the nitride fuel.

So the nitride fuel properties are natively similar to the carbide. The main difference lies in the fact that this fuel requires nitrogen 15 enrichment in order to avoid carbon 14 production, which is a waste. Another important point for the nitride behavior is a possible dissociation at low temperature, around 1700 degrees, which is 1000 degrees lower than the melting temperature.

So next slide, please.

On the oxide fuel. With regard to the mixed oxide fuel, the principal features are low thermal conductivity compensated by a high melting temperature. A special design such as a central hole in the pellets leads to an higher margin to melt and this allows higher power. Hopefully, this high temperature above 2000 degrees generates a total release of fission gases, and thus minimize the gaseous swelling.

Solid swelling is low, a high value compared to the metal and carbide fuels. And the thermal creep is also very efficient at this temperature. And therefore, reduces the mechanical interaction with the cladding. The low level of swelling makes this pin design quite easy. The pellet clad gap is reasonable, and the pin is filled with helium. So next slide, please.

I've chosen to present two properties on the oxide. Because I have no time to have an overview of all the properties, so I have chosen the melting temperature and the thermal conductivity. So let's start with the melting temperature. You can see on the figure that the most recent measurements achieved in Japan and also in [Unclear] are quite spread.

We have recently confirmed the solidus for the 25% of plutonium with a value of 3040 kelvin. We expect a minimum around 70% of plutonium, but it's not well defined. You can notice discrepancies between the data even for the same plutonium content, and especially above 60% of plutonium.

The melting temperature of PuO2 was re-evaluated at 3017 kelvin. It was in 2011 by De Bruycker at ARC and also by Kato-san in Japan. But it does still exist 200 kelvin of deviations between this data as you can see on the figure mainly the twin – the blue point and the red ones. It's established that one source of the discrepancy is stoichiometry, so the impact has to be evaluated.

With the CALPHAD tool – CALPHAD is a thermochemistry tool. We can estimate this melting temperature, but up to now it underestimates the solidus. The existing low for melting temperature should be revised following all these recent results and the correlation of the melting temperature with the plutonium content and the stoichiometry is really necessary.

We need additional measurements, especially for high plutonium content, also in order to check the effect of the stoichiometry. And we need to evaluate the plutonium content for the lowest value of melting temperature. This is for the safety analysis.

So the next slide, please, on the thermal conductivity. The figure on the right upper side describes a general trend of the lambda with the temperature. It's composed with several contributions. The phonic conduction due to the lattice, and effective at low temperature. And then after 1200 kelvin, the electronic conduction as well as the radiation are much more effective and contributes to the increase of the global conductivity with the temperature.

So I could spend two hours to explain all the different parameters impact on the lambda of the MOX fuel. You have just to remind that there is a strong effect of temperature, stoichiometry, plutonium content, density and all the effects due to the irradiation. These effects does explain the discrepancies between the data and also between the different laws used for the lambda in the different codes.

The uncertainty associated with this law is quite high, around 10% for the fresh fuel, and around 20% for the irradiated one. And this uncertainty lead to an uncertainty of until 3000 kelvin for the maximum temperature of the fuel. That's the reason why we have an intensive experimental program in Europe with the measurements of heat capacity, the diffusivity, and the associated conductivity, but also on the melting temperature and the thermal expansion.

We need to cover several plutonium content and several burnup. And this has been measured or will be measured at JRC-Karlsruhe on the CA fuels in order to assess the formulations with a different effect of the input parameters. Here, you can have an overview of this experimental program with the different European projects involved, ESNI+, ESFR-SMART, and the PUMMA. And we will try to cover all the range of compositions and conditions.

On the right side, you can have here the first data of thermal conductivity performed on irradiated MOX fuel for fast reactors. So there are no large differences observed between the three investigated radial positions. We have a slight decrease of the thermal conductivity at the same temperature, which is observed from the center of the pellet to the periphery, which is associated to an increase of the burnup and an increase of the plutonium content.

So this thermal conductivity is higher than expected after this burnup and we have several possible reasons. And here temperature during the irradiation that lead to less damage effect. A loss of most of the fission products that could affect the diffusivity, like cesium; an increase of the metallic fission produce that enhance the conductivity, and less porosity mainly due to the gas release. We are still working on the interpretation of this data. So next slide, please.

So now we will move on the fuel element design. We have seen that there is the main candidates for advanced reactor are carbide, metal oxide, nitride and so on. We can have several forms – fuel forms, single phase, solid solutions, or composites. And for the fuel packing, it can take the form of pellet, which is a cylinder with a central hole. It means annular pellets or full pellet. We can have also a sphere-pac with fuel particles.

On the next slide, we have a description of the different fuel elements foreseen for these advanced reactors, starting with a very standard pin fuel, which is a cylinder made by cladding and filled with a stack of pellets. And the most innovative one was a pin with an innovative cladding. Here, a composite SiC-SiC fiber. It was mainly devoted to GFR. And the goal is to improve its refractory cladding. So it's to improve the behavior during nominal and off-normal conditions.

And we can have the additions with this SiC-SiC fiber cladding of different coatings inside and outside in order to prevent from any reaction with the fuel and also in order to improve the tightness. So next slide, please.

Another kind of fuel element is a standard pin with vipac or sphere-pac fuels. We have also – it's mainly foreseen for sodium fast reactors. We can have also coated particles foreseen for VHTR and only possible for VHTR because of the poor physical [ph] density and we have developed also a plate fuel which was devoted to the GFR, and the idea was with the plate to increase the heat transfer. And by this way to compensate the bad heat convection of the helium coolant.

So next slide, please. So now the part two, devoted to the fuel behavior under irradiation. So this slide, so we are on the slide 23. So this slide shows how complex is a fuel behavior during the irradiation. It results from the interaction of many phenomenon. Moreover, the nuclear reactions as well as the chemical reactions leads to evolving modules of the fuel element.

Chemical composition will change, as well as crystallography and properties. The conditions will also change during the irradiation period because the geometry and the reactor operations are changing. So the system is even more complex because not constant with the time.

So next slide, please. So slide 24. This schematic representation of all the phenomenon that can occur on the microstructure of the MOX. We have to notice in several hours the fuel has completely changed in structure and compositions. So we will detail this phenomena that affect the materials. You have the schematic descriptions on the left side and a real ceramography performed in the LECA facility here in Cadarache in France on a real MOX fuel irradiated in the Phénix reactor. So we will detail the phenomenon and the effects on the materials.

So next slide, please, 25. The original microstructure is destroyed on most of the pellet within hours and spread in four different areas, as you can see on the ceramography. So you have, on the right part, the central hole formation, then the columnar grains, then the equiaxial grains, and finally the unrestructured zone. This is mainly due to the thermal gradient, which is consequences of the high power and the low thermal conductivity.

So the pore migration is due to the thermal gradient. The thermal gradient is even higher than 5000 kelvin per centimeter. And because also of the high temperature, higher than 2000 kelvin, we will form a central hole early in the irradiation.

In fact, the initial porosity resulting from the fuel pellet fabrication is homogeneously distributed in the pellet as small pores. But due to the very high summer level, these pores are redistributed along the radius through an evaporation condensation mechanism between the hot side and the cold side of each pore, as you can see on the graph on the right side.

So this matter movement contributes to the central hole formation and the columnar grain structure. The columnar grains of 1 millimeter long in the central part are formed above 1800 degrees. And the pore migration as well as a high vapor pressure of uranium and plutonium above this temperature leads to a redistribution of the plutonium content close to the central hole very early in the irradiation.

This increase is about 30% compared to the obtained value at the end of the fabrication. So this means that if you have 20% of plutonium at the fabrication, after several hours of irradiation close to the central hole, you can get 30% of plutonium. This is very important to notice.

Regarding composition, the figure on the left side illustrates the evolution of O/M. The stoichiometry decrease around the central hole and increase on the periphery of the pellet. The oxygen migration done to the thermal gradient. At the end of the fabrication the fuel is slightly under-stoichiometric, around 1.97. And this oxygen redistribution is very fast because its diffusion velocity is very high.

The oxygen migration is due to the solid phase transport and gaseous transport also. For example, we have here the example of an initial stoichiometry of 1.97 at the end of fabrication, close to the central hole, you can get 1.93 or 94, which is very low. We will see the effect.

When burnup is increasing, fission is oxidizing, and thus contributes to the increase of the O/M. It's at a medium burnup as the stoichiometry is close to a 2.0 everywhere in the pellet. So next slide, please.

Now we will speak about the fission products. So each fission creates two fission products. And the fission products can be grouped into four main categories. The fission products in solution in the oxide matrix in yellow in the case of most of the lanthanides. We have also the elements forming metallic precipitates in the case of molybdenum, technetium, lutetium, palladium – well, it's in red – and some others.

We have also the elements forming separated oxide precipitates in the case of barium, niobium, zirconium, cesium, and molybdenum. It's in blue. And we have some volatile fission products: helium, xenon, krypton, cesium in green. And a few elements like cesium, strontium, barium, molybdenum, tellurium, and zirconium are marked with mixed colors because they are distributed in different kind of phases.

So the chemical state of the fuel depends strongly on the oxygen chemical potential of the MOX fuel and it increases during the irradiation. We have seen that the fission is oxidizing. As you can see here, the oxygen potential is increasing with the burnup from the yellow status after the fabrication until the green curve after 13 atom percent.

We have a modification of physical and chemical properties of the irradiated fuels due to these fission products in solutions or under different oxides precipitates or even under metallic precipitates. We have also, because of the fission products diffusion, the formation of the JOG. The JOG is a joint between the oxide and the cladding. You can see here on the ceramography on the figure in the left. This is mainly compound with the molybdate of cesium plus other compounds.

We can have also a fuel clad chemical interaction or corrosion and it's a reaction between some fission products, terrarium, iodine, cesium that reacts with the components of the cladding, mainly, iron, nickel, and chromium. In order to produce the cesium chromate, the iron tellurides and also nickel tellurides. So next slide, please.

Now we will see each phenomenon due to this effect of irradiation. So the slide 27. So we will see each phenomenon and due to the irradiation, and in particular the effect of neutrons and fission products that could affect the performances of the MOX pin. So this slide is to illustrate that due to the neutron effect in combination with the temperature, the clad is swelling.

And also, we have an evolution of the mechanical properties of the clad that can be affected. I have no time to describe exactly all the phenomenon in the cladding, but this is only one figure to illustrate in particular the diametral strain due to the swelling induced by the neutron. It's a strain as a function of the actual positions of the pin.

Our preference is clearly to have a stainless steel that have demonstrated the low levels of swelling, like the austenitic 1515.

So next slide. The clad is also affected by a chemical interaction with the fuel named FCCI or corrosion, which leads to reduce the thickness of the tube. The interaction is mainly, as we have seen, with terix [ph], cesium and iodine. It depends clearly on the initial O/M of the fuel that has to be high for the thermal properties but not so high for these corrosion issues. So that's the reason why the target value for the fabrication, it's 1.97 to 1.98 and not the stoichiometry.

So the evaluation of such a corrosion by some fission products can be done through thermodynamic studies of the interface between the fuel and the clad. And the temperature – we have to say that the temperature threshold for the corrosion attack on the cladding is around 500 degrees, but it's also depending on the fuel, as I said, and, especially on the stoichiometry.

The maximum value seen is 200 microns, which represents 40% of the clad thickness. So you can expect that the performance reductions due to the risk of failure with a thinner clad, which was – and this thinner clad submitted to pressure and creep could have a risk of failure only due to this corrosion.

So next slide, please, 29. So in parallel, we have some fission products like cesium or molybdenum that diffuse until the clad pellet gap to form the so-called joint oxide joint, or JOG in French, sorry, composed with several fission products to form oxide. So mainly is Cs2MoO4 and Cs4MoO7. So the JOG can reach 160 microns of thickness in the case of low clad strain. But it's even larger if the cladding swells much more.

So it will lead to an improvement of the thermal behavior of the pin with a quite low thermal conductivity but much higher than a gap filled only with gas. A reduction of several hundred kelvins is expected in the fuel, thanks to the good conductance of the JOG in the gap.

So we have observed that JOG formation starts around seven atom percent, and we assume that there is no mechanical effect because it's a plastic material with an actual extrusion in the gap. So next slide, please.

So now considering the fuel gaseous swelling, on the curve representing the retention of fission gases in the fuel it's noted that on the central part of the pellet where we have the maximum temperature, all the gases are released while in the peripheral part of the pellet the lowest temperature reduces the gas diffusions.

Under first neutron conditions, we reached more than 80% of gas release for the whole pin. We have several experimental devices that does exist to measure the gas retention in the fuel and to evaluate the gaseous swelling. This is some pictures with the device we have at the LECA facility on the irradiated fuel: EPMA in order to see the gas dissolved at the submicronic level; the SEMs for the total gas; the TEM for the gas bubble, and the MEB-FIB to see in three dimension the shape of the gas bubbles. And we have to add that with heat treatment. We can get the final inventory of these gases. So next slide, please.

Another important effect of irradiation damage is the solid swelling of the fuel material. This is due to the increase of the number of atoms inside of the fuel with burnup. And this leads to the increase of the fuel volume. As two fission products atoms are created when one heavy atom is consumed, the total number of atoms is increasing.

So we explain on this figure that we have a linear dependence of the solid swelling with the burnup. It has been evaluated to 0.6% by atom percent, which is very low compared to the other fuels.

So next slide, please. So very quickly because I spoke about the properties. All the mechanical and thermal properties are affected by the irradiation, not only by the fission products inclusions, but also with disorder in the structure due to the fission reactions and the recoil of the products, but also due to the neutron effects.

We have also to take into account the evolution of composition stoichiometry and density on these properties. And we have several device in order to evaluate this damage coming from the irradiations, especially the TEM.

So next slide please, on the thermal behavior of the fuel element. Now, a description of the reach temperature in the fuel element. So first, the purpose of this assessment is to predict the clad and the fuel temperature with all the evolutions we have just listed, so toward the actual temperature.

First, the actual temperature profile results from the linear heat rates actual profile with a maximum named max flex plane close to the mid plane and of the core. The actual fuel temperature in green follows this linear heat rate profile. For sodium fast reactor, the circulating coolant from bottom to the top of the pin will heat of about 150 degrees in contact with the hot fuel elements.

The clad temperature in dark blue will actually increase from about 400 degrees up to 600 degrees at the top. Towards the radial temperature distribution, the radial profile temperature across the pellet is due to the low thermal conductivity of the fuel and the small gap conductance. So the oxide fuel operates at relatively high temperature.

We have 1200 kelvin in the outer part of the pellet and 2400 kelvin in the center part. This means that the thermal gradient, as I said before, is higher than 5000 kelvin per centimeter. So these temperatures decrease after some days and we start with the blue curve and after the opening of the central hole, we have the green curve with a temperature lower of about 300 degrees.

And then when the gap is closed, the temperature is even lower. It's a pink curve. So the safety analysis with the evaluation of the margin to melt is achieved all along the irradiation but the highest temperature is reached during the beginning of irradiation.

So this is an advantage because the thermal conductivity is not yet affected by the irradiation. So the uncertainties on the properties is the lowest.

So next slide, please, on the mechanical behavior of the fuel element. So regarding to the mechanical behavior, the objective is really to predict the dimensional changes such as the clad strain or the closure of the gap. It's also to predict the risk of clad failure in both nominal and incidental conditions. The evaluation of the mechanics of the fuel element is an important element towards the reactor safety as the clad is the first safety barrier.

The mechanical phenomenon to learn for the fuel. It's first, the swelling, the creep, the mechanical properties, the cracking due to the very high thermal gradient with differential thermal expansion. And we have also to take into account the relocation of the fragments that can enhance the heat transfer.

For the clad, it will be taken into account the swelling at high dose, the creep, the embrittlement, and the evolution of the properties during irradiations like the elastic limit as we can see on the figure and it's lower after the irradiation than on the fresh fuel.

So next slide please, still on the mechanical behavior. We have seen that we have two main mechanical phenomenon observed. The first is the clad pellet mechanical interaction which is controlled by a relatively low oxide swelling rate due to a high fuel temperature, which by thermal creeps leads to non-rigid behavior towards the structural material. Also because of the JOG formation that acts as an elastic seal without a stress transmission.

Finally, the design of the fuel element contributes to avoid this interaction, this mechanical interactions with the smear density adapted to the evolution of each of the materials with the performances request. This means that we will have to adapt the smear density depending on the burnup you want to reach.

Concerning the chemical interaction between the fuel and the clad, named FCCI, it leads to reduce the thickness of the tube, and thus, limit the burnup. So FCCI may be evaluated with the fission products diffusions and the thermodynamics of the interface. The R&D on clad materials has a goal to develop corrosion resistance stainless steel in order to prevent from damaging corrosion. So next slide, please.

Concerning the behavior of MOX fuel under transients. First of all, we have to select the relevant accidental scenario that depends strongly on the core design and the reactor system. Here, we have the main types of accident. So an unexpected control rod withdrawal, which is a low power transient. Unprotected transient of power, which is a fast power transient. We have also unprotected loss of flow. And finally, we have the possible total instantaneous assembly inlet blockage.

And for all this scenario, we have to say that the behavior is strongly dependent to the core design and the reactor system. So, I will not present any results, because as I said it’s dependent on the core, on the pin design, but also on the different safety device in order to prevent from severe accidents. We call this device complementary safety devices.

So the experimental data acquisition is made from separated effect or integral test. We have the test of single rod in the CABRI safety reactor here in France in Cadarache or the test of fuel bundle in the SCARABEE facility. The feedback does exist mainly from the safety reactors CABRI, TREAT, but some other in the world. Like you can see on this table, we have the list of the different tests in the CABRI reactor.

There are numerous on the oxide pins for our fast reactors under different conditions of transient. Part of this test had been launched through international agreements and provided a lot of valuable results. For example, on the right side, you can see a ceramography of MOX fuel after fast forward transient with a super Phénix design with 85% of the radius that have been melt.

Nevertheless, this kind of test is still low and expensive and in the same time a large panel of scenario and uncertainties still exist. So we need to develop simulation codes in order to take into account all the complex interactions between the different phenomenon and also to cover all the safety situations.

So next slide, please. The next slide is devoted to the summary of all the descriptions I have explained on the behavior of the – on the microstructure, the thermomechanical and the thermochemical behavior. As I have noted so many times, I propose to go to the part three devoted to the fuel element performances, the design, and the qualifications.

So slide 39. So there is a vast experience of using MOX fuel in fast reactors with a high burnup reached. I will not detail this past experience with all the reactors from the 50s up to now, or fast reactors filled with MOX fuel or MOX driver fuel or experimental MOX fuel.

So the table here gathers the main results we get recently and especially in the recent sodium fast reactors. So we reach until 20 atom percent for the burnup those of 155 dpa and the highest linear heat rate was 550 watt per centimeter.

Several accidental tests have been also carried out as we have seen, and reprocessing have been tested at industrial scale on these irradiated fuels. So performances – so the fast reactor in operations now. So it's mainly in Russia above 60, BN600 and BN800 with a MOX driver fuel not only, but part of the core is loaded with MOX fuel. And also the case for the JOYO reactor in Japan. And we hope that before the end of the year, in India we will have the PFBR loaded with MOX fuel. So next slide, please.

During all this experience, we have improved the fuel element design and the improvements were mainly devoted to the geometry, especially the annular pellet because of the safety or improvement during nominal conditions and also under transience. In order to avoid the fuel melting, we choose the annular pellet.

A large pin diameter has also been developed. Axially heterogenous pin also for safety improvement. We have a large range of composition, not only with the uranium but also for the plutonium. We can take into account in a fast reactor from 15% to 45% of plutonium with several grades. And we have demonstrated that the minor actinides transmutations is possible under different ways diluted in the drive fuel or in dedicated fuels like targets or blankets.

Towards the specifications of the fuel, it's mastered with several fabrication processes. It's adapted to industrial fabrication and it does respond to safety issues. So the next slide, please.

Towards the fuel element qualification. So the objective for the qualification is to get the licensing. The licensing is the authorization from the safety authorities to load this fuel element in nuclear-powered plants. The requirements are coming from the guidance, the regulatory guidance which asks for a higher level of safety, a qualification of computational tools. It's not possible to provide only experimental results. The tools are also evaluated.

And the uncertainties of both experimental tests and the fuel performance codes consists – the uncertainties of both must be consistent with the safety margins. The criteria for the safety authorities are mainly maintaining the cladding integrity as it's the first barrier, the coolable geometry, and limiting the impact, the radiological impact. The fuel failure as well as the fuel degradation like melting have to be identified and controlled.

So now to all the fuel element qualifications. So the essential part for the fuel qualification is to define a test envelope to cover expected conditions, transience, and accidental conditions to assess the fuel performance and to validate also the fuel performance codes. I have no time to explain how we applied the initial technological readiness level to the nuclear fuel elements because this scale came from the NASA and was applied to the nuclear licensing.

So here you have, on the left side the descriptions of the content of each level of the scale from 1 to 9. At 9, you get the licensing. And on the right part, this scale was applied to the fuel element. So it’s described what you have to provide for each step.

From the level 1 to 2, it's a selection phase. The 3 to 4 is development, so mainly R&D. And at the level 4 starts the test for the qualifications. So you can see here that between 4 to 5, we have some tests at pellet or pin scale with out of five tests.

Then from the level 5 to 6, we have to test under representative conditions with representative composition and geometry. This means at pin level. From the 6 to 7, it takes into account all the conditions including off-normal. And from 7 to 9, we start the licensing with a demonstration of several sub-assembly until a whole core loaded with this new fuel. You have this reference, if you want to have more details on this TRL application for the fuel element qualification.

So next slide, 43. This is a tentative of description of MOX qualification for the different advanced systems. We put as parameter the plutonium content and the linear heat rate, but we could have the pin design and the burnup in order to be very complete.

We can just say that for compositions between 18% to 28% of plutonium with a conventional Fenix geometry even with central hole or a super Phénix type, the qualification was fully achieved including at an industrial scale for the fabrication. And the whole core were tested until 13 atom percent with different safety tests. It was for the SFR.

For the other systems that have different compositions or different conditions, the qualification level is lower, is the case for example for the GFR and also for the LFR.

Next slide, please. We have seen that the behavior of the MOX fuel is well-known with phenomenon identified as well as a coupling effect. So during a qualification process, it's not possible to provide only experimental results for all the possible conditions during normal and off-normal situations. That's the reason why we need tools to predict the pin behavior.

The name of this kind of codes is fuel performance code, as it provides the performances of the fuel element. Performances meaning thermomechanical and chemical behavior in order to make an evaluation towards safety criteria on the fuel and the cladding.

So this tool is a combination of different components dedicated first on material evolution, then on thermal analysis, on mechanical evaluation, on physical chemistry mainly with the fission gases, diffusion, and release. Then we have a component on thermochemistry calculations, mainly to reach the chemical form of all the species [ph] and the combinations of all these components can predict all the effects we have seen.

I have to say for the material evolutions on the left part, that several scales are used for the prediction of damage and properties evolutions. From the atomistic modeling up to very representative elementary volume that takes into account not only the compositions but also the microstructure like a grain size and the grain boundaries and porosities and the shape of porosity.

And you have here these references, if you want to have more details on the few performance codes, because I have no time to explain exactly the content of these kind of tools.

Next slide, please. Now the conclusion. So the slide 46. So if we summarize. The oxide fuel is able to achieve high burnup and even very high burnup, 20 atom percent. The limit is due mainly to structural materials, namely the cladding, and the hexagonal tube. A high thermal creep because of the high temperature and the optimized design lead to avoid the fuel cladding mechanical interaction.

We also note a very high melting temperature, a stable and isotropic structure, and the low swelling. However, chemical interaction of the fuel with the sodium in case of clad failure has to be managed, as well as the corrosion generated on the clad at a high burnup.

So we have a compatibility with the stainless steel and the cladding. We have a large feedback on safety tests. The fuel performance codes are numerous and qualified on a set of reliable experimental tests. I had no time to explain that the fuel performance codes are associated with databases with a lot of irradiation results performed in the fast reactors and not only also in material testing reactors in order to test different irradiation conditions.

The manufacturing and reprocessing process are very similar to light water reactor. This is an advantage because we take into account a large experience on PWR and with the existing facilities. Throughout the fuel cycle we have a well-known fabrication process and a large experience on the reprocessing on the MOX fuel.

Towards a different scenario, the fuel cycle scenario. This advanced reactor associated with the MOX fuel are very flexible towards the plutonium management, taking into account both the plutonium content and the grade, but also towards the uranium use and the high capabilities for minor actinide transmutations. So next slide, please.

On the perspectives for the R&D, I would like to present the R&D still needed on the MOX pins. On the fuel modules, the property measurement is an important element because it impacts directly on reducing the uncertainty on the results coming from the fuel performance codes.

The developments are also underway to manage different fuel compositions, and thus to adapt all the options of transition scenario of the pac [ph]. So mainly as we have seen, plutonium and isotope. So we have to enlarge the range of composition.

Regarding the cladding material, the achievement of high doses and the resistance to corrosion is a priority for the R&D program.

Finally, the trend of pin design would be to increase the pin diameter in order to reduce the coolant volume and the volume of structural materials and large diameters are also associated with annular pellet in order to reduce the maximum temperature during all the conditions.

Improvements are also needed on modeling and simulation in order to be more predictive and to answer to the safety requirements for a reduction of experimental demonstration.

An assessment of the pin behavior during the incidental and accidental scenario is also needed one more time for the validation of the fuel performance codes.

So this is the end of my talk. I just want to mention the different sources I used. So first of all, several books dedicated to the fuel behavior for advanced reactor. You will find not only the oxide but also the metal, carbide, and nitride in these books. You have some international courses or schools, some conferences. The fast reactor conferences are devoted not only to the core but also to all the components of the core, including the fuel. You have also the global conferences devoted to the fuel cycle. And dedicated conferences – workshops like IEMPT devoted to partitioning and transmutation. But also a workshop like NUMAT devoted to the behavior of the different materials, and ATALANTE devoted to the reprocessing.

We have current international activity on the oxide, but also on the other fuels. At OECD, we have an expert group on innovative fuel elements, where we are performing benchmark exercise and we will intend this year to provide recommendations for fuel properties on MOX fuel and metal fuel.

At AIEA, we have started last year a CRP on fuels and materials for fast reactor and we want to share experimental irradiations in order to increase the validation database for the codes.

In the GIF, we have devoted management – project management board for each system speaking about the fuel and the fuel element. And also, we have some European projects I have mentioned for especially the properties measurements.

And it's very interesting to have a look on the databases. At AIEA, we have THERPRO dedicated to fuel properties. At OECD, we have TAF-ID, which is a database devoted to thermochemistry data. And also at OECD, we have the IFPE database devoted to irradiation results for the validation.

And that's the end of my talk.

Berta Oates
Thank you very much, Nathalie. Did you have anything you wanted to talk about the prototypes and industrial SFR graphic?

Nathalie Chauvin
Yes, it was the final slide. It was just an overview of the different prototypes or industrial fast reactors in the world.

Berta Oates
Great. Thank you very much.

If you have questions, go ahead, and type them into the questions box. While those questions are coming in, we'll take a quick look at the upcoming webinar presentations. In February, an Overview of the Waste Treatment Plant, Hanford Site. In March, Introducing New Plant Design Code. And in April, a presentation on the Experience of HTTR Licensing for Japan's New Nuclear Regulation.

I'd like to give, Patricia, just a moment to talk about the Pitch your Gen IV Research.

Patricia Paviet
Yes, thank you very much, Berta. I would like to invite you as the Chair of the Gen IV International Forum Education and Training Working Group to look at this event. We are hosting an exciting competition for the young researchers.

If you are interested, you will be asked to submit a one-page executive summary in a research related to Gen IV Advanced Nuclear Energy System. And the jury will select up to the 25 outstanding research topics and they will be asked to present a three-minute video pitch.

So please spread the word out. We are very exciting with this Pitch your Gen IV research competition. You have the flyer in the handout box. And thank you again for spreading the word. We will start to open the competition on the 1st of February, next Monday. Thank you.

Berta Oates
Thank you. There are several questions that have been posted. Do you see the questions, Nathalie? The first.

Nathalie Chauvin
Now the first one – so the first one question is what do you think of vented fuel pin designs?

Well, in the design we have sodium fast reactors. The cladding acts as the first safety barrier. So with vented fuel pins, it's no more the first barrier. So well, towards the safety issues I am not convinced that, for example in France, we could be allowed to choose this kind of design.

The second question is, is the metallic fuel better than oxide or mixed oxide?

Well, it's different to compare because the oxide fuel – we had the maturity on the oxide fuel because we have developed an industrial process for the fabrication, for example, and for the reprocessing. So this could be one reason for the difficulty to move to the metal fuel.

But metal fuel is very interesting because some performances are very good and the metallic fuel most of the time are chosen for the doubling time.

Berta Oates
Did I lose you? So I am not exactly sure where we were when we lost you.

Nathalie Chauvin
You lost me on the metal – the comparison between metal and oxide – if the metal fuel is better than the oxide.

Well, my answer was, well, we knew the oxide fuel as it has been tested at an industrial scale especially for fabrication, the reprocessing but not only. We had several fast reactors with driver fuel with MOX fuel. So we have a very large feedback.

The metal fuel is very interesting with very interesting characteristic and it reached high performances, especially in burnup. As far as I know, the main issue now is to reduce the interaction between the fuel and the cladding.

And the other point is to test at an industrial scale the fabrication and the reprocessing. Most of the countries that I have chosen the metal fuel as the objective for the future is mainly for the performances but not only because it's very comparable to the oxide. It's mainly due to the doubling time, which is higher for the metal fuel.

So the next question is – there is no more questions. The other questions was if it's possible to have the slides? I think it's okay.

Berta Oates
Yes. So there's a question 'considering that SFR fuel would be reprocessed, why do you target such high burnup level, 13% to 15%?'

Nathalie Chauvin
Yes, we have tested this kind of fuel but with a quite standard plutonium content. In the coming year, we will test reprocessing on a high plutonium content, for example, more than 40% of plutonium because there is an issue towards the reprocessing. So it's within the PUMMA European project.

Berta Oates
Thank you. So are you able to see the questions in the question pane? How much of the SFR MOX fuel knowledge and technical readiness level are applicable to LFR?

Nathalie Chauvin
So, we get a quite high level of TRL for MOX fuel under SFR conditions. This means that for Phénix or Phénix with the central hole, which is the case, for example, for the Russian reactors and also for the Indian reactors, we get a TRL of between 8 to 9. With different design or composition, the TRL is lower.

For the LFR, as far as I know they want to have a lower linear heat rate and higher plutonium content. So probably the TRL level is lower. We have to check, but I don't know for these kind of compositions if we have some safety tests, for example, in order to reach the TRL 6.

Berta Oates
Thank you. A question – there's a question. MOX fuel seems to be very beneficial but appears that this leads to increased substantiation time. Do you think that this time requirement prohibitively hinders the Gen IV development?

Nathalie Chauvin
I cannot see this question. Please where it is?

Berta Oates
There should be a pane labeled questions.

Nathalie Chauvin
Yes. Well, the development of this kind of fuel takes time. Well, it's depending on the condition. It's very difficult to answer because it's really depending to the condition of use, but most of the time we need more than 10 to 15 years to achieve a qualification.

So the next question is – okay, some references for potential fuel types, like standard pin with vipac or sphere-pac? Yes, there is some TECDOC at IAEA. If you go to the website of IAEA, you could find some TECHDOC reports devoted to this different design and the performances reached, for example, with vipac or sphere-pac. And you have also publication from our Russian colleagues with the experimental test achieved in the above 60 on this kind of special design.

The next question is how do you expect the effect of cauliflower structure at a very high burnup, higher than 10%?

So cauliflower, what is this? Excuse me, but I don't know this cauliflower, this name of effect. If it's a kind of a ring structure that we can have in PWR or MOX fuel. We have seen in a fast reactor and for example three years ago on NESTOR [ph] samples irradiated the Phénix reactor we have observed this kind of structure and we have seen the small grains.

The main question now and we don't have the answer is the effect of this structure, for example, on the thermal and mechanical properties. We have an idea for PWR, but for fast reactor we need to check because we have also to take into account the redistribution of the spaces in this area.

So the next question is I noticed that the recycling option is not included in your validation slide. Does it mean for the SFR speed reactor it would be limited to one true cycle only or is there validation data already available?

Yes, you know that in France we are working on the recycle options and inside of the requirements we have the recycling requirements. And we had a lot of freezes because, for example, in the Markul [ph] Center we had a facility devoted to the recycling of the Phénix spent fuel. So we have a lot of results on this topic.

But now we are wondering not only on the multi-recycling of the spent fuel coming from the owned fast reactors but also from coming from the spent fuel of PWR. And for example the multi-recycling of plutonium is one option to use the plutonium.

So the next question is, 'if the versatile test reactor were built in the US, what test of MOX fuel would you recommend to be performed only or even?'

Yes, as I said, we still need experimental tests. And in this kind of experimental reactor with fast spectrum, probably we will have some needs, especially for the validation of some models at beginning of life but not only. And it's quite important in this kind of experimental reactors to achieve some not only transient tests but test for off-normal conditions. And this is what we need for the validation of our code.

Okay. The next question is, what is the compensation of plutonium-239 required for each time of recycling to achieve same power output?

The compensation is the plutonium content. You need to increase the plutonium content. That's the reason why if you want to multi-recycle the plutonium with a quite low grade, you need to go to until 30 to 32 or even 34% of plutonium. That's the reason why we are interested now in a higher plutonium content. Yes, that's the answer.

So next question is, could you please explain why gas fission products won't exist in the internal zone of MOX pellet in slide 28?

So the slide 28. Well, it's because in this slide is the behavior [ph] at the beginning of the irradiation. The idea was to explain on this slide all the phenomenon that occurred during the first hours. That's the reason why we don't have any fission gases on this slide.

So next question is, are there potential alternatives to sodium for sodium bonding in metallic fuels? Most repositories do not allow for sodium to be disposed off in them and sodium treatment is required?

Yes, but it's not simple to perform, so an alternative would be preferred. I don't know but some other measures have been studied. But at the end and very early in the 60s and 70s, the sodium bond was chosen. And as far as I know, there is no more R&D on other bond.

So I guess that it's because of the compatibility, the good compatibility between the sodium and the metal fuel. How do you use TRL, a kind of map for the next challenging construction of the fast reactor?

That's a good questions. TRL are now applied on all the different components of a reactor. So I have just illustrated the application of TRL on fuel element, but it's also possible for all the core. So I don't know if it's done or not. I have to say that to OECD in most of the expert groups, we are trying to apply this scale because it's quite easy to explain the level of maturity for the different components. But I don't know for whole construction if it has been done or not.

Okay. How do you use thorium matrix to improve MOX fuel performance or you do not seem to use thorium at all?

Yes, it's depending on the resources you have. Thorium has different issues and especially towards the fuel cycle. And in all the cases, I understood – I am not specialized in thorium, but I understood that in all the cases you have to start with uranium in order to produce plutonium in order to start a core, because it's not possible to achieve it directly only with thorium.

So well, we are not in this case in France. And as we have a very long experience on uranium and MOX fuel, we use MOX fuel.

What are the advantages of metallic fuel during severe accidents? Thorium [ph] handling in the vessel phase?

It's difficult to answer to these questions and the comparison of oxide with metal cause under severe accidents. It's not in my field of skill. But I know that there is an expert group at OECD, who are dealing with the comparison of these both scores under transience and severe accidents. The only way, the only thing that I can answer.

Berta Oates
Thank you so much, Natalie. And I apologize for the technical issues that we experienced at the beginning with the delay. I think we overcame that well though. Your presentation was wonderful. You can tell the level of engagement from the number of people who hung through this Q&A while we disconnected. We still have 67 people listening to your responses. So a great, great job. Thank you very much for sharing your expertise.

And thanks to the audience members who stuck with us. I don't see any more questions that have come in.

Nathalie Chauvin
No. No more. So thank you very much for inviting me. Thank you to the audience, and hope that we will have the opportunity to meet each other, for example, in international conferences or in some international instance in order to have more in-depth discussions on the field. Thank you very much.

Berta Oates
Thank you.

Patricia Paviet
Thank you, Natalie, again. Thank you, Berta.

Berta Oates
Bye-bye.

Patricia Paviet
Have a good day. Bye-bye.

Nathalie Chauvin
Bye-bye.

END