In-Service Inspection and Repair Developments for SFRs and Extension to other Gen-IV Systems
Dr. Francois Baqué, CEA, France

Berta Oates
Welcome everyone to the Next Gen IV International Webinar Forum Presentation. This morning's presentation will be In-Service Inspection and Repair Developments for SFR and Extension to the Other Gen IV Systems will be presented by Dr. Francois Baqué.

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

Patricia Paviet
Thank you so much Berta. Good morning everyone. It's a pleasure to be with you today to introduce Dr. Francois Baqué who works as a Senior Expert on inspection for fast reactors at Commissariat à l'Energie Atomique et aux Énergies Alternatives, CEA Cadarache IRESNE in the Nuclear Technology Department. He was the manager of the R&D activities associated to In Service Inspection and Repair for the ASTRID Project at CEA for almost 10 years. In this frame, he was the leader of CEA staff acting for the development and qualification of ultrasonic and electromagnetic sensors and related inspection methods.

Presently, he supervises Ph.D. works on ultrasonic methods with French University and the National Center for Scientific Research. He is an active participant to the Gen IV SFR Component Design and Balance of Plant group for inspection systems and methods. He published a number of papers on associated studies and participated in the relevant international conferences such as ICAPP, Fast Reactor, ANIMMA and others. He was a former manager of the French Sodium School who developed international activities. Again, thank you so much Francois and it's a pleasure to give you the floor. Thank you.

Francois Baqué
Thank you, Patricia. Thank you, Berta. So, I am very happy to say good morning, good afternoon, good evening depending on your location on the earth to all of you. And thank you again for attending this webinar. Sorry for repeating the ten first slides because we had that problem last week. It is an honor for me to present you R&D actions that we performed at CEA in that frame and with many collaborating teams, so probably some colleagues can listen and it's really pleasure for me.

So, coming now to the content of my presentation, there will be two slides on sodium fast reactors. Just remembering the specifications for such plants. Then, seven slides dealing with the frames, the conditions, and the objectives for nondestructive examinations that we call also in service inspection. Then, we will move to more technical aspects giving you some information on the sensors and on the methods. Then we will have some examples, applications that we had for the French ASTRID projects dealing with in service inspection and also giving you some information on tightness, in sodium tightness and robotics which is a very specific aspect.

And then before concluding and giving some perspectives, I will give you some information about in service inspection, what could be in service inspection for the five other generation 4 systems. So for the next slide, is it me or Patricia or Berta?

It should be me. Sorry. I was too fast. Okay. This third slide dealing with the frame of generation 4 systems not only SFRs but other systems. Just to tell you that in service inspection will be an important part, more or less important, dealing with the six main specifications we have for generation 4 systems for safety of course because it will be a part of demonstration for robustness of safety. For operability, you know that we would like to reach a load factor at least 80% or more. And to reach that point, we have to be able to perform the in-service inspection operation in a quite shorter time, that is to say less than 1 month, during the shutdown periods. And last, but not least, we have to ensure that we are mastering the investment costs, the French experience with Phénix and Superphénix mainly but also with Rhapsody [ph] in the '60s and '70s was not so good and we experienced a number of problems and we had to rush at that time to find some clues. And now we want to be ready to face such problems.

So, on the next slide, we see the very specific conditions for sodium operations I would say. As you know, sodium is opaque and that leads to mainly select ultrasonic tool systems, techniques able to give some information within liquid sodium. High temperature because even if we know that melting point of sodium is about 100-degree C when it is quite pure, for shutdown conditions which corresponds to the in-service inspection operations it is something like 180-200 degree C which is not so high but which is not so less. So, we have to face that temperature. And as you know we have corrosion risk due to in case of any air or water, moisture ingress and stress caustic corrosion is very high and something very important tool to be faced. And you know the reactions between sodium and water, sodium and oxygen in the air are exothermal and we have also to face these hazards during the in service inspection operations and helping to face those hazards. So, I come to the next slide.

Speaking about the main general objectives for in service inspections, it refers to all the measures required to and this is something which has been very clearly defined by the international agency and by other institutes. But at least by international agency we have to check first that the operating conditions to which the structures are subjected are in line with design assumptions as the life duration is something like some decades, can be 3, 4, 5 decades. It's rather long and we have to check from time to time at every 5, every 10 years, that the structures, the components are still in a good health and can face the conditions they are submitted to.

Second, we have to guarantee that there will be no defects that are still incompatible with the safe operation of the facility. It is a main aspect of in-service inspection to check that the plant is in good health. And when I say the plant, you see on the right side the principal design of the main vessel. It is a pool-type reactor because we know in France we are developing such reactors. That was the case in Phénix, Superphénix, and for the ASTRID project. There is a main vessel which is rather large, something like ranging from, I would say, 15 to more than 20. In Superphénix, it was 21 meters, the diameter of the main vessel filled with liquid sodium with many immersed components, at least some primary pumps, intermediate heat exchangers. And the many structures helping for the right thermal hydraulic behavior within that quite complicated domain. And third enable, we have to enable implementation of additional comprehensive examinations. Again, to face any abnormal conditions, to face any abnormal mechanisms leading to some damage on the structures or components, we wanted to enlarge all the techniques and the tools for inspection in order to be ready and to solve that problem.

I am coming to the next slide. And I just finished last week with this slide about the risk informed method which is applied for the inspection of SFRs in France at least. Because of course in the best world I would say that we would like inspect everything but in the real life we know it is impossible for many reasons. First reason is it would be very long, very costly, and probably very complicated. So it is why it was decided to use this method, selecting, finding only the few structures or components or parts of structures, parts of components which really should have to be inspected. So, leading with high level inspection, medium level inspection, lower level inspection. On the left side, you see we can define some categories. Blue category on the left, then orange category, and red category from the lower to medium to higher level of inspection corresponding to first cumulated potential damage that that structure or that components will face during the life of the plant and also looking after the seriousness of damage in case of a rupture. That is to say that we will have higher level inspection for the structure being highly potentially damaged, that is to say very high level of temperature, thermal shocks, high pressure, high creep level, such things leading to potentially high damage. And also looking after for the structures with in case of any break, any rupture, very bad consequences. So, looking after these two parameters you can define these three categories.

And on the right side, you can see the example for Superphénix reactor block inspection. So, main vessel filled with primary sodium. You see on the right a huge primary pump, on the left a huge intermediate heat exchanger. In the middle up is above core structure with control rods and instrumentation as the core outlet. Right in the middle is the core itself. And in the back very important structure to be inspected which corresponds to the diagrid and the core supporting structure.

And what you see is there are few higher level inspection zones/areas. Just three comments. One of them corresponds to the wealth and the shell connecting these core supporting structure, very important, for the safety to the main vessel itself and that's red shell being cylindrical, not very high but very large in diameter, is connected to the main vessel and connected to the core supporting structure with some weld, very important to be controlled. Another important point is the skirt of the above core structure. There is a weld here in red and in case of any big problem on that weld you can imagine the consequences in case when the skirt could fall down to the core outlet. And the third example corresponds to the rotating plug support because the rotating plug is very important to assume that the control rods can be immersed properly within the core. This something of course important for the safety.

So, this is only an example for Superphénix plant. Of course, it was a bit different for Phénix plant, a bit different for ASTRID, and probably for all the plants you can develop in the countries you are.

So, I move to the next slide. Sorry, yes. And the main concrete objectives for in service inspection. At the very beginning of the project, that is to say at the early stage of the preliminary design phase, is first to minimize as much as possible the surveillance, the examination, and repair needs. That is to say that to try to reduce all the risk, all the risk that you can face in the plants. Having a robust design proposal, that is to save quite large margins in the design. I would say thermomechanical margins. And reducing also all what we can call the weak areas, for example, reducing the lengths of the welds, reducing the number of the welds.

And secondly make possible every kind of examinations. First, very important aspect is to have some access, to have some ports. In this example of the pool-type design, these ports will be located in the upper roof and of course as a designer we have many pots for the components, for many, many things, argon regulation, pressure regulation, such things, sodium purifications. But don't forget the in service inspection accesses also.

Secondly, examination ability improvements. That is to say that we will try to have a design able to be very well inspected. I will come in more detail later. And also, we plan to have some provision for exceptional inspection. Just in case if something is very bad, we would like to be able to discharge the whole core and then to be able to drain partially or totally the sodium, the primary sodium. And the third aspect is to solve a failure case. We think that in order to be ready to face any big problem we have to try to imagine a failure case, that is to say something wrong in the, for example, core supporting structure. And we would like to check that we are ready to perform first inspection, detection, so all that problem, and then perform some repair having the robotic systems and the tools for repairing.

And of course in that approach, in the early design phase, if the components are removable, if you can replace the components of course it should be easier to repair them. But of course at least the main primary vessel, we are not able to replace it.

So, we come to the next slide. Here is our – was our and is still our organization at CEA, I would say in France because we have some partners with EDF which is a French utilities and Framatome now, AREVA before, being the designer of the SFRs in France. So, we think on the left we have to optimize the design. It's a very important work but only performed at the very beginning of the design activity. And then we will develop some skills, some tools for first, continuous monitoring. Continuous monitoring is all the way, you have to monitor during normal operation and today my presentation mainly focuses on the two next aspects which are in yellow; periodic examination. So, answering these are mandatory as questions that the French nuclear safety authority are asking us. And developing some methods and tools for the periodic controls.

And the third aspect in orange are exceptional interventions. These interventions again in case of any doubts and warnings.

So, I come to the next slide. Just to give you some more detailed aspects about the developments of the techniques for in service inspection. So, as I said before, inspection is mainly performed with ultrasonic means. And ultrasonic has been chosen because we think it's a key technology. And while performing in sodium inspection, we will look after propagating the ultrasonic waves within liquid sodium, having some dumping within liquid sodium, then some reflection and diffraction when shooting on the immersed components and structures. Just to tell you that there is a quite low ultrasonic wave attenuation within the sodium. That's a good point. And the velocity of these waves are quite high, that is to say more than 2 kilometers per second to be compared to 1-1/2 kilometer per second in water at room temperature.

So, the French R&D program we developed for the ASTRID project mainly dealt about telemetry; that is to say measuring some distances within liquid sodium, performing imaging of many things. General imaging, having a general view within the main vessel or more local view, detecting, and recognizing lost parts if any, being able to see opened cracks, being able to identify fuel elements with a barcoding system, and of course being able to position the robotics within the primary sodium. And third but not least, last but not least, is volumetric controls. That is to say that we consider that the weak parts will be of course weld and in that weld we worry about any flows, any bad defect, and we would be like to be able to detect such defects. I move to the next slide.

So, just funny slide to illustrate ultrasonic. Of course you know the sonar system able to detect, for example, the Titanic on the floor of the North Atlantic Ocean. In the industry, many nondestructive examinations are performed during manufacturing and then for in-service inspection. And of course in medicine, the lovely babies can be seen very early. We are moving to the next slide.

Also, to illustrate what will be the ultrasonic measurements we will perform in liquid sodium, so the principle is to have an emitter on the left sending ultrasonic waves within liquid sodium in red. The target is located on the right. And target will induce some echoes coming back to the emitter which become a receiver in fact.

And so on the lower part of the slide you can see the same image. But what you see is amplitude of the echoes that you send is much reduced after coming back from the target. So when measuring anything within liquid sodium with ultrasonic, you would compare the amplitude of the echoes you received after they could propagate through the liquid sodium.

And if we look only to the telemetry, telemetry is measuring distance. That distance we measure is very classical, is we assume that we know the wave speed in that medium, about 2400 meters per second multiplied by the time of flight and divided by two because we measured outward and return flight.

We move to the next slide. From this slide, we are – I can tell you some words on the very technical aspects. If we want to perform any ultrasonic measurement, we need sensors, sensors able to operate within liquid sodium. If not, they will operate out of the sodium medium and we will see that later. So, in France we developed the high temperature ultrasonic sensor which is called TUSHT. You can see some pictures of that sensor with a flat front face and with a focused front face. It has been qualified in water and also in sodium. It is ranging from about less than 1 megahertz to less than 5 megahertz. So, in that frame, we know that the accuracy of the measurement is something like I would say in the range of less than 1 millimeter to some millimeters. The problem we had to face is a wetting of the front face in liquid sodium. Because at 200-degree C, which is temperature for in service inspection operations, there is no wetting and that is to say that it is not possible to propagate acoustic waves within liquid sodium unless you use some coating on stainless steel envelope of that sensor or you wait some hours but at more than 350-degree C. Because above that level of temperature you will reduce the oxidized layer from chromium and nickel that you find at the surface of that sensors. I am moving to the next slide.

What you see here is the qualification in sodium which ranged from 200-600 degree C. And what you see is that some sensors were mounted on the kind of cylinder with a target located at about 20 centimeters from the sensor. And on the right, you see the signal we could recover from one of them or one of the sensors. And what you see is emission on the left first and then first main echo at about 200 microseconds and if you double by two a second because the waves are coming from the sensor to the target, then again, then again, then again.

And what is very interesting is to see smaller echoes that correspond to the backwall echoes within the targets. And we discovered that even that sensor has a quite high constant sensitivity, we are able to measure the thickness of the target because we know the time of flight within the target which is made of stainless steel, and we know the time, and having these two parameters we are able to determine the thickness. And that was very interesting because we thought it was not possible and finally using such a sensor we think that we could be able to detect any big trouble within the thickness of the target.

I am moving to the next slide. What about other transducers? Of course, the former transducers I showed you were the single element transducer and it is a piezoelectric transducer. And in that family, we also developed phased array transducers. So in collaboration with a French company Sonaxis, we developed the transducer, actually you can see on the left side, which is a transducer with many dozens of elements, each of them being independent from the others. We also developed antennas with Toshiba, a Japanese company. You can see a linear – a first linear antenna that we had I would say 2 or 3 years ago, and the very last is a perpendicular two-antenna system that you see with a gold coating to assume the wetting in sodium at 200-degree C.

And developing that sensors, we are using the CIVA software. CIVA is a software which is widely split all around the world in the industry and that will help for designing and optimizing the sensors because we can simulate any kind of piezoelectrical sensor and it’s very efficient to check that we are able to focus at the right distance. You see here, light blue corresponds to the place where all the elements located here can be focused to get high energy and so high echo response.

I am moving to the next slide. There is also Framatome Company, formally AREVA, developing a sensor being I would say the brother of our TUSHT sensor. But that sensor is only developed for nondestructive examination and can only operate at less than 200-degree C. But the constant sensitivity is very low, that is to say that we are supposed to be able to detect very small defects and we had some test at CEA using the system that you can see the design with some design able to rotate, to translate the sensor in front of a block which is immersed within sodium pot. And we could check that we were able to detect some flows, machine flows of course. One is here, R2, one is here R1, and also the corner and also this part of the block. And when looking after the ultrasonic echoes that we could recover, we could see that R1, R2, and D part of the block could be detected. So that was a very good result. And that was published 2 years ago in the Sensor journal. I am moving to the next slide.

There is another family of sensors which are not piezoelectrical anymore but electromagnetic acoustic transducers, so-called EMAT that we have developed for sodium – in sodium inspection. So you know probably the principle on the left, having some magnets, having some coils, and mixing the two you will have some force directly within the liquid sodium. No wetting problem. This is very efficient. We could check it. And this force will create some waves, acoustic wave because we are at rather high frequency. And it's possible to send the waves and to register the echoes, and again to measure also the distance telemetry or to make some image. Because we could develop 12 elements phased array system able to steer and focus the ultrasonic beam at the place we want in order to check – to make some images and probably to perform nondestructive examinations. That has not been checked until now but we think it's possible. We are moving to the next slide.

So, after these words about the sensors, we will see the applications. First application is under sodium telemetry. For that, we performed a number of tests choosing that specific market which is about 1 meter diameter from the left to the right. And in that mockup we had one sensor, one TUSHT sensor shooting on different targets. There are many targets, small targets, bigger targets, flat targets – not flat targets. And we could check that the measurements, the ultrasonic distance measurements could be better than 100 microns, 0.1 millimeter. And of course for that we had the help of CIVA software but also these were many data in order to perform the qualification of CIVA software for that telemetry application. I am moving to the next slide.

Another application is the SONAR device. You remember the SONAR device for detecting the Titanic boat in the ocean? And here we had developed same kind of measurement just for checking the movements of two fuel sub-assembly heads in the Phénix plant. And that device was developed, designed, manufactured, tested, and used during more than 10 years in

Phénix plants and it was located just above the core outlet and operating at more than 500-degree C as you know that sensor – sorry, I didn't say that there were three TUSHT sensors. One of them shooting on one head, the other shooting on the other head, and one just shooting vertically to know the altitude of the rod with the sensors inside. You see that rod. And it was very efficient and that was linked to the safety system of Phénix plant; that is to say that in case of any problem we had to – we had to measure the distance of these two sub-assembly heads day and night every day during these more than 10 years. And that was very efficient. Next slide.

Correspond to another application which is performed only when fueling and defueling in order to reach as there is no obstacle and it is using ultrasonic system, sending wave in a horizontal plant. It is so called VISUS system for vision ultrasonics, checking that there is no obstacle between the above core structure and the upper part of the sub-assemblies. The distance between the two is not so large, it's something like 10 centimeters. And so before the fueling or fueling, we are sending acoustic wave in the plant just to check that there is no obstacle and then we can use fueling and defueling machine in order to perform the fueling and defueling. And again, it was very efficient. There was a same device in the Superphénix plant and for ASTRID it was planned.

Next slide please.

As I said before, we have to phase the sodium medium which is very special, very specific. But if it is possible, we check and we developed some methods in order to be able to have the sensor not immersed in the liquid sodium but out of liquid sodium, that is to say in the case of the primary vessel located on the outer surface of the wall of the primary vessel. And we had a number of underwater tests because the water tests are likely to be quite similar to sodium tests and most of the time the sodium tests are performed only as a very last qualification phase. But if the water tests are a success, it is a very good point in the development of such systems.

So, having the sensor out of the vessel and shooting perpendicularly to the main vessel surface, of course we are able to send acoustic waves within the primary vessel and then having the target being a pipe or a tube or a plate and having an echo. But if there is an angle, that is say that the incidence is not normal incidence, there will be about 15-degrees threshold and in that case it will be more difficult to get an echo because the longitudinal wave will not cross the interface but we are happy that the shear [ph] waves are able to cross that interface and the maximum amplitude of the shear waves will be at about you see just after that threshold.

What you see on the right are some test device with a sensor on the left, some plates immersed in water, and some very specific target which is we call that three-plane target which in fact is a corner of a cube. If you cut the corner of a cube, you will have such a target with the three planes being octagonal from the others. And using the targets, we know that it is the best target in order to get an echo, as the drawback of that method from the outside is that when crossing the interfaces between stainless steel structures of the main vessel or immersed components and liquid sodium. Of course, the energy is decreasing very fast. Coming to the next slide.

And looking after vision, ultrasonic vision, we try to develop a kind of camera, sodium-proof movie camera able to perform some imaging within liquid sodium. For that, we need ultrasonic sensors with electronics. We need some method for scanning all the structures immersed in liquid sodium. We need also some techniques for image reconstruction. And for that again the CIVA software platform will be of great help. What you see at the bottom of the slide are some elbows with the echoes in orange. So, you see a real picture, optical picture and then the acoustic echoes on the same slide. And what you see, there are only six elbows and more echoes. So, you see that using ultrasonic system sometimes you can have some trouble when trying to imaging such a system. And on the right what you see is a specific mockup we developed with a number of specific design pipe, bowl, Y-shape, U-shape, T-shape, and that was used for under water first and then under sodium tests.

On the next slide, what you see is what can be the two perpendicular antenna system. One antenna for emission with phased array system, that is to say a number of elements, linear antenna, and another perpendicular antenna which is called a reception antenna with the same number of elements and so emission focusing at that point and reception focusing at the same point but in a perpendicular way. And so the measuring point is at that red point. But as it is electronic sweeping, it is very fast and it is very fast to focus at any point at any distance and at any angular positon when compared to the antenna. So, you see all the parameters for developing such a system. And it was an important part of our work for a long time now.

Yes, okay, I am moving to the next slide.

What you see here a number of results we got using different sensors. And on that slide using the TUSHT sensor, what you see on the left, up left is water tank we are using at CEA Cadarache and then a mockup which is a flat plate with some engraved slits. And what you see here is the acoustic image we could get using the amplitude of the echoes, not using the time of flight but only the amplitude. So you see, we were able to recognize this – to detect these slits. And even the smaller which is only 0.8 millimeter large, this 0.8-millimeter value is very important as it corresponds to the specification that ASME, American Society of Mechanical Engineers, asked as the requirement for the detection of any flow for water cooled reactors. So, for the sodium cooled reactors, we decided to adopt, to have the same threshold, the same specification and we could prove that using that sensor in that condition we were able to detect it.

We were also able to detect some letters. You see CEA [ph] letters up to the 6 millimeter size letters. And for that we had some collaborations with our colleagues from Belgium and also from India.

Next slide please. Some other view. Again, there is the mockup with all that different specific design shapes and here what you see is in-water test result. We could recognize here. You see a kind of chair. It looks like a chair when you see from the one corner. And we were very happy of that result. And again, you see the elbows which were mounted with an Indian device in Kalpakkam in India. But not only elbows but some hammer, plier, a plate with slits again and letters. And here you see just as an example the plier image that we could recover during sodium tests.

Next slide. Next slide corresponds to the last test we could perform at CEA Cadarache. We are just now preparing the next test with the other sensors because for that test, very first test, we use again the TUSHT sensor which was there were two sensors mounted on that robotic system able to have some very accurate movements in a 3D positioning system. It was a very long costly development but we are very happy of that. And that robotic system was mounted in a 1-meter diameter pot, 2 meters high and liquid sodium at 200-degree C and we will use it for the future tests. In that test, we had for example a plate with some engraved slits with a type of triangular target, some letters, engraved letters, and a type of tubular target. What you see in blue corresponds to the acoustic echoes imaging, the image we could perform using the acoustic echoes. And performing specific signal treatment, we could recognize the CEA letters which are engraved here. SCK being our colleagues from Belgium and IGCAR in India. And we could have a very good detection and even sizing of engraved slits. And the smallest one is again 0.1 millimeter large.

Next slide please. All these former slides corresponded what we call to near distance viewing; near distance means less than 20 centimeters. Of course, in the big plants we have – we would like to be able to perform some imaging for larger distances. Near distance imaging is very good, for example, detecting flows because flows are very small, detecting lost parts, because lost parts are supposed to be small parts. But if we would like to have general view of the primary vessel. As the image you can see, this is Phénix plant view before sodium filling so a long time ago, in 1973 probably. So for larger distances, we had some connections with American lab in San Diego which is marine physical lab and we wanted to use submarine acoustic techniques. This submarine acoustic techniques, they try to take the benefit of ambient noise. In fact, we don't use any sensor. We don't send any acoustic wave but we only use the acoustic wave we have in the ocean for submarine applications and in the plant. And of course you know in the plant there is a large noise, background noise due to the pumps rotating, due to the sodium flow in the exchangers – between the pumps and the exchangers etcetera in the core. And so many structures and components vibrating. And that is to say that on the left you see a cylinder being immersed and receiving noise from everywhere and we would like to detect the defect which can be a flow or the whole at that location. And that can be done when comparing the acoustic answer when the structure is in good health as a reference state and the structure to be controlled with that local defect. And when using the comparison of all the echos you can recover – coming back from that system, you are able to detect that defect. And here you see another water tank we have at Cadarache with some test inside using hydroforms.

Next slide. Next slide again. We find the two perpendicular antenna system. You will see it here. And we wanted to make the image of a bolt, locating at half a meter from that sensor. And what you see on the right is the acoustic measurement imagine that we could reconstruct and the CIVA software simulation. So again, CIVA helped us to develop that sensor and the technique of scanning for obtaining good imaging with a good image quality, not so blurry images. And it also helped for the CIVA software qualification. Next slide.

So next slide corresponds to the developments we performed for nondestructive examinations of the welds. We had some work looking at the topological energy method. That method is very efficient as it is able to detect very small defects located in a very disturbed medium. Very disturbed medium means very inhomogeneous structure as weld. A weld joint is something which is very thick welds as we have in our plants, is something very disturbing. So, we will calculate this value corresponding to…

I will show you on the next slide.

The reference state is supposed with no defect. So imagine, there is an inhomogeneous medium here, something like a weld joint. Phase array system, linear phase array system sending acoustic wave in that medium, having only echoes from the other side of the wall, having the same system shooting in that medium with a hole, a small hole located at that black point. And sending back the signal we obtained here. But compared with the reference state and assuming time reversal of that signal, there is automatically focusing on that point, on the point where is maximum of topological energy.

Sorry it's quite complicated, but I think that you can understand that it's likely to really focus on the places where there is something new, something different from the reference state. And looking at the map, the corresponding map of topological energy it was very obvious that we had that spot very easy to be detected. Next slide.

That slide just to show you that we performed the number of simulations for nondestructive examinations. We supposed – it was only supposition. We supposed that we had a flow here, 100-millimeter long flow in the core supporting structure, so very important to be detected using a TUSHT sensor located here. And when shooting to that place – next slide please – we could simulate on the left the acoustic wave propagation and echoes and we could check that we were able to detect some echo.

On the right side, is a specific mockup, very small when compared to the actual size of the plant but we could design having some welds, adding some machine defects in that welds and assuming simulation with CIVA and then performing some underwater and under sodium tests. That was very important. This is different steps. Next slide please.

Coming back to the thick welds, we know that these welds are very difficult to be inspected because there are many passes, many layers, at least some dozens, because the thickness of that welds is something like some centimeters, 5, 4. And understanding the macrostructure of all these passes. If we can understand this macrostructure, we can simulate it and we can avoid the bad effects that we can see on the bottom. That is say that the acoustic wave will come in certain directions but not in others, will be split, will be dumped, will be divided, so it's really very important to have this approach to be able to detect some flows, some small defects. Next slide please.

Again, from the outside, you had some words on telemetry from the outside. And then it is nondestructive examination from the outside. You can imagine having a sensor located on the main vessel outer surface shooting through that vessel, crossing first layer of sodium, shooting a first immerse plate, then coming to the next layer of sodium and trying to detect a defect located in a third plate immersed in sodium. So, for that it was proved that it is possible to use ultrasonic lamb wave propagation. This type of guided wave can propagate very easily. And if you select the right modes symmetrical, anti-symmetrical, you are able to propagate very far and detect some defects because you will have some echoes being disturbed by that defects. There is a PG work in this year, finishing last lecture. Next slide please.

Yes. Trying to check the cross-supporting shell welded on the main vessel. It is possible to use the fact that it is welded. So, if you have a sensor on the main vessel out of wall, you are able to propagate some wave within that shell. The problem is that propagation is disturbed due to the fact that sodium is everywhere, so some energy comes to liquid sodium. And for that we decided to use linear sampling method which is very efficient also, to propagate waves efficiently on a long distance. What you see here is scale 1 mockup which is something like 3-meter long made of stainless steel. And here what you see is air test using a sensor located at the far bottom and sending wave all along that very long structure. Next slide please. I hurry because we are a bit late I think so.

Very last technique is to use time reversal technique. As a general surveillance for the structures and its components located within liquid sodium. We check that having some sensor welded – connected to the outer skirt of the main vessel, we were able to detect some flows using that technique with three stages. First stage is learning stage, that is to say having some source within the system and listening to that source waves, having some sensors at the outside of the main vessel. Then, checking that we are able to focus using the time reversal technique, to focus all the way to the point where was the source. And then finally, performing the surveillance, just listening to the noise coming to that point. So, it's something very efficient and that should be developed for the future.

Next step. We come now to the repair techniques just to say that we repair – we develop some single laser tool, single for all the applications that are sodium removal, structure machining in case of any defect to be removed, and welding in order to get back, to come back to the reference state of that structure. So, I will not come into detail to that except if there are some questions.

I come to the next slide. In sodium tightness, we developed some silicone sealing, so some joints, some pipes for electrical cables able to face sodium at 200-degree C. And we also developed a specific bell that should be used for inspection but mainly for repair tools which should be inside that bell under argon gas conditions. And that bell opening just during the repair operation. Next slide please.

So, in-sodium robotics is very important because all the sensors I mentioned. If we don't have any robotic system it will not be useful. And so we developed a number of things in order to face and would be able to use this robotic system. Main results are prototypic brushless motor, able to work at that temperature without any cooling and specific robotic mockups using electromagnetic connections in order to get the tightness, in-sodium tightness. Next slide please. Sorry. I was too fast.

And just to finish with extension to the other Gen IV systems, you know them the gas-cooled reactors, the lead-cooled, the molten salt, the supercritical, the sodium-cooled fast reactor, it was my presentation, so I will not come back to that, only in the conclusion, and the very high temperature reactor. For that what we know is that, there will be some requirements coming to the National Nuclear Safety Authorities. What is very important, it is my message, is to have that approach for in-service inspection at the very early design phase in order to see all what is important to get easier, faster, cheaper, in-service inspection operations. Of course, developing inspection tools and looking after inspection conditions. So, the fast analysis I performed for the five next generation IV systems. I used John Kelly paper that I could find which was very good for me in order to get all the conditions and the challenges for performing in-service inspection. So first, looking after lead-cooled fast reactor. As you see, John Kelly mentioned a number of very specific conditions. What I would say is that high density of lead is something very special, more than 10, so leading to high buoyancy effect of any two and robotic system immersed in lead, very high temperature conditions due to the melting point which is very high, chemical toxicity will be something to be faced, lead coolant is opaque, same as sodium. And wetting is probably something to be looked at for ultrasonic systems. And high corrosion of course. So, something very special and mainly on the three first lines.

Next slide deals with supercritical water reactor. Again, John Kelly raised the main aspects. I would say that probably it would be difficult to maintain the supercritical conditions while inspecting. It's just a question. I don't know. Water coolant is not opaque, so probably optical inspection will be possible and something very different from the sodium and lead conditions. High pressure and temperature operating conditions is something which is probably leading to high stress for structures and perhaps stronger inspection need that has to be checked. And okay, and that's it.

Next system will be very high temperature reactor. And again, not opaque system. Perhaps stronger inspection needs due to high pressure and very high temperature conditions. I wondered if heat insulation which will lead to some difficult access or perhaps some screen effect, something to be checked. And perhaps helium inventory, something which is not easy to maintain when performing inspection operations. Next slide please.

Gas cooled fast reactor is something quite similar to what we see before. So I don't come very deeply to that. And molten salt reactor is something very strange as you know because there is fuel and salt together. So, again, we don't know if it is opaque. If it is not opaque, optical inspection is possible; if not, ultrasonics will be very important to be developed. I don't know exactly the conditions for inspection. And the salt treatments is something very special. Is it something – salt treatment is something to be checked and all the device is something special. I don't know. Sorry. So, it is leading to many, many tracks for the future.

And just to finish we come to conclusions and perspectives. Just to say that we are in harsh environment for all the reactors. But for the sodium fast reactors, we know that we have to face 200-degree C in liquid sodium conditions, so developing sensors for that condition. The development will be eased by using some software. In France, it was CIVA software platform. And the development of robotics is something important because if you have some sensor you need also some robotic system.

Next slide. Just to say that we use technological readiness level range in order to come to up to 5 to 6 and then of course after that it will be some other companies which will develop really these sensors and all the equipment for inspection. As a very conclusion of conclusion, don't forget inspection need to be take into account from the very beginning of preliminary design phase. It is something important because you will not face big, big problem later.

And just to say a special thanks to my French colleagues working in many companies and many parts of CEA, Framatome, EDF, French National Institute for Research, and Universities. And you will find some bibliography. It is not exhaustive but these are the main documents that we developed recently with a sensor issued – Sensor Journal issuing 2 years ago. So, thank you for listening. Sorry to be perhaps rather long. So, I let you Patricia probably telling some words on upcoming webinars.

Berta Oates
Thank you Francois. It was not long. It's very interesting. Thank you for sharing your expertise. If you have questions, go ahead and type those in now. And while we are waiting for those to come in, we will take a quick look at the upcoming webinar presentations. In July, Evaluating Changing Paradigms Across the Nuclear Industry. In August, a presentation on Graded Approach: Not Just Why and When but How. And in September, Experimental R&D in Russia to Justify Sodium Fast Reactors. There are a couple of questions in the box.

If I may be so bold as to take the first one. Yes, the presentation is available. It's actually in the handouts pane. You can download it as a PDF right now and it will be posted when the audio recording of today's presentation is posted on the Gen IV website. Just give us a couple of days to get that updated and uploaded at www.gen-4.org.

Francois Baqué
Yes, I would just like to apologize because I rushed at the end of my presentation as I could see that it was more than 1 hour.

Berta Oates
You were great. No, you were great.

Francois Baqué
If there are any questions, I will answer.

Berta Oates
You have time for the question, so that's perfect. Do you see the questions? The first is how is ASME 11 to be applied and what is the period of examination; that is, often to examine high, medium, and low?

Francois Baqué
I don't see the question but I can understand. Yes, the question is what about the periodicity of these inspections, is it correct Patricia or Berta? Sorry.

Berta Oates
How often is the ASME 11 to be applied, yes the periodicity, what is the period of examination; that is, how often to examine high, medium, and low?

Francois Baqué
Sorry, in fact, that periodicity will be determined considering at least two things. First thing is that the operation of the plant has to be as high as possible. You remember the load factor which could be at least 80% and more. Because for ASTRID I remember it was 90%-94%. And so, we have to avoid some shutdown – specific shutdown for inspection should be very bad. And most of the time if it is possible and we will see the second condition, we have to use, I would say, the normal, the mandatory shutdowns that are planned in order to fuel, defuel or for other things. So we will take the benefit of that. I told you that it was about 1 month. In the development of the techniques for inspection, we were asked to have something available for 1 month's operation, not more. And of course the second very important point is to assume that when inspecting there will be not any flow improvement – there will not be any increase large enough so that we will have a break or a rupture before inspecting; that is to say that we are inspecting I would say at a time T0 and after inspecting at time T0 we assume that we will not have a bad effect, any rupture, any flow in increase before the next inspection. That is to say that using leak before break approach or such thermomechanical approach, you would determine that in that component, in that condition, you assume that you have a small flow that you are not able to detect. And you look after the increase of that flow during the time before the next inspection, and you just check that it would be okay, that even if the flow increases we will have the inspection and we will be able to detect that longer flow, larger flow before the rupture. And finally, having these two conditions in hand, probably we try to – the designer will perform the design with that values in his mind and he will decide to have the right margin so that we would inspect every some years. Difficulty to have a number of years, but it will not be every month of course. It will be probably more than 2 or 3 years. It will be not more than 10 years.

Berta Oates
Great. Thank you.

Francois Baqué
But it's a big problem. Sorry, when I say it's a big problem it's just something to be studied carefully and not easy and fast response for that.

Berta Oates
No, you are great. Yes, exactly. Can you speak to the relative amplitude of the 4A components of the turbulence which will have the same frequencies in various locations and flow regimes throughout the volumes as your signals?

Francois Baqué
Sorry, I didn't check exactly the question. I didn't get the question.

Patricia Paviet
Yeah, we don't see the question Berta.

Francois Baqué
Could you Berta tell me again?

Berta Oates
Can you speak to the relative amplitude of the 4A components of the turbulence which will have the same frequencies in various locations and flow regimes throughout the volume as your signals?

Francois Baqué
Okay, so this is something which didn't seem to me to be connected to my presentation but I can give some words on that. I understand that you are asking what about the turbulence spectrum within the sodium flow. I don't see if it is the right question. And leading probably to some fatigue on the structures. It is the right question?

Patricia Paviet
Berta, can you copy-place it in the chat box that he can read?

Francois Baqué
Yes, thank you.

Berta Oates
Yeah. There is a questions pane, do you see there is a chat box that's labelled questions?

Patricia Paviet
We don't see. We see the question but there is not [Unclear] Berta.

Francois Baqué
Hello.

Patricia Paviet
Yes, I am here too. I don't see Berta.

Berta Oates
No, that didn't catch it.

Francois Baqué
In the chat, can you copy in the chat?

Berta Oates
Yeah, I am…

Patricia Paviet
Yeah, I am sorry I didn't get very well the question. I understood the amplitude and 4A transform.

Francois Baqué
Perhaps to try to answer. We didn't come to that detail up to now, that is to say that we have some studies dealing with the sodium flow in the main vessel and elsewhere. Trying to get some information of that thermal hydraulic behavior of the sodium flow; that is to say, trying to detect any disturbances in that flow behavior. That is to say, some specific noise appearing or disappearing, some specific vibrations. Yes, you send. Okay, I will see. I catch it. Can you speak to the relative amplitude of the 4A components of the turbulence which will have the same frequencies in various locations and flow regime.

Yes, so I did listen that question but I can't understand it very well because you are speaking of turbulence, so turbulence, sodium flow turbulence of course. And again, we are not really connected to the sodium flow turbulence because for all the techniques I mentioned during my presentation, the wave speed is very high when compared to the sodium speed. It is to say that having ultrasonic wave speed being more than 2 kilometers per second when compared to sodium flow being probably less than 10 meters per second, it's really negligible. That is to say for all the applications I mentioned, we don't take into account the sodium flow behavior. But we take into account the thermal flow behavior because thermal flow – the thermal gradients are very important, are very disturbing for the wave propagation.

Berta Oates
Thank you.

Francois Baqué

Probably if I can catch later through email or anyway, another way, that question I will try to answer or to ask my colleagues. Because really, I don't catch exactly the meaning of that question in the frame of my presentation. Sorry.

Berta Oates
Sorry. Thank you. No, don't apologize.

Francois Baqué
There is another question?

Berta Oates
Yes, yes. I don't see another question from the audience. Robert, I think you have put in two and I think we have addressed both.

Francois Baqué
Sorry, I can read another question. If the item being observed are the [Unclear] harmonic at the incident frequency, will this make it invisible to the technique? Okay. Yes. Again, sorry. I will make some comments. In fact I couldn't comment during my presentation so I come back here now. Speaking of our sensors, ultrasonic high temperature transducer we developed in France, it's a very special sensor. That is to say that he has several main frequencies ranging from I would say 1 to 5 megahertz. And it is something disturbing in one way but it is also something very useful in another way. Why? Because using the five – there are five methods that can be slightly different. Using the main frequency pics, we are able to distinguish different behaviors. For example, when performing the lovely pictures I could show you using the robotic system in the sodium pot, we used higher frequency. Because as we know, the higher frequency corresponds to the better resolution, so with the best images that we are able to recognize. But that can happen that at that high level of frequency the damping is highest also. So, that can happen that if you shoot at long distance, that wave will not propagate up to the target, so you need another lower frequency. But in fact there is not invisible – we consider that we have no blind effects when performing any of our inspections.

Berta Oates
Thank you.

Francois Baqué
But again, I can answer if that person would like to send me any – or even I can try to give a longer – but I don't know exactly what is the meaning.

Berta Oates
Yeah, that's perfect. That definitely is all the questions that are currently in the questions pane. So opening up one more time, if you have questions go ahead and type those in now and we will take one or two more if we

have time. While any lingering questions are coming in, I do want to thank Patricia for organizing the presenters and these webinar series and today I want to do a particular thank you to Francois for doing two takes on this presentation. I apologize. We had technical difficulties last week and it's very generous of you to come back and spend time with us again today.

Francois Baqué
You are welcome.

Berta Oates
Behind the scenes, I have had a lot of assistance from Meghan Conroy [ph] and I want to reach out and thank her today as well also.

Francois Baqué
Okay.

Patricia Paviet
Thank you so much Francois and thank you Berta because without you I am not sure we will be able to manage all these webinars. Thank you again.

Francois Baqué
So, thank you to all of you and mainly to Berta and Patricia. It was a pleasure and really I will encourage some colleagues to be candidate for such not easy but interesting exercise.

Patricia Paviet
Okay, thank you so much Francois. Thank you Berta.

Berta Oates
Thank you. Have a great day.

Patricia Paviet
Have a good day.

Berta Oates
Bye, bye.

Patricia Paviet
Bye, bye.

Francois Baqué
Bye, bye. Thank you.

END