ASTRID – Lessons Learned
Mr. Gilles Rodriguez, CEA, France

Berta Oates: ...I think we'll just get started. Today's presentation is on Astrid – Lessons Learned. Doing today's introduction is Patricia Paviet. Patricia is the Director of the Office of Materials and Chemical Technology in the Department of Energy, Office of Nuclear Energy. She is also the Chairperson for the GIF Training and Education Task Force. Patricia?

Patricia Paviet: Yes, thank you so much, Berta. Good morning, everybody. It's my pleasure to introduce Gilles Rodriguez from the French Atomic Energy Commission, the Center of Cadarache, where he is Senior Expert Engineer. He has been occupying the position of Deputy Head of the ASTRID Project team since 2016. He graduated from the University of Lyon in France in 1990 with an engineering degree in chemistry and he obtained a Master of Science in Process Engineering from the Polytechnic University of Toulouse in 1991.

His areas of expertise are fast reactor technology, liquid metal processes, process engineering. From 2007 to 2013, he was project leader of the sodium technology and components within the CEA SFR project organization. Since 2013, he has joined the CEA project on Sodium Fast Reactor: ASTRID, for Advanced Sodium Technological Reactor for Industrial Demonstration, first as responsible for the ASTRID Nuclear Island.

So without delay, I am going to give the floor to Gilles, and I would like to thank him strongly for volunteering to give this webinar. Thank you, again, Gilles.

Gilles Rodriguez: Thank you, Patricia, and thank you, Berta. Hello, everybody. So I will start my presentation which is named ASTRID: Lessons Learned. So the outline is the following. I will just recall or present the French nuclear policy and its position regarding the several GEN IV systems and related coolants. I will try to explain to you why we are much more focused in France on the development of sodium fast reactors within the GEN IV systems. So I will just try to explain the advantages and challenges of the sodium fast reactor concept.

And after, I will make an overview of the ASTRID Program and its related design where I will try to explain to you and to show you the main achievements with some drawings of the ASTRIC Project. And so after, I will finish with what I have put on the lessons learned regarding the development of a large and complex project, and the development in particular of the sodium fast reactor design.

So first of all, I would like to show you the rationale for a closed fuel cycle in France. So in fact, you have to keep in mind that the trend in France is to move from Pu-monorecycling to a Pu-multirecycling system. And so, as far as with Gen II or maybe the Gen III system, you can make some Pu-monorecycling, like within a light water reactor. In the way that you want to move to a Pu-multirecycling system, you need to incorporate in your system fast reactors.

So the thing is we want to move from a current closed fuel cycle but with only monorecycling to a future closed fuel cycle with multirecycling of Pu to consider Pu, a large valuable material and not like nuclear waste, which is very important in the way of having major resource savings, Pu stockpile minimization, energetic independence and economic stability, decrease of waste burden and optimization of the disposal, and in such a way also public acceptance in the way that you are decreasing your Pu stockpile.

So this is a strategy that we developed in France, and you have to keep in mind that all the things that I will present are a sort of strategy that we consider within France, and in the case of nuclear energy, the strategy from France could be different from the strategy of the European Community for instance. We have a sort of independence in that specific subject.

So in that case, in France we carried out the Multi-annual Energy Plan, the French Multi-annual Energy Plan, which is updated every five years, and an update will be issued at the end of 2018, so I cannot forecast what will be the continuation. Up to now, I could say to you that the strategy is a future closed fuel cycle, and in that strategy, so by Pu-multirecycling, the need of fast reactors is essential.

So of course, in that case we have a reference for the roadmap but based on the reprocessing of oxide fuel and on the use of fast reactors, and in that case, we made a survey of all the systems, the Generation IV systems, and we took the decision to go forward with sodium cooled fast reactors, and I will explain to you on the coming slides why we have made this kind of choice.

So because I think you have seen a lot of presentations, you very well know all these six systems that are the basis of the Generation IV International Forum, and so among these six systems, you have several systems which are on closed fuel cycle, so the sodium fast reactor, which I will explain later, gas-cooled fast reactor, lead-cooled fast reactor, and molten salt reactor, and two others which are open fuel cycle but which are developed as a Generation IV for some other purpose, and so the cycle is not completely involved in these two open fuel cycle systems.

So the thing is, we have to select because of course it's huge work to work on all of these, and the purpose of the Gen IV system is to share the work by all the countries which are involved in the Generation IV system, so maybe you are very well aware also of this table where you can see currently all the countries which are involved in the Generation IV forum, and on the different line, the different system, and you can see in green where there is a contribution of each country for each system. So if you go to the fourth column for France, we have the major input and impact on sodium fast reactors through the ASTRID project, but we still keep involvement in some other systems, such as VHTR, materials, hydrogen technology and production, on gas fast reactors with the involvement on the ALLEGRO project, and also on the molten salt reactor, but in that case it's much more the CNRR, so the science department which is involved, so the French Science Department, and not completely CEA, just an overview for CEA in that case.

But you can see that we have a sort of matrix why we can see that we can fulfill within this matrix all the systems by several countries. Of course, we are not fulfilling all the countries by all the systems, but it is not subjective as a Gen IV system action.

So if I just try to present you a quick analysis of the different cooling technologies which are compatible with fast neutrons. I will not say, even if we have chosen sodium, I will not say that sodium is the best. In fact, we have to fulfill with some advantages and some drawbacks, and so each of the coolants has its kind of advantages that I want to highlight but also some as well drawbacks.

Why did we select sodium? In fact, it's a consensus – because it is a natural technology in France, and so it was much more efficient for us to start to work or we started to work because we had already several sodium fast reactors in development in France, so we started to work with all this accumulated knowledge and gain experimental (stats).

So if I'm just focusing on the coolant, of course for sodium the major advantages are the high conductivity. It is liquid from 98 to 883°C at atmospheric pressure, so it gives us a large and a wide range of liquid, which is quite interesting for safety development and safety demonstration, and we have no (state) change and we have a large margin before having a boiling state.

Sodium has a low viscosity when it is a liquid and so high conductivity, liquid, low viscosity means that we can make some hydraulic testing not with sodium but with water, and after we can quite easily the transposition, which is something which is very convenient when you have to make some qualification tests because of course it's much more easy to handle water than sodium in any case.

Something which is also a major advantage – and you have to keep in mind when you are using a selection coolant, it has compatibility with steels, and in that case, sodium is not so aggressive with stainless steel, but we can see that we have not a lot of difficulties regarding corrosion systems as we could have with lead for instance.

It's an industrial fluid so it's quite easy and you have a large quantity also so the impact on the cost of the coolant will not be very important, so it was the directly then just below.

We have a relatively low-cost sodium, metallic sodium, when you have to buy it. As you might know, sodium is done by electrolysis, and in fact to make an electrolysis of sodium chloride, sodium chloride is something that you can find everywhere because it is a salt from the ???, and so the price roughly, to keep in mind roughly, the price of metallic sodium is very dependent on the price of electricity because you need to give power and electricity to separate sodium from chloride.

But I have to talk about the major drawbacks of using sodium, and you have two major ones about the chemistry of sodium.

Sodium is very reactive because it's an ??? chemical, and so it can easily react with air and with water, so we will have to deal with this kind of system by using or developing the sodium fast reactor design. And it is one of the major drawbacks of sodium, metallic sodium in that case. And the second major drawback is that sodium is opaque, so you will need to have a different system in order to be able or an innovative system to be able to make an in-service inspection and reparability within sodium fast reactors. But I will explain it later in my presentation.

And so immediate consequences of its reactivity is that you will need a secondary circuit on the design of sodium fast reactors. And so this is a price to pay in order to use sodium fast reactors. You will see that from the early beginning you needed to have a secondary circuit.

If I am going through the other coolant, so lead is considered for fuel as a variant. It has the advantage as the opposite of the drawbacks of sodium, so no reactivity with air and water, no chemical reactivity I will say. And it is a good coolant. Also it has good cooling properties. But after, the drawbacks are corrosive, toxic, very dense, opaque, high temperature for maintenance, the density is quite high, and you can have a risk of vapor explosion in the primary circuit if you put an injection of the steam inside lead.

So usually you can use lead, or sometimes we are using also to try to decrease the constraints or the drawbacks of these materials. Usually we can use a eutectic with lead-bismuth, but it will not alleviate all the drawbacks but sometimes decrease the difficulties mainly in the toxicity and on the density.

So if we deal now with helium, helium is considered in France as (ORC) as an alternative. In that case, there is no temperature constraint because as a gas there is no boiling temperature, so no phase change. It is inert, and it is transparent, so it is quite easy to make in-service inspection and repair in that case. I wouldn't say easy or not easy, but easier.

But what you have to keep in mind, you will have some drawbacks also. Low density, so you will need to have high pressure in order to be able to high efficiency for the reactor because as a final goal also it's to produce electricity, so you need to think about the yield, and for heat transfer you need to have some pressurization of the helium fast reactors. You will need to have a challenge for decay heat removal architecture with passive systems.

And something also you have to keep in mind is that helium is not such an abundant material on Earth, so for the deployment of this kind of system, as a Gen IV reference system, it's not so of use because in that case we could investigate a sort of lack of helium leading to raising the price of the material in itself.

So if I'm going to the French Generation IV program, so as we told you, the French nuclear policy towards a more sustainable nuclear energy. So I said as my first slides, it requires a cycle based on fast neutron reactors in order to have the multi-recycling system. We want to have those for the possibility of deployment of commercial fast reactors in the second part of this century, and in that case, the need of having a system with a quite high maturity is quite important. So the reason also of the choice of the sodium cooled fast reactor because if we go to the maturity analysis level, I can sum up that there are about 450 years of operation in the world with sodium fast reactors, which is on the table here. I try to update this table every year. I have not done it exactly, but I think for 2018, it's up to date.

So in green you have the fast reactors which are still in operation, in white, the reactors that have operated but have now stopped, and in the light green the reactor that has to be commissioned or we make starting soon. So if you turn up all these dates and all these years, you achieve 450 years of operation, but it spread all over the world, so it's a real truth or real proof that you will need to share the knowledge in order to gain from all the community the experimental feedback as the operating of sodium fast reactors.

And the other system has not such a high value of accumulated years of operation all over the world, so we should make a quick decision about the level of maturity, and when you want to deploy sodium fast reactors, sorry, when you want to deploy fast reactors, it turns to evidence, that you have to give the big advantage to sodium fast reactors compared to the others. And there was no implementation of lead fast reactors, of molten salt reactors or gas fast reactors in such a power and for such a long time. So in fact, yes, the balance is very for sodium in that case, if you just focus on the level of maturity.

So in that case, the French fast reactor program is the following. So the priority is given to the sodium fast reactor system, but in all scenarios, so the reactor and its associated cycle, we have the ASTRID project. So ASTRID will help to validate breakthroughs on cycle and on sodium fast reactor design at the same time, on the same level. And we want the team to make some active survey on some other Gen IV fast and thermal neutron systems through the contribution to European projects through IAEA, (of you), OECD collaboration, of course through the contribution to Gen IV International Forum, as I presented previously on my table, and also through a specific collaboration frame, for instance for gas fast reactors or for molten salt reactors.

So we keep a major effort on sodium but we do not keep the other systems, and we keep survey involvement inside the other systems as well.

This table also is just here to show you that sodium fast reactors are developed worldwide and by major countries. When I am talking about major countries, I am talking about major countries involved in the development of nuclear systems and nuclear reactors. So as I told you, of course we have France and the ASTRID project. In Russia, there is BN-800, but we have also some other projects like MBIR or BN 1200. In China, there is a development and the operation of CEFR and there is the future development of CFR600. In Japan, there was a prototype, Japan sodium fast reactors, which is ??? by now, but we will see that there is some link between the development of JAEA on sodium fast reactors and on the ASTRID project right now.

In South Korea, there is a PGSFR. In India, there is a PFBR, plus some other projects on the deployment. And in the US, you have also some different projects using sodium, Terrapower, PRISM, and recently VTR, Versatile Test Reactor. So here again the collaboration is under discussion with the ASTRID project and USA in the coming months.

So you can see it is a worldwide development, and so the trend of Generation IV is to try to make mutual development between the old system, keeping in mind that you can have your own design, but you can share also some knowledge and feedback through the different countries as I explained before.

So just to focus now on sodium fast reactor design. As you can see here, it's a simple design. This is the kind of design we are using usually to present sodium fast reactors on the Gen IV International Forum. Why I picked this simple design? You can see that the drawing of this pump is very simple, and you cannot define this pump like this. You need to have an extraction from the primary vessel, but basically, you have the main function of a sodium fast reactor within this drawing. It's a pool type reactor meaning that all the primary sodium is remaining in the primary vessels, which is separated into two parts, what we call the cold plenum here and what we call the hot plenum here. So you have a pump which will force the sodium to go through the core for heating, going outside for temperature from 530 to 550°C, and after, you will have to extract this heat in order to produce electricity.

And so in that case, as I was telling you, the major drawback of sodium chemical reactivity is it forces us to provide an additional circuit, which is here, you can see, to produce steam through the steam generator with a pump. So we cannot put and add directly a steam generator inside the primary vessel because of the bad consequences that we could have on sodium water reaction in case of loss of tightness and the high depressurization of steam inside the primary vessel.

So it was quite obliged by using sodium to develop an additional circuit, what we call an intermediate circuit or secondary circuit sometimes, and this additional circuit of course will make in such a part an extra cost compared to the investment cost of the PWR.

At the exit of the steam generation, so from here, we could say that all this path is very conventional and there is no specific impact of this system on sodium fast reactors. So we just have to concentrate on all these systems. You have here a man so you can see roughly the position and the size of the primary vessel, so to give you roughly an idea, for instance, on an ASTRID fast reactor, the diameter of the main vessel is about 16 meters, and the height is roughly this part to this part, it's also roughly 15 to 16 meters. So you can see it's a huge vessel, not pressurized, no need to pressurize because it's a very good hat coolant, but you can have in that case the sort of figures in your mind.

So I will just quickly recall the favorable features of sodium fast reactors.

The whole primary circuit is contained in the main vessel, including the core, intermediate heat exchangers, and the primary pumps. The primary system is not pressurized. The intermediate system transfers energy to steam generators, providing for an extra containment between the primary circuit and the environment. We have a very large boiling margin of sodium, over 300 Kelvin. The large quantity of primary coolant provides high thermal inertia in case of loss of the main heat sink. And we again have a very important gain on that subject according to the safety demonstration case.

We have good natural convection and circulation features that allow to design a passive diversified decay heat removal system. This is also a gain that we could have and we can demonstrate in that gain that we can fulfill all the safety scenarios related to the loss of electricity for instance.

We have a power control by a single rod position, no xenon effect, no need of soluble neutron poison, so in that case, we can say that the operating of the core is quite easy to handle related to PWR. And something also which is not very well known, but the collective dose on a pool type sodium fast reactor is very low compared to PWR, so it's something that is also something quite important to deal with. But in fact, sodium is making a sort of auto-radiological protection from human beings.

So, of course, as I told you, we have developed some sodium fast reactor, but it's not because you have developed sodium fast reactors in the '50s or in the '60s that you have developed sodium fast reactors as a Gen IV system, because a Gen IV system, in order to be claimed to be a Gen IV system you have to fulfill different specifications and requirements, and in that case, you have to make some improvements in your design. It's the reason why, when we developed ASTRID, we do not reproduce the previous reactor that we had, for instance in France, the Phénix reactor or Superphénix reactor, which were operated in the '70s and '80s or in the '80s, '90s for the Superphénix case. Why?

Because these reactors are not Gen IV systems. They are sodium fast reactors, and you have to keep in mind that there is a big difference between what's been done in the past as a sodium fast reactor design and want we want to build in the future to claim and to be a Gen IV system. And for instance we identify all the parts that we have some lack in the design, and we wanted to fulfill this lack in order to be able to say that we are going towards a Generation IV system.

For instance, we have some core sodium voiding reactivity in the previous sodium fast reactor. We wanted to invent the safety in that case, and so we developed some or explored some development of a heterogeneous core in order to be able to decrease or completely remove the sodium void works.

As I told you also, we have some drawbacks about this sodium chemistry, sodium-water interaction. We wanted to enhance at the same time safety and the availability, and so in that case, for the ASTRID reactor project, we developed in parallel two kinds of systems or two kinds of solutions. One is robust steam generators, and the second one is to remove completely water and to put an additional third circuit with a Brayton cycle system by using nitrogen, pure nitrogen, (pressurized), instead of or in place of the steam water ??? cycle.

But of course you cannot make this just by say saying, okay, we will remove. After, you have to take some R&D direction and work in order to be able to demonstrate if it is feasible and also in order to be able to raise the level of maturity of this new system, which was not developed in the '80s or '90s before the ASTRID project in the case of the French sodium fast reactor development.

We wanted also to develop or to improve the demonstration still regarding sodium fire, and so we developed a lot of innovative sodium lead detection systems in order to be able to quickly detect a tiny leak of sodium which we could have and to make a sort of quick intervention in case of the indication of a sodium leak.

We have also to manage the R&D about the sodium aerosols in order to make a protection from the environment and in case of a large scenario, safety scenario, with large and spread sodium fires, to demonstrate that we can protect the environment from sodium aerosols.

We have also to develop a lot of demonstrations regarding the safety and regarding severe accidents, and this line was mainly a line and a kind of development that has been quickly increased due to the Fukushima event. So we developed a core catcher and we did some research on corium and sodium-corium interaction in order to be able to demonstrate that in the scenario of a total melting of the core, in that case we have a quick draining of the mixing of the core with sodium, what we call the corium, down to the core catcher with no primary energy (interruption).

We have also to demonstrate the ability of the decay heat removal in any case scenario, and so in that case we have to make a combination of the proved decay heat removal system, and also to see that this kind of system or all of the systems can find a solution to operate either in forced convection or also in natural convection in case of an (unprotective) loss of electricity or station blackout for instance, long-term station blackout.

And for in-service inspection and repair, which is related to safety and availability, in that case we have to demonstrate that we are able to inspect in all the systems and in all cases the different parts which are suspected to be able to evaluate or to have some cracks or failure, so mainly the weldings, which are the major part where you can encounter cracks and failure with time.

So, I will now move to the ASTRID program just to explain to you what it is and how it works, and after I will show you different figures and different drawings of the ASTRID project as it is drawn now.

So ASTRID is considered a technological demonstrator, so it's not the first-of-a kind of commercial reactor, meaning that in that case, because it's not the first-of-a kind, we keep having the opportunity, we still have the opportunity to incorporate some innovative technology and to raise the level of maturity of this innovative technology within the ASTRID reactor in operation, which is not the same constraint when you have a first-of-a-kind where the level of maturity is in such a way quite high because you are a first-of-a-kind of commercial reactor so you are closer to a commercial reactor.

So the development of the program is based on the feedback experiences on the fast sodium cooled fast reactor, and we have to demonstrate in the ASTRID case at a scale allowing the industrial extrapolation, the relevancy of performances of innovations, in particular in the field of safety and operability.

So we have to demonstrate that what we demonstrate in ASTRID could be extrapolated for future large-scale and large-power commercial fast reactors.

And we have also a big connection with an R&D facility to test and qualify innovative safety design, to qualify different fuels so we can change the core by time or maybe make some external (sub-fuel) assembly, to obtain the necessary data to justify the useful lifetime of 60 years for future sodium fast reactors, so just to demonstrate that staying actually in major parts can fulfill the 60 years lifetime in contact with hot and metallic sodium, liquid sodium. And to confirm performances of innovative components and to establish a reference for sodium fast reactor cost assessment, for the building and operation, not only for the cost investment but also with the planning and the price for operating the reactor.

So one of the targets is to say that the technology of ASTRID allows us to have a very resilient design to external events, and this was an impact of the

Fukushima event, but even before the Fukushima event, we had to take into account this time external events. So of course earthquakes, flooding, loss of power, airplane crash, et cetera, et cetera. I could put also malevolence, et cetera. So this is an impact that was not so important and so major in the '80s or the '70s. I will not say that it was not taken into account but in that case the number of scenarios, the number of questions has been raised a lot compared to the system developed previously.

So just to recall for you the project organization of ASTRID. As you can see, we have here the ASTRID project team, which is located in Cadarache research center. We have some assistance from EDF and relay also on the Marcoule site. And after, we are working by work package. One is on the reactor core, where CEA is responsible and Framatome is in support. One is the Nuclear Island with the big involvement of Framatome, also a big involvement of JAEA, MFPR, Mitsubishi Heavy Industry, and SEIV for the hot cells.

Another work package is on the power conversion systems, and in that case, this was led by General Electric. Another work package on civil engineering led by Bouygues, and another one on balance of plant and infrastructure, which is led by NOX company.

And we have some also some crosscutting use or development by different partnerships, Toshiba, Velan, Nim, Onet, and Technetics, which are for the search for innovation, and if these kinds of innovations are incorporated, in that case, they will go through inside the Nuclear Island development.

On the left part here you can see that we have also strong support from the R&D field, so of course this support is on the major work done by R&D carried out by CEA but also on some international or European R&D development, a project called ARDECo by EDF, the French electrical supplier, and also with important collaboration with JAEA, MHI, and MFBR in the R&D field. So we have a close relationship on R&D and the organization, and in fact I will have to put an arrow because all of this R&D will fulfill the innovation and will be implemented if they are accepted within the Nuclear Island design.

I will not go into detail on this slide, but you can see that there is of course a lot of partnership organizations that you can see, with countries, with organizations, and with companies. So here on the ASTRID project, we are working altogether with 14 companies here, industrial companies, and these industrial companies are really industrial partners, so we have not to consider them as subcontractors or contractors; they are considered as partners. So in that case, they have the right and we claim for them to give their opinion, to get their feedback, and so it's a kind of exchange. And of course we have also to define the work to be carried out altogether, but it is not the conventional commercial relationship that we are carrying out with all the partners. So in that case, after we have some international cooperation, but it's much more focused in that case by the R&D teams compared to the ASTRID project.

I don't know if I told you – sorry I am going back to the previous slide. So, yes, here's the ASTRID project team organization. It's about 20 persons belonging at CEA. All of them are in Cadarache, and the contracting also, which is here, the strategic management is carried out by two persons who are located in Saclay, so in fact the program department in that case.

And as you have seen, of course we have to develop a lot of R&D and innovation because, as I told you, the previous sodium fast reactors we developed for Phénix or Superphénix in the case of France, were not the Generation IV system, so to achieve the Generation IV system you need to have some innovation and development, and when you need to have some R&D development, innovation, in that case, you will need to have to test some systems.

So of course modelling is making great progress now, but in any case, at the very end you will need to validate your modelling. So computing codes are helping us a lot, but at the end, in any case, you need to have some experimental platform to be able to be sure that either your system is fulfilling the requirement, is making good results, or even that your computing code is giving you good results when you compute it.

So it's the reason why you need to have in support of design development a large, wide and scope of experimental platforms that we develop either at the CEA or sometimes we have also to exchange with some other countries for a large sodium platform, for instance, in Japan we consider that we can have some large sodium loops in some other foreign countries. This is very important because the price of an experimental platform is quite important.

And here again, the international share is something that we have to keep in mind; otherwise, if we want to have the development of all the systems in parallel and independently, it will be very costly and it's not the way that we are developing cost-saving in other countries in that case, and this is a strategic point that you have to keep in mind.

So as I told you, because we wanted to put innovation, we put a lot of digital in the ASTRID project for the design, for the computing. So, sorry. For the design, for instance here – Sorry, I didn't have the green arrow anymore, I don't know where it is. Okay. I will continue anyway – For the design here, for instance, for the assessment of performance, and also – Oh, thank you, thank you, Berta – and also sometimes to have some meeting because we have a complex project where we have to rule 13 partners and over 500 participants spread out all over the world, and you have to share the knowledge, and sometimes it's not obvious, so you have also to deal with this kind of situation.

And the use of digital is also something which is very important in project management. In the design for instance, you can have a lot of modelling that you can do now by platforming and by computing code, and it provides a big enhancement of the presentation or the demonstration for the decay heat removal system for instance and for the modelling. So here we have a major gain, but as I told you, once again, even if we have the major gain with computing code, you will need to validate this computing code, and at one time you will need to have some external source feedback validation for the codes as well. So you have to keep that in mind, the performance of computing code is helping save money in the development of experimental tests but not in a way to go to zero tests; it's impossible. You will need at any time to validate your code, and this is done by external source feedback. You cannot avoid this. So less external code but no zero externals.

As I told you, we have also the management of a large complex project. We have a lot of partners. We have to exchange data with them. We have to exchange the organization, which is based on an engineering approach, an engineering system approach, and so we decided to develop plant life management in order to be able, not yet shared amongst all the partners but within the ASTRID team to have online surveillance and online following of the project by plant life management, and of course, after, we are developing something which is very well-known and used now, like 3D numerical modelling and configuration management.

You have some data here. We have over 15,000 interface data to look after for all the partners, so this is a major point of importance and of ??? within the ASTRID project team in order that we can share all this data among all the teams at the same time.

We put also some effort about the promising development in the use of virtual reality because we think it's worth it to be able to see in 3D what the future will be and one where we can handle the system, and this was much more focused because we had many more constraints regarding the operability of the system. So this is something that we take into account early in the design of the reactor in the project.

So the main achievements for 2015 are the following. We had made a synthesis to the government in mid-2015, which allows us to move towards the basic design period from 2015 until the end of 2019. So now we are deeply involved in the basic design phase, and we will presented our main achievements at the end of 2015 on the preliminary design, which allows us, by the government, to go forward to the basic design system. And all the partners have accepted to continue this kind of adventure with us on the basic design phase, except one partner, otherwise, the others, they have said, okay, we'll continue with you as a partnership until 2019.

So I just want to recall now the main technical choices we started to use and to decide in the early design of the ASTRID project.

So a power reactor with 1500 MWth, that is to say, roughly, a 600 MWe reactor. As I told you, it was a pool type reactor. You have another process which is called a loop type reactor, but we do not continue this kind of design. Of course it was designed with an intermediate sodium circuit. Even if we want to alleviate this, we could not find any easy solution to try to remove this one, so a cost important decision because we know it will be more costly than PWR.

We have a CFV core, which is a core with a low sodium void worth, so we put innovation here. The oxide fuel is a UO2-PuO2 system, which is in (tolerance) with the fuel management in France.

We have a preliminary strategy for severe accidents with an internal core catcher, with the design of no large mechanical energy release, so a sort of scenario where once we have the corium, we want to quickly drain it down to the core catcher in order to be able to go to prevent from a big ??? excursion.

We wanted to demonstrate that we can have a diversified decay heat removal system able to freeze or to cool down the reactor in any case situation, in the case also for long-term station blackout for instance, which is one of the major difficult systems to demonstrate because you will have only a natural cooling system in operation in that case.

And also we have fuel handling in sodium in combination of internal storage and small external storage, which was devoted to design an increase of the availability rate.

So some drawings now. So just here to show you that, here you have the reactor but in fact it's a small part of the ??? here. It's 15 meters diameter, and you can see that all the nuclear (iron) here, it's quite large with very high height here, and also you will have some secondary circuits on the two parts that belong to the reactor. In the case of ASTRID, in fact we have three secondary circuits, sorry, four, four secondary circuits.

So this is a drawing that we have carried out with the steam water power conversion system, so you can see not exactly, but here behind, you have the steam generator, or you can see here on the building the steam generator system.

We have drawn in parallel another system, so here it remains roughly the same, but we have to adapt the secondary system here to be able to put some steam, sorry, gas conversion system, and you have here four sodium gas systems, heat exchangers, so after you have the Brayton cycles here which are in the turbine hall. So we have in fact developed today in parallel as the preliminary design stage two systems, one with steam water and the other one with pure pressurized nitrogen.

So this one is a view about the Nuclear Island, why you can see that we have the reactor hall here, a polar table here to prevent some risk assessment and the falling down of a big component on the roof of the reactor. You have here the reactor block, and you have here the very basic drawings of an anti-seismic raft to preserve about the earthquake event.

On this drawing you see the fuel handling route, so this is the fuel handling route for the fresh fuel, but if you are talking about burned fuel, it is the opposite one, so for the fresh handling goods, you go from 1 to 4, so first here, after you put it for sort of thermal consideration, and after you go through this corridor, you will put it on the (extra ???) storage tank, and through a ramp you will go and put it inside sodium. For the burned fuel, you will go exactly in the opposite way, except that here you will have on the internal vessel a decay heat system, then another additional if necessary decay heat inside sodium here. After you will go to cleaning and washing before making the ??? for the final decay heat into the water pool.

Something which is very important that you have to focus on, as we have started to work on the ASTRID project with this idea to give at the beginning, early beginning, an implementation position of the reactor, which was located as a scenario in Marcoule, in order to be able to have the complete difficulties of all the project because when you are drawing this, or when you are drawing this, if you are doing the drawing without the environment, in that case, in fact, the feedback of the cost evaluation that you will do on your reactor is false, and sometimes you are giving some hypotheses which are favorable. So we wanted to be able to have the hypothesis on the real case, and that's the reason why we put the Marcoule area in order to be able to design and implement all the reactor structures to evaluate the balance of plant and the constructability. And sometimes you have some constraints on the design, on the Nuclear Island, which comes only due to the (crane) because you cannot implement your (crane) to design or to build what you wanted to design.

So it's very important to go to the very far, the very end of the basic project in order to be able to have all of the constraints at the early beginning of the design and it gives you much more constraint, but for the future it will give you much more assessment that your reactor or your project is suitable and you will have a much more up-to-date schedule and cost estimation.

So you can see here the balance of plant as we have drawn it at the end of 2017 with the Nuclear Island, which is here, here in the building for the fuel running system, in light red or light pink. You have here the two buildings for the gas cooling system, so one here and one here. And here, in the cooling system, we will place the big cooling tower by the small cooling system in order to prevent from the view of the large cooling tower from far on the Marcoule side.

And so you can see for instance to operate this kind of balance of plant, you have to take into account that you are close to a river, that you have to go through and to break a sort of mountain or hill here, and so it will give you some constraints that you will not imagine if you have not at the beginning of your design the site, an example of the site to be able to perform and to design completely your reactor in the frame of the balance of plant. And so I have to focus on that point because I see a lot of sometimes projects where there is no balance of plant. Sometimes, a concept estimation that you will provide is largely underestimating the real cost estimation that you will have to fulfill in case of the balance of plant design.

So just going now on my slide of lessons learned about the sodium fast reactor, and mainly on the ASTRID project.

So I think I have two slides. Yes, that's right. I have two slides. So the first one, which is much more general and just to recall what I presented to you. So nuclear energy is a well proven source of large baseload electricity, with no greenhouse gas emissions, and it will remain one of the pillars of the future French low-carbon energy mix. So as I told you, we made a five-year plan; this five-year plan will end at the end of 2018, and we have, it's under discussion right now, to discuss about the future five-year plan for the five years to come.

So for us, the closed fuel cycle – when I say us, okay, it's CEA of France – associated with the fast neutron reactor, will lead to a drastic improvement of uranium resource management, and important reduction in the footprint and radiotoxicity of the final wastes. And moreover, of course, we are using and making the multi-recycling of plutonium, so you have a sort of combination of the work and the handling of strategy of PWR and strategy of fast reactors, which are very close and very prominent altogether.

So as I told you, the French program on Generation IV is based on the ASTRID program. The basic design phase is ongoing from 2016 until 2019. The schedule and organization for the next phases are under preparation, so August 2019. And we had to investigate one option that could be to review the power of the demonstration reactor, and this was due to first feedback of the cost investment of the reactor, with some constraints given by the government asking us to decrease the cost investment of the project. So one idea was to reduce the power, but all the innovations and drawings remain roughly the same.

And we made also an active survey on the other Gen IV fast and thermal neutrons test in parallel. as I presented to you at the beginning of my talk.

So another slide on lessons learned, but I wanted some message to give through this presentation. As I told you, the sodium fast reactor is a mature technology because many sodium fast reactors were built from the '50s to the '70s and then were operated. But the gap to achieve a Gen IV system is significant because the Gen IV is requesting improvements, mainly in safety, operational, and economic aspects, and it is impacting the related design, so it is not why we are working on sodium fast reactors that you are designing Gen IV systems. And you need to have all the expectations of the Gen IV or the requirements of Gen IV incorporated then inside your design, which is a very crucial point.

So even if it is a mature technology, the sodium fast reactor technology is not obvious because you are not daily using sodium as a coolant at home or in some other industry. And in that field, the knowledge preservation and transmission to the coming young generation is also a key challenge, and if you want to keep this key technology available for decades, which is the ratio of time for the nuclear project, you will need to have a sort of knowledge preservation and transmission strategy in parallel with your development.

And the use of sodium as a coolant, as for the other liquid metal or Helium coolants, needs courses, practice, skills, or presentation through a webinar, as I am doing it right now.

And innovation also is the way to design new reactors. And I’m not doing innovation for the pleasure of making innovation. I'm making innovation to fulfill the Gen IV requirements, to fulfill the new safety demonstration that we need to have, and also to fulfill the cost investments that we have to reduce.

So to make this kind of innovation it needs to get a close relationship between industry and design teams on one hand and the R&D teams on the other hand. And this was the rule of the ASTRID team project to make them learn together and to be able to exchange the data and to put them in the same way of understanding each other

And the sodium fast reactor design cannot be achieved without international collaboration, and I am sure of this, mainly to mutualized technological platforms and infrastructures because this kind of platform is very expensive, and in that case, if you can mutualize them through some international collaboration, to my opinion, it’s a win-win cost-savings approach that you will need to have in order to be able to develop such an important project development.

Okay, I think I have been through all my presentation. Thank you to the audience. I am open for questions and answers if you have some time.

Oates: Thank you, Gilles. Thank you very much for your presentation. If you have questions on this webinar presentation, please do go ahead and type those into the chat pod now. And while we're waiting for questions to come in, we'll just take a look at a couple webinars. In August, we anticipate a presentation from Dr. Rachkov on the BREST-300 Lead-Cooled Fast Reactor, in September, a presentation by Dr Alemberti on the Advanced Lead Fast Reactor European Demonstrator or otherwise known as ALFRED Project, and in October, a presentation from Dr. Ammirabile on the Safety of Gen IV reactors.

Rodriguez: Okay, thank you just now.

Oates: There are a couple of questions that have been entered into the chat pod, and if you roll your mouse over the Q&A pod, you can see those two tabs. One is a presenter and one is a participant view. If you look at the presenter, do you see the questions?

Rodriguez: I don't see any questions right now, but the Q&A window, but nothing. I hope it was here anyway.

Oates: To the right of where it say Q&A, roll your mouse over. There's an icon of someone with a computer monitor, and then just a person's head. Click on the one with the computer monitor. Do you see those? There's a question that's from Suketu Gandhi that says, "Russia seeks to develop nitride fuel for their sodium cooled fast reactors. Which is a better fuel: UO_2 or UN?"

Rodriguez: So we are not using nitride fuel up to now, only oxide fuel, because in fact all of our facilities are based up to now on oxide fuel, so all our facilities for the fuel handling or for fuel process fabrication are devoted to oxide fuel. So this is the reason why we are using oxide fuel. I can give you some other explanation later by the comparison between nitride fuel and oxide fuel, but here the choice was not very difficult to do. To make an additional fabrication with some other process, it was such a big involvement in terms of time and money that we selected our historical fabrication process.

I am not giving you a clear answer about this, but the compilation of ??? oxide was not done in that case, but okay, I can give you some other comparison.

And once again, the comparison has been done and the position has been done on coolant. That was not the best coolant; there were only advantages and drawbacks on every coolant. I think it will be the same for the fuel, either metallic nitride, oxide fuel, we find some advantages and drawbacks, and after, you have to deal with them. So you take the advantages of the positive features of your fuel and after you have to deal with the drawbacks.

Okay, thank you, David.

Oates: Okay, I don't see other questions coming. There are thanks and accolades. We have time for maybe another question if there are any questions from the audience.

Rodriguez: Okay, so otherwise, I hope you enjoyed my presentation. I tried to do my best to get rid of my French accent, that it was not ??? anyway. And if you have some additional questions, please feel free to send me an email. I think you got my email on the presentation, so I can give an online answer afterwards.

Oates: Exactly. Thank you very much.

Paviet: Yes, thank you, Gilles. That was so interesting.

Rodriguez: Thank you very much.

Oates: Good-bye.

Paviet: Okay, good-bye everybody. Have a good day.

Rodriguez: Okay, bye-bye. Au revoir.