Phénix and Superphénix Feedback Experience
Dr. Joel Guidez, CEA, France

Berta Oates: Welcome, everyone, to the next Gen IV International Forum webinar on Phénix and Superphénix Feedback Experience. Dr. Patricia Paviet is the Director of the Office of Material and Chemical Technologies at DOE, Office of Nuclear Energy, and she is also the Chair of the GIF Education and Training Task Force. Patricia?

Patricia Paviet: Thank you, Berta. It's my pleasure to have Joël Guidez with us today. Joël is working at the CEA, the French Alternative Energies and Atomic Energy Commission.

He began his career in the field of sodium-cooled fast reactors after graduating from the École Centrale Paris in 1973. He worked at Cadarache for eight years on the design, dimensioning, and testing of sodium components for Superphénix. He also followed the initial results, in his field, from the Phénix sodium-cooled fast reactor startup in 1974.

He joined Phénix where for five years he was in charge of measurements and tests on the power plant. In 1987, he returned to Cadarache to lead a thermal-hydraulics laboratory, where many tests were performed for Phénix, Superphénix, and the European Fast Reactor Project.

After a period of apparent unfaithfulness to fast reactors, during which he successfully managed the OSIRIS research reactor located in Saclay and the European Commission's reactor HFR located in the Netherlands, he returned to Phénix in 2002, where he restarted and managed the reactor until 2008, during its final operating phase.

He is now an international expert for the CEA. He wrote the book *Phénix: The Feedback Experience* in 2012. It was translated in 2013, and a new edition in 2014, and also the other book *Superphénix: Technical and Scientific Achievements*, which was edited in 2015, translated in 2016, and a new French version edition in 2017.

It's really my pleasure to have you with us, Joël. I give you the floor, Joël, and I thank you again for volunteering to give this webinar. Thank you, Joël.

Joël Guidez: Thanks, Patricia. Today is the summary of the procession from first when we speak of fast breeder reactor objectives, generalities and objectives of the fast-breeder reactor. After, we speak of the story of the world of fast breeder reactor, and especially of the French experience. Then we have some more of the Phénix and Superphénix feedback experience, and then analysis theme by theme, and after the conclusion is the ???.

The objectives of fast breeder reactors: uranium availability, the possibility of plutonium management, the possibility to manage the REP waste of the water reactor, the transmutation possibilities, the optimization of the fuel cycle, and its ???, the sustainable energy for the future.

Some work on the optimized cycle of the fast breeder reactor. You see on the *schéma*, the reactor optimized cycle with the possibility to make the fabrication of the fuel with depleted uranium, that is very available today, and with the plutonium obtained with reprocessing of the fuel. And with the depleted uranium and the plutonium, it's possible to have fabrication of fuel and to use it in the fast reactor after we make some recycling activities, and we can come back with very little waste, only 4% of the fuel, though for this optimized cycle we need no mines of uranium, we need no uranium enrichment facilities, we can manage the plutonium, we can also manage the transmutation of actinides with the time of the possibility of the waste. We can burn all the waste produced by the water reactors, and we can obtain a drastic reduction of the final waste with a reduction in quantity and a reduction in time.

With the fast breeder reactor, in this *schéma* we can see the conventional energy available in the world with and without fast reactors. With or without fast reactors, if we take our needs of conventional energy, you see that coal remains the main energy for the future. That is very dangerous for the planet and the climate of (such man). And if we use the fast breeder reactor, we see that the uranium can lead the future as the main conventional energy to be used.

In GIF, the fast breeder reactors.

We have in GIF International Forum four types of reactors that can be fast reactors, so sodium reactors, the lead reactors, and the molten salt reactor, and the gas fast reactor, but the only type of reactor that has been built and operated is the sodium fast reactor. So the molten salt reactors, there was a US prototype a lot of years ago, but it was not a fast reactor, and so the lead reactor we have only the experience with lead-bismuth reactors in the Russian submarines. On the other hand, large experience is available on the sodium fast reactor in the world and in France also.

The sodium fast breeder reactor in the world, we have now, the first nuclear reactor to produce electricity was a sodium reactor, in fact it was a NaK reactor in 1951. Twenty-seven sodium fast reactors have been built in the world and operated.

A lot of countries have worked on this type or reactor: the USA, Russia, France, Japan, India, China, the UK, and Germany.

The last one to have started is the BN 800 in Russia, 800 MWe. It was connected to the grid in 2016. And now we have in India a 500 MWe that should start next year. You see a lot of experience in the world on this type of reactor.

For the French experience, we have had four phases. The first was the Rapsodie, from '66 to '83. It was a ??? reactor of 40 MWt. After that, we had Phénix, from '73 to 2003. It was operating at 250 MWe. Superphénix began to operate in 1985 and stopped work in '97. It was a 1240 MWe, and after the closing of Superphénix, Phénix restarted after a safety reevaluation, from 2003 to 2009, and it was active with only two-thirds of its power, which means 170 MWe. So we see that in France we have big experience on this type of reactor.

The Rapsodie experience.

It was a little loop type reactor that was built mainly to test materials and fuel. There was no electricity production. The aim of this reactor was to test materials for structures, components, and fuel assembly during the life of the reactor, and this experience with components and the fuel were used for Phénix choices because Phénix was built during the operation of Rapsodie. A lot of problems on the corrosion of the fuel pins were studied in Rapsodie and were resolved.

And at the end of the life of this reactor, very interesting tests were provided, particularly an ULOF test where the sodium flow rate was stopped at nominal power without any control rod shutdown to show the ??? safety of this type of reactor.

For Phénix, the feedback experience was a large experience.

The reactor was producing electricity. This reactor also holds a special place among French nuclear power plants. It was built in '68 by an integrated CEA/EDF/GAAA team. It went critical in '73 and was cooperated on with EDF. It was 80% CEA and 20% EDF from 1974 to 2009.

During the 35 years' lifespan, it played a dual role as an electricity generator and experimental research reactor. Thus, it gathered considerable experience for the fast breeder reactor systems: demonstration of design and operation, breeder potential, transmutation possibilities, development of all technical fields involved, and the validation of the technology used.

This book has attempted to summarize the wealth of scientifically exciting experience feedback from the 35 years for the future fourth generation.

After the Phénix book, we tried to make the same type of ??? on Superphénix. It would develop the (group of) Superphénix technical and scientific achievements. Huge industrial experience was acquired during the reactor construction, the biggest sodium fast reactor ever built in the world. And the reactor was built in seven years, from '77 to the beginning of sodium filling of sodium in '84. And the nominal power was reached two years later in December '86.

Despite the complicated political life, with the strong opposition of ecologists, a big experience on all the technical fields was also acquired until the reactor shut down ten years later for political reasons.

Then two books were written to try to summarize this experience. The first book is a book on Phénix, *Le retour d'expérience*. It has been edited by EDP Science in 2012, and a reedition was necessary in 2013. The English translation, *Phénix Feedback Experience,* is also available in EDP Science.

The book *Superphénix. Acquis techniques and scientifiques* was done in collaboration with Gérard Prêle from EDF, has been edited by EDP Science also, the same editor, in 2015, and a reedition was also necessary in 2017. The English translation was provided by the Springer editions in 2017, the title, *Superphénix. Technical and Scientific Achievements*.

You can see here the two covers of the books. The book *Phénix*, it is a publication by EDP Science, and the book *Superphenix. Technical and Scientific Achievements*, that you can find in the Springer editions.

What were the principles of these books? The principle of these books are the thematic analyses.

The books are not organized along a chronological experience but only with thematic analysis. The main themes studied are neutronics, materials, components, thermal-hydraulic matters, fuel, handling, and maintenance.

In the presentation of today, I will give only three examples of all this accumulated experience described, theme by theme, in these two books.

The main themes of the Phénix book, for example, we have a general presentation of the reactor, that is useful because it gives... I can go back to this... There is the general presentation of the reactor. That is useful because it gives a general view and general information of the reactor, general data also. After, the objectives of the reactor. Operation review, always the reactor has been operative, doing all those years. The safety review or the problem of safety ??? during the operation, the 35 years of operation, with also all the incidents. All the problems related to the decay heat removal of the plant, that is a minor theme. The core physics with all the neutronic matters. The fuel element, with the experience acquired on the fuel and the material of the fuel. After arrival, the lead components. The intermediate heat exchangers, there were a lot of problems of (neutronics) as I explain, and we were getting very ??? heat problems. All the problems that arose with the steam generators. The sodium pumps and the control rods are the main components. All those are the main components of the plant.

After, we have the list of all the main irradiations made in this reactor and the initial examination with the main results that we obtained. The demonstration of transmutation possibility with a lot of tests that were made specifically on the second side of the ??? neutronics. And the results of main tests made on the reactor.

After all, we had the final tests that were used at the end of life of Phénix, special tests were made. After, we have the experience of the materials, the difficulties, and some corrosion problems. After, we had all the experience acquired in the in-service inspection. The washing, decontamination, and repair. You have to know that all the components had been taken out of the plant, waste and ??? in Phénix with the big experience on the subject, with handling matters and sodium leaks. We had exactly more than 30 sodium leaks in Phénix, and we explained the experience that we acquired in nuclear matters. Other problems of sodium chemistry, also the sodium technology, that is also ??? apart to ??? ???.

The results of environmental reports. The negative reactivity trips from accidents that we had in Phénix, at the end of life of Phénix. Also, the activities of reprocessing and multi-recycling. Co-generation experiments. And Phénix's contribution to Superphénix.

So you see that we got a lot of very useful themes with a lot of technical results.

And on the Superphénix book, they will come back and I have the same types of theme. The construction review of the reactor. All the tests at the beginning to operate the plant in two years, with some problems of (vibration), the (shelf). The operational results of the plant. The problem of safety, especially for the (fission) fire experience. We have the operating experience of the plant. The fuel subassembly. Also neutronics matters. It is the largest core on the sodium fast reactor that was ever tested in the world, and this experience, theirs is always a very interesting (law), so the code of neutronics.

After ??? to the lead components. Primary pumps, the secondary pumps, intermediate heat exchangers, the steam generators. We give for all the components all the experience that we have had on these components. After, we have the problem of sodium/water reaction.

And after, we had a sodium leak and fire. We had some sodium leaks at the plant and we explained the reason for the leaks. The reactor shutdown and control system. The decay heat removal. The materials, we give very interesting experience because we had the huge experience of Rapsodie, then with Phénix and Superphénix has the largest experience and the materials to be used for the sodium fast reactor.

After, we have all the problems of thermal-hydraulics that are the difficult problems. The in-service inspection. We had a new methodology that was tested in Superphénix. The chemistry of sodium, how to clarify the sodium and how to maintain a good level of ??? sodium. The sodium technology with ??? and other matters. Handling. The environmental results. Dismantling, it was not in the book on Phénix. And Superphénix Children, which is on the design experience that we tested after the end of Superphénix, which it doesn't do, and with the (European) fast reactor.

Today, it's clearly impossible to see all these themes because it's a very long history of ??? procession. We chose only three examples.

The first example is the reprocessing experience on Phénix because it is an industrial experience unique in the world, and because of that, when we speak of a sodium fast reactor we need also to speak of reprocessing because the two are necessary for the interest of the ??? start of a reactor.

After, we speak of the SPX construction because it's an impressive industrial work. It's the biggest reactor ever built in the world. And after, we speak of the neutronics of the Superphénix core. It remains today a very interesting case for all the neutronics studies.

It's clear that a lot of other points could have been interesting to discuss as chemical matters, materials, fuel behavior, water sodium reaction, et cetera, and even dismantling. But it is not possible in such a short time. For example, in July 2017, with Gérard Prêl, we were in Korea, we needed three days only to present the summary of the Superphénix book. But today, we only have three examples, and even on these three points, I will be relatively short in comparison with the presentation we do usually.

Phénix reprocessing. The first case, 520 Phénix assemblies were reprocessed. It represents 4.4 tons of plutonium. In '73, we had the first irradiation of Phénix fuel. In '80, we had the first Phénix assembly loaded in core and built with recycled plutonium coming from the reprocessing process. In '91, we had the end of the Phénix fuel reprocessing activities.

And we have the *schéma*, and here we have the years, and here we have the number of assemblies that were fabricated, loaded in the core, unloaded from the core, dismantled, reprocessed, and totally reprocessed.

This reprocessing activity was made with three different lines. The first line was the AT1 line in La Hague. It was the first French prototype facility for the fast reactor spent fuel reprocessing. It was operated from '69 to '77. Capacity was 150 kg/year, 1 kg/day. And we tried reprocessing activity of Rapsodie-Fortissimo and Phénix.

And here is a table with all of the one reprocessing campaign, batch, bad batch, with the number of the campaign, number of pins, the amount of uranium and plutonium, the megawatt joule per ton of the fuel assembly, and the months, the time necessary in a short time.

In the book we tried to explain all that was made in terms of reprocessing on the screen, there's AT1 in Marcoule, after in ???. The AT1 line with dismantling of assemblies in the Phénix hot cells. After, the shearing operations, needle by needle in AT1, and the dissolving carried out intermittently with successive extraction cycles to separate uranium and plutonium.

In the APM, the Atelier Pilote Marcoule, the TOP line was operated from '73 to '83. First, we had this one-third the fuel of Rapsodie-Fortissimo and KNK, the German reactor. And '76 to '78, the first core of Phénix reactor. And after, from '78 to '83, we had reprocessed 6.8 tons of MOX cores of Phénix.

After, this is the renovation of APM was moved to TOR. It was a new installation. And this TOR Line, we have another batch of Phénix fuel that we reprocessed in this new line.

After, we went from '79 to '84 to UP2. UP2 is the reprocessing, it is the ??? that is in La Hague in the north of France. And we reprocessed 10 tons of Phénix internal core fuel.

The conclusion. We reprocessed, we had 520 assemblies of Phénix, the equivalent of four-and-half Phénix cores. That includes the first uranium-enriched core; this represents a little over 26 tons.

The measurements made during the reprocessing operations allowed an experimental estimation of an overall breeding rate of 1.16, which confirmed the expected theoretical value, 1.13.

Here we see all the cycles of the fuel in Phénix. Phénix is in Marcoule. We had 4.4 tons of Pu created by these 520 assemblies going to reprocessing in Marcoule and La Hague. After 1.1 tons had gone to other cycles of Pu, plutonium, and 3.3 tons went back to fabrication in Cadarache of fuel, and the fabrication of fuel, the MOX fuel built with plutonium, came back to Phénix. Here we see the comeback of the fuel to Phénix. And 5.3 tons of plutonium were coming from Marcoule to make the global fabrication of all the fuel in Phénix.

The conclusion on the Phénix fuel reprocessing and fabrication.

About 3.3 tons of reprocessed plutonium were used to build the new Phénix fuel. That means that about 40% of Phénix fuel was built and burned with plutonium coming from their own reprocessing. For several assemblies, this complete fuel cycle, reprocessing plus fabrication plus burning, was three times achieved. This unique experience in the world has allowed an industrial demonstration of multi-cycling possibilities in a fast breeder reactor.

If I go back to the construction, we have more expenditures in the chapter on the reprocessing and fabrication up to the ???. It's a near summary.

Now we arrive at the second example, the Superphénix construction. Here we can see the site of Superphénix before construction.

Then we see Superphénix as a European reactor. The owner of Superphénix was not there. The NERSA company established it in '74 with EDF but also ENEL, a German company, and also British Nuclear Electric and ???.

And a law was enacted to authorize this organization to operate in France. The order for industry was passed in '76, and the authorization decree was also in '76.

There were some negative consequences in the European organization because you had to choose, sometimes it was difficult to choose the best industrial supplier because each country wanted to get back its money.

For the turbine, the Italian provider was ANSALDO, which had no turbine with a power of 1240 MWe. The choice of two turbines of 620 MWe was made. Some providers were not well known and sometimes out of the nuclear field. And some technical difficulties would arrive later due to these poor choices, such as the material of the drum vessel.

This complicated organization was also the cause of extra costs and extra deadlines.

We needed to do some exceptional transport. When it is possible it is better to manufacture in a factory, so all the large components from heat exchangers and steam generators, were transported to the site. Here we see the steel reactor arriving at the site of Superphénix.

The rotating plug in two parts and the diagrid, 8.9m in diameter, were the biggest parts transported by exceptional transportation into the site. Here we can see the diagrid arriving from Italy on the site of Superphénix.

The reactor block. The civil engineering work began on site with the reactor block construction. The reactor pit and storage drum pit were built inside the reactor block. You can see a bit of the construction, and here we can see the block construction. Gantries were managed in the block. Gantries can be seen there. Gantries were managed in the block to allow later transportation of the main structures inside the ???.

So you can see the workshop building. You can see there the hole that would be necessary to ??? the material. For the Superphénix reactor, we had large structures. For example, the safety vessel had a diameter of 22.5m and a height of 15.9m. The weight was also important, until 850 tons. So their transportation from the factory was not possible and they were manufactured on site in the workshop building. You can see there the workshop building, they are rebuilding there. And all the large structures were built inside there.

So I have to give some notion of packages. So inside the workshop, before transportation, we had to build the safety vessel. You see the diameter and the weight. We had to build the main vessel including structures as a core catcher, core support, and ???.

The internal sections, the diagrid, the slab, the two rotating plugs, and the dome. And on the (place), they are rising inside the pit as the ocean ???...

Oh, where I am... Ah, there is something seeing ???.

Welding procedures. You had to build the elements in the workshop, and at this time, the base elements available in the factory had a length of about 1.8m. We had to preassemble and to weld on site. We had a large quantity of welds to provide. Only for the main vessel, there were 800 meters of welds provided. All the welds were performed manually because at this time there was no possibility for automatic welding. One hundred percent of radioactive control. The post welding heat treatments were not possible for such large structures. It was not possible to make it that much. We needed special procedures. And final welding, as the main vessel, with the slab for example, was to provide inside the reactor block.

Though even we kept rising all the packages, the first package was the safety vessel, which was arising inside the reactor, and here we can see the pit and the safety vessel would go inside the pit.

After, in the safety vessel, that is there, we had the arising of the main vessel, that vessel is there, that would arise in the safety vessel. And here we can see the chocks that were installed between the two vessels for this provisionary installation.

After, we had the internal structures that arose inside the main vessel. There we have the internal structures.

After, we had the fourth package, the reactor slab. You see here on the right the slab that was arising over, above the main vessel. It was the heaviest one. It was 850 tons.

The simplified schedule shows that we started in '77, the beginning of the operation of civil engineering. Then we began filling sodium in '84, and the nominal power was reached in '86, so ten years, about ten years before the first concrete and the nominal power of the plant.

These are the final schedule results. We can see that there was some over-delay. You see that the over-delay has even transparency, and nominal power was reached in 112 months instead of the 70 announced at the beginning. It was 42 months slippage, but when we compared to the delay to build the new reactor, I think it was a good performance.

The conclusion of this resumé of the Superphénix construction. It was successful innovative manufacturing on site with the workshop. In the future, development of automatic welding adapted to fast breeder reactor materials has to be used. It was seven years of construction for 7 billion euro in 2012. It was for a prototype, the last prototype, with a very honorable performance. We had 30 months over-delay that could be reduced in "a series" production.

(No other reactor itself is more powerful) today. It was a neutronic operation of the Superphénix core. This core had 5.7 tons of plutonium inside. We had the largest sodium fast reactor ever operated in the world. And we have the list of all the elements inside the reactor, 360 fuel subassemblies, 21 control rods plus 3 special control rods, 222 breeder subassemblies, and you saw a lot of elements inside this core.

There were two enrichment zones in each core to flatten the flux curves. The fissile core in periphery core 2 had higher enrichment than the inner core, core 1. And the weight enrichments were different between core 2 and core 1. There was 19.53% plutonium in core 2 and 15.52% plutonium in core 1.

The management mode. It was a cycle of 320 EFPD, equivalent full power days. Each subassembly remained in the reactor two cycles, so 640 equivalent full power days. At each shutdown, half the core was reloaded with fresh fuel, and the core was rearranged for the next cycle. It was frequency 2 management. The first core had an excess of reactivity, that meant a special management of the first cycles.

The neutron monitoring was managed with 12 management channels located under the reactor vessel. Two trains with three low-level channels and three high-level channels were installed. For the first divergence, three measurements in a special device, BOUPHY, were implemented in the center of the core, with three low-level channels allowing more precise measurements.

The control rod system will be analyzed in chapter 15.

And the treatment of the signals delivered variables as reactivity, double time of power.

We had thermal monitoring. The inlet temperature was measured in the primary pumps and used for the related diagrid part. That gave entry of the temperature in the fuel assembly. The outlet temperature was measured for each fissile subassembly with two thermocouples chromel/alumel.

All these temperatures were managed by the core monitoring system to survey abnormal heating and to calculate the maximal clad temperature in line.

For the clad failure detection and location, the clad failure detection system was called DRG. A sampling system with eight modules allowed to measure delayed neutrons emitted by fission products released in sodium.

The clad failure location system with six sodium sampling modules allowed with rotating selectors to measure each outlet and to identify the concerned subassembly.

A test in reactor with the source CARAMEL was made to demonstrate and calibrate these two systems to measure the time of transfer.

A measurement of the cover argon contamination was also made with gamma measurements.

We had some (subcategory fields). If there was any fuel co-loading, the core had been loaded with dummy fuel assemblies for further hydraulic tests in sodium. You will see, at the beginning, we fill, before to fill in sodium, we made the initial core loading.

After the hydraulic test in sodium, the dummy subassemblies were replaced by fresh fuel by batches. The loading was made by a checkerboard approach to criticality. No neutron source was used. After each loaded batch, the BOUPHY measurements gave a reactivity evolution.

After the loading of 325 subassemblies, a first divergence was achieved. The replacement of the 33 remaining dummy subassemblies was performed in two batches. And we have here the core divergence with the amounts, the ??? in ???.

There was also in the core a lot of experimental measurements. Twenty-two experimental subassemblies were used for the measurement of flux distribution in the core, and the maximal linear power density at full power was confirmed at 480 W/cm.

And we had the measurements of the (counter-reaction) coefficient, the coefficients K, G, H. K is the core inlet temperature coefficient, G is the core heating efficient, H is the power coefficient. All of these counter coefficients were negative. So that showed the safety of the neutronics of the core.

The measurements were made by steps on reactivity and the primary pump speed and secondary pump speed, and then by calculation with three equations with three unknown values.

A lot of other measurements were provided on this core in about six months: the negative reactivity values of each control rod, the average isothermal coefficient, the Doppler coefficient, the Doppler constant, and all the heating of each subassembly as compared to the forecast calculations.

The operating experience has shown a lot of things. The core thermal monitoring was efficient to prevent flow blockage. We had an accident with a rubber plug inside the subassembly foot that was loaded in the reactor. And the problem, the little ??? inside the subassembly was measured, and you could follow the core status in (terminal) transient situations.

The core neutronic monitoring was efficient but could be improved. We figured it would be better to have complementary measurements inside the core.

We had also mechanical problems on the DRG/LRG and the detection of ???.

We had spatial effects due to large cores, and that led to some initial discrepancies between calculation and measurements, up to 17% for some subassemblies powers and 20% for some control rods' worth, although we had a lot work on the core to come back and to explain this difference.

In conclusion on the Superphénix neutronic experience, the Superphénix core with 360 fuel subassemblies and about 5.7 tons of plutonium was the largest sodium fast reactor ever operated in the world. The fissile zone was approximately 10m3 for 3000 MWth. The loading, divergence and monitoring options were well validated and didn't pose any particular difficulties to the operator. Measurements allowed further improvement in neutron calculation codes. And some monitoring improvements were suggested for the future in the book.

In conclusion, a large experience exists with the construction and operation of the French SFR reactors Phénix and Superphénix. These two books on this subject give a first idea of this experience with a lot of recommendations for each topic.

We hope that they will be useful for all designers to further enhance the design of these future promising Generation IV reactors.

Thanks, again.

Oates: Thank you, Dr. Guidez. If you have questions on the presentation today, please go ahead and type those in the chat box, and while we're waiting for questions to come in, I'm going to go ahead and just give you a sneak peek of the upcoming webinars.

In December, we anticipate a presentation on, The sustainability, a relevant framework for addressing GEN IV Nuclear Fuel Cycle, from Dr. Poinssot from France, and in January, a presentation on the China HTR-PM from Prof. Dong

Jujie, from China, and in February, a presentation on GEN-IV's reactor materials and their challenges from Dr. Maloy from the United States.